ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

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CONTROL OF TIME-DELAYED SYSTEMS WITH EXPERIMENTAL APPLICATIONS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA-2018

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

STABILITY ANALYSIS AND CONTROL OF TIME-DELAYED SYSTEMS WITH EXPERIMENTAL APPLICATIONS

Necdet Sinan ÖZBEK

PhD THESIS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of degree of the Doctor of Philosophy by the board of jury on 02/07/2018.

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This PhD Thesis is written at the Department of Electrical and Electronics Engineering of Institute of Natural and Applied Sciences of Çukurova University.
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This thesis was supported by the Scientific Research Project Unit of Çukurova University (Project Number: FDK-2015-5088). This thesis was supported by TÜBİTAK under the 2214-A Grant Programme.

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ABSTRACT

PhD THESIS

CONTROL OF TIME-DELAYED SYSTEMS WITH EXPERIMENTAL APPLICATIONS

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Supervisor : Prof. Dr. İlyas EKER
Year: 2018, Pages: 272
Jury : Prof. Dr. İlyas EKER
: Prof. Dr. Mehmet TÜMAY
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Time delay is an important problem in control engineering that has been working for more than half a century. More precisely, a stable feedback system may become unstable for some delay value yet, a delay value may stabilize an unstable system or enhance the control performance, and this paradox makes time delay systems very attractive. A number of novel control schemes are presented in the thesis and analysed in order to improve the capabilities of control systems. First, considering the negative effect of delay, a number of predictor based control strategies are proposed for different system types. It is observed that the proposed control strategies give extra robustness and improve the capability of the control systems. Second, from a different perspective, the favourable effects of the time delay are investigated. Toward this goal, delay-based control schemes are designed and experimentally applied to an electromechanical system. The control methods are tested in simulations and then experimentally applied to real systems. The experimental results are presented graphically and tabulated in terms of some performance measures. According to the results, the proposed algorithms are very effective in controlling the time delay systems in the presence of noise, internal/external disturbances, and uncertainties.

Key Words: Time Delay, Fractional Order Control, Optimisation, Sliding Mode Control, Delay Based Control

ÖZ

DOKTORA TEZİ

ZAMAN GECİKMELİ SİSTEMLERİN DENEYSEL UYGULAMALARLA KONTROLÜ

Necdet Sinan ÖZBEK

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
ELEKTRİK – ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Prof. Dr. İlyas EKER
Yıl: 2018, Sayfa: 272
Jüri : Prof. Dr. İlyas EKER
: Prof Dr. Mehmet TÜMAY
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Kontrol teorisi açısından, zaman gecikmesinin etkilerini anlamak kontrol mühendisliğinde yarım asrı aşkın süredir çalışılan önemli bir sorundur. Daha doğrusu, kararlı bir geri beslemeli sistem, bazı gecikme değerleri ile kararsız hale gelebilir, aynı zamanda, gecikmenin uygun bir şekilde seçilmesi, kararsız bir sistemi kararlı kılabilir veya kontrol performansını artırabilir; bu paradoks, zaman gecikmeli sistemleri çok cazip hale getirmektedir. Bu tezde zaman gecikmeli sistemlerin yeteneklerini geliştirmek için, bir takım yeni kontrol şemaları önerilmekte ve deneysel olarak gerçeklenmektedir. Kararlılık analizi detaylı olarak tartışılmıştır. Öncelikle, gecikmenin olumsuz etkisini göz önünde bulundurarak, birtakım öngörü tabanlı kontrol stratejileri önerilmektedir. Önerilen kontrol stratejilerinin sisteme ekstra gürbüzlük kazandırdığı ve kapalı çevrim sistem performansını arttırdığı gözlenmektedir. Ayrıca, farklı bir perspektiften bakılarak, zaman gecikmesinin olumlu etkileri araştırılmıştır. Bu amaca yönelik olarak, gecikmeye dayalı kontrol şemaları tasarlanmıştır. Kontrol yöntemleri önce benzetimlerle test edilmiş ve daha sonra gerçek sistemlere deneysel olarak uygulanmıştır. Deneysel sonuçlar bazı performans kriterleri açısından grafiksel olarak ve tablo halinde sunulmaktadır. Sonuçlara göre, önerilen kontrol algoritmaları, gürültü, iç/dış bozucular ve belirsizlikler varlığında zaman gecikmeli sistemleri kontrolünde daha etkindir.

Anahtar Kelimeler: Zaman Gecikmesi, Kesir Dereceli Kontrol, En iyileştirme, Kayan Kipli Kontrol, Gecikmeli Kontrol.

EXTENDED SUMMARY

Recent advances in sensing technology, communication networks, embedded computing devices, and information-processing abilities have made it possible to develop highly compatible modern control systems. Moreover, control theory and applications are key points of many successful applications of today's emerging technology such as high manoeuvrable autonomous air and land vehicles, air defence systems, biological and chemical processes, swarm robots, networked control systems, and humanoid robots. However, present research addresses a number of time-delayed process control applications under different operating conditions.

Performance of a control system may become worse in the presence of constraints such as noise, delays, sampling, and unmodelled dynamics. In this respect, enhancing the performance of control systems under different conditions and constraints is an important topic, which is considered with various theoretical and practical approaches in the last half-century. Among these imperfections, time delay phenomenon is one of the crucial problems in control theory and applications.

Time Delay Systems (TDS) have been encountered in various applications across different areas such as; networked control systems, robotics and mechatronics, teleoperation of robots, congestion control in communication networks, traffic-flow and car following models, distributed and cooperative control for the coordination of unmanned vehicles, adaptive combustion control, haptics interfaces, motion synchronization, and biological systems as cell/virus dynamics, etc. Moreover, the importance of the delay phenomenon has been increased during the development of the theoretical and practical application of today’s emerging technologies. Thus, the investigation of favourable and detrimental effects of time delay has been done with a number of novel experimental applications.

In this thesis, a number of predictor based control strategies are addressed. The proposed control schemes are simulated and experimentally applied to different industrial control processes. Each of the elaborated control techniques has the ability to improve the performance of the closed-loop system in the presence of disturbance, uncertainties, and time delay. In order to test the control techniques, the systems are first identified. The design of the control system has been realized for different types of system. Discrete-time and continuous-time models of the system are obtained at different model orders. Toward this goal, various identification algorithms such as process reaction curves, recursive least squares based digital identification, are experimentally applied. As a contribution an interactive system identification tool has been developed that allows real-time identification of different systems.

It should be noted that fractional calculus and fractional order controllers are very attractive in the control community. However, fractional control needs more effort to present the efficiency of the control technique. A number of fractional order control based predictor structures are elaborated. The aforementioned controllers are designed for first order plus dead time (FOPDT) models. The central notion of each technique is discussed according to their advantages and drawbacks. The performance results are examined with both simulations and experimental applications. The closed-loop system and trajectory tracking performance are satisfactory in real-time applications compared with conventional techniques.

Yet another contribution of the thesis is to investigate a number of robust control based SP structures with experimental applications. More specifically, first-order sliding-mode control and second-order sliding-mode control techniques are implemented for a second order plus dead time process. The performance results of the used methods are presented in the related section. In this section, the most effective method is determined by comparing the disturbance rejection capabilities of each control strategies. All methods are investigated for set-point regulation,

trajectory tracking, noise suppression, and disturbance rejection. The performance measures are presented in a tabular form. By comparing the performances of the methods used in the present research, it is observed that second-order sliding-mode control based SP provides better control performance than classical PID control based SP for the closed-loop control system in the presence of uncertainties and disturbances.

The combination of fractional order control, fuzzy control, and Smith predictor has been combined in a novel control scheme. Toward this goal, a gain-scheduling Smith predictor (SP) system is proposed and experimentally applied for the first time with the aim of compensating for a dead time process in the presence of disturbance and uncertainties. Further, a nature-inspired optimization algorithm solves the controller-tuning problem. The proposed control scheme is optimized by genetic algorithm. The performance results are examined using the Matlab/Simulink program for different case studies. Using this method, the control performance is enhanced in the presence of internal/external disturbances as well as uncertainties compared with integer order fuzzy control techniques. The reference tracking performance, applicability of the control signals, the transient regime and steady state of the system are observed, according to the results, optimal fractional fuzzy PI-PD based Smith predictor is determined as the best control scheme.

A further contribution of the present research is to investigate the positive effects of time delay on control performance. Concerning the matter, a number of research studies revealed that the time delay, in some cases, might be beneficial for stability and control of the dynamical system. A further benefit of utilizing delays is allowing the designer to replace derivative term. Delay-based control design has attracted a great deal of interest in the last few decades. However, most of the research studies are based on simulation results. In this respect, the design and experimental application of the proposed controller constitute other important contributions of the thesis.

A deliberate introduction of a delay may enhance the control performance without relying on accurately tuned estimates for derivatives of measured signals. The research addresses various delay-based control strategies. The strategy is based on a delayed controller, which has some intentional delay on the controller. The control strategies namely; Proportional Integral Retarded (PIR) and Proportional Integral-Proportional Retarded (PI-PR) are investigated respectively. The elaborated methods include the optimal parameter tuning of the controller as well as the stability analysis. At this point, a very interesting result has been achieved. It is observed that an intentionally introduced time delay improves the system performance if it is chosen appropriately. The theory and performance of the proposed technique are also presented with experimental results. Experiments over a set of processes as well as a comparison with conventional a PI-PD controller are performed to highlight the advantages of the proposed scheme.

GENİŞLETİLMİŞ ÖZET

Algılama teknolojisi, iletişim ağları, gömülü işlemciler ve bilgi işleme yeteneklerindeki son gelişmeler, son derece yüksek kabiliyetli modern kontrol sistemlerinin geliştirilmesini mümkün kılmaktadır. Bununla birlikte, kontrol teorisi ve uygulamaları günümüz gelişen teknolojisindeki, birçok başarılı uygulamanın, örneğin, yüksek manevra kabiliyetli otonom hava ve kara araçları, güdümlü füzeler, hava savunma sistemleri, biyolojik ve kimyasal süreçler, çok erkinlik robot toplulukları, ağ tabanlı kontrol sistemleri, insansı robotlar, kilit noktası durumundadır. Bununla birlikte bu çalışma, farklı çalışma şartlarındaki zaman gecikmeli süreç kontrol ve mekatronik uygulamaları ele almaktadır.

Kontrol sistemlerinin performansı, gürültü, gecikmeler, örnekleme ve modellenemeyen dinamikler gibi birçok kısıtlamanın varlığı durumunda daha da kötüleşebilir. Bu bağlamda kontrol sistemlerinin değişik şartlarda ve kısıtlar altında performansını arttırmak araştırmacıların son yarım yüzyılda farklı teorik ve pratik yaklaşımlarla ilgilendiği önemli konulardandır. Bu zorluklar arasından, zaman gecikmesi kontrol teorisi ve uygulamaları açısından en önemlilerinden biridir.

Zaman gecikmeli sistemlere, farklı alanlardaki çeşitli uygulamalarda karşılaşılmaktadır; ağ tabanlı kontrol, robotik ve mekatronik, robotları uzaktan kontrolü, iletişim ağlarında tıkanıklık kontrolü, trafik ağı ve otomobil takip modelleri, insansız araçların koordinasyonu için dağıtılmış ve kooperatif kontrol, uyarlanmalı yanma kontrolü, haptik ara yüzleri, hareket senkronizasyonu ve biyolojik sistemler; hücre/virüs dinamikleri. Ayrıca, zaman gecikmesinin önemi günümüz teknolojilerin teorik ve pratik uygulamaları sırasında daha da önem kazanmaktadır. Böylece, zaman gecikmesinin hem olumlu hem de olumsuz yanları birçok farklı yöntem bir takım yeni deneysel uygulamalar ile yapılmaktadır.

Bu tezde, öngörü temelli farklı kontrol stratejileri ele alınmaktadır. Önerilen kontrol şemaları benzetimlerin ardından farklı endüstriyel kontrol süreçlerine deneysel olarak uygulanmaktadır. Ele alınan her bir kontrol tekniği

bozucu, belirsizlik ve zaman gecikmesinin varlığında kapalı çevrim kontrol performansını arttırma kabiliyetine sahiptir. Kontrol tekniklerini test etmek için, önce sistemler ayrıntılı olarak tanılanmaktadır. Kontrol sisteminin tasarımı, farklı sistem türleri için gerçekleştirilmektedir. Sistemin farklı derecelerde ayrık ve sürekli zamanlı modelleri elde edilmektedir. Bu amaca yönelik, süreç reaksiyon eğrileri, özyinelemeli en küçük kareler yöntemine dayalı dijital tanılama gibi çeşitli algoritmalar deneysel olarak uygulanmaktadır. Literatüre katkı olarak değişik sistemlerin gerçek zamanlı tanılanmasına olanak sağlayan etkileşimli bir sistem tanılama aracı geliştirilmektedir.

Belirtilmelidir ki kesir dereceli matematik ve kesir dereceli denetleyiciler kontrol topluluğunda çok ilgi çekicidir. Bununla birlikte, kesir dereceli kontrol, kontrol tekniğinin etkinliğini sunmak için daha fazla çaba gerektirir. Bir dizi kesir dereceli kontrol esaslı öngörücü yapıları ayrıntılı olarak irdelenmektedir. Bahsedilen kontrolörler birinci derece ölü zamanlı modelleri için tasarlanmaktadır. Her tekniğin arkasındaki felsefe, avantaj ve dezavantajlarına göre tartışılmaktadır. Performans sonuçları hem benzetimler hem de deneysel uygulamalar ile incelenmektedir. Kapalı döngü sistemi ve yörünge izleme performansı, gerçek zamanlı uygulamalarda tatminkârdır.

Kesirli dereceli kontrolcüler, bulanık kontrol ve Smith öngörücüsü yeni bir kontrol şeması içinde birleştirilmektedir. Bu amaca yönelik olarak, bozucu ve belirsizlik varlığındaki bir ölü zaman sürecini kontrol etmek amacıyla kazanç ayarlamalı Smith öngörücüsü sistemi önerilmekte ve ilk defa deneysel olarak uygulanmaktadır. Dahası, doğadan ilham alan bir optimizasyon algoritması, kontrol parametre ayarlama problemini çözmektedir. Önerilen kontrol şeması genetik algoritma ile en iyileştirilmektedir. Performans sonuçları farklı durum incelemeleri için Matlab/Simulink ortamında benzetilmektedir. Bu yöntemi kullanarak, kontrol performansı, belirsizliklerin yanı sıra iç/dış bozucuların bulunduğu ortamlarda geliştirilmektedir. Referans takip performansı, kontrol sinyallerinin uygulanabilirliği ve geçici tepkileri incelenmekte, elde edilen

sonuçlara göre optimum kesirli dereceli bulanık PI-PD tabanlı Smith öngörücüsü en iyi kontrol şeması olarak belirlenmektedir.

Tezin yine bir başka katkısı, deneysel uygulamalarla gürbüz kontrol temelli farklı Smith öngörücüsü yapılarının incelenmesidir. Daha spesifik olarak, birinci dereceden kayan kipli kontrol, ikinci dereceden kayan kipli kontrol yapıları, ikinci derece ölü zamanlı modellenen bir sistem üzerine uygulanmaktadır. Önerilen yöntemlerin performans sonuçları ilgili bölümde sunulmaktadır. Bu bölümde, en etkili yöntem, her kontrol stratejisinin referans takip ve bozucu bastırma gibi kabiliyetleri göz önünde bulundurularak belirlenmektedir. Tüm yöntemler, ayar noktası düzenlemesi, yörünge izleme, gürültü azaltma ve bozucu bastırma yetenekleri ile irdelenmektedir. Performans ölçütleri tablo biçiminde sunulmaktadır. Bu çalışmada kullanılan yöntemlerin performanslarını karşılaştırarak, ikinci dereceden kayan kipli kontrole dayalı Smith öngörücüsünün yapısının belirsizliklerin ve rahatsızlıkların bulunduğu kapalı döngü kontrol sistemi için klasik PID tabanlı Smith öngörücülerine göre daha iyi kontrol performansı sağladığı görülmektedir.

Bu araştırmanın bir başka katkısı, zaman gecikmesinin kontrol performansı üzerindeki olumlu etkilerini araştırmaktır. Konuyla ilgili olarak, bazı araştırma çalışmaları, zaman gecikmesinin bazı durumlarda dinamik sistemin istikrarı ve kontrolü için yararlı olabileceğini ortaya koymaktadır. Gecikmeleri kullanmanın bir başka yararı, tasarımcının türev yerine gecikme terimini kullanılabilmesine olacak sağlamasıdır. Gecikmeli kontrol tasarımı son birkaç on yılda büyük ilgi gördü. Bununla birlikte, araştırma çalışmalarının birçoğu benzetim sonuçlarına dayanmaktadır. Bu bağlamda, önerilen denetleyicinin tasarımı ve deneysel uygulaması, tezin diğer önemli katkılarını oluşturmaktadır.

Zaman gecikmesinin kasıtlı olarak uygulanması, ölçülen sinyallerin türevleri için doğru ayarlanmış tahminlere dayanmaksızın kontrol performansını arttırabilmektedir. Araştırma gecikmeye dayalı çeşitli kontrol stratejilerini ele almaktadır. Bu kontrol stratejisi, denetleyicide bazı bilinçli gecikmeler içeren, bir

gecikmeli denetleyici olarak adlandırılabilir. Kontrol stratejileri; oransal integral gecikmeli ve oransal integral-oransal gecikmeli olarak araştırılmaktadır. Detaylandırılan yöntemler, kontrolörün en iyi parametre ayarlaması ve kararlılık analizini içerir. Bu noktada çok ilginç bir sonuç elde edilmektedir. Gecikmenin çok iyi hesaplanarak sisteme bilinçli eklendiği durumlarda gecikmenin sistem performansını arttırabildiği gözlenmektedir. Önerilen tekniğin teorik doğrulaması ve performansı deneysel sonuçlarla da sunulmaktadır. Önerilen kontrolcünün avantajlarını ortaya çıkartmak için bir takım süreçler üzerine yapılan deneyler ve önerilen kontrol şemasının geleneksel yöntemler ile karşılaştırılması yapılmaktadır.

ACKNOWLEDGEMENTS

I would like to present my endless gratitude to my supervisors Prof. Dr. İlyas EKER for his unlimited support, guidance, patience, and motivation for the successful completion of this research work.

I wish to express my special thanks to Prof. Dr. Mehmet TÜMAY and Assoc. Prof. Dr. Ramazan ÇOBAN, for their valuable help, support and suggestions. I wish to express my special thanks to Assoc. Prof. Dr. Turgay İBRİKÇİ, Assoc. Prof. Dr. Alkan ALKAYA, and Asst. Prof. Dr. Murat FURAT for accepting to be the member of examining committee for my thesis and for their valuable suggestions.

I am also thankful to Res. Asst. Özgür Çelik and Res. Asst. Kasım Zor for being more than a colleague.

The financial support of the Scientific and Technological Research Council of Turkey during my Ph.D. is gratefully acknowledged.

I would also to thank and acknowledge the financial support of Scientific Research Project Unit of Çukurova University for my thesis (Project Number: FDK-2015-5088)

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LIST OF ABBREVIATIONS

TDS	: Time Delay System
NCS	: Networked Control System
FOPDT	: First-Order Plus Dead-Time
SOPDT	: Second-Order Plus Dead-Time
TOPDT	: Third-Order Plus Dead-Time
LMS	: Least Mean Squares
LS	: Least Squares
RLS	: Recursive Least Squares
RELS	: Recursive Extended Least Squares
ARX	: Autoregressive Exogenous
ARMAX	: Autoregressive Moving Average Exogenous
GUI	: Graphical User Interface
SP	: Smith Predictor
IMC	: Internal Model Control
PPI	: Predictive Proportional Integral
SMC	: Sliding Mode Control
SOSMC	: Second-Order Sliding Mode Control
GSC	: Gain Scheduling Control
LPV	: Linear Parameter Varying
LTI	: Linear Time Invariant
PID	: Proportional Integral Derivative
PI	: Proportional Integral
PD	: Proportional Derivative
PI-PD	: Proportional Integral Proportional Derivative
FOC	: Fractional Order Control
rpm	: revolution per minute
IAE	: Integral Absolute Error

ISCI	: Integral Squared Control Input
ISE	: Integral Squared Error
ITAE	: Integral Time Absolute Error
TV	: Total Variance
MAE	: Maximum Absolute Error
BSC	: Backstepping Control
VSC	: Variable Structure Control
DAQ	: International Electro-technical Commission
PIR	: Proportional Integral Retarded
PI-PR	: Proportional Integral Proportional Retarded
LPF	: Low Pass Filter
V	: Volts

1. INTRODUCTION

The research is introduced in the present chapter. Initially, delay phenomenon is given, and then a brief review of stability analysis and control of time-delay systems are presented. The importance of delay phenomenon and its effects on system stability is discussed with various examples from different application areas. Further, a number of trends in control engineering framework are highlighted. The main objectives, contributions, and the organization of the thesis are provided at the end of the chapter.

1.1. Background and Motivation

Control systems are the cornerstone of many engineering progress those applied in automotive systems, aerospace industries, chemical processes, transportation systems, medical systems and many other areas. Meanwhile, advances in software and hardware have made it possible to develop more capable control systems. However, a number of important issues should be clarified as shown in Figure 1.1, before all the benefits of utilizing a high-performance control system can be harvested (Ge et al., 2017; Zhang et al., 2017).

Among the problems, stability analysis and stabilization of time delay systems are popular research fields encountered in various areas such as; robotics, distributed control for the coordination of unmanned vehicles, vehicle platoon control, adaptive combustion control, haptics interfaces and motion synchronization, and biological systems as cell/virus dynamics (Niculescu, 2001; Normey-Rico and Camacho, 2008; Sipahi et al., 2011).

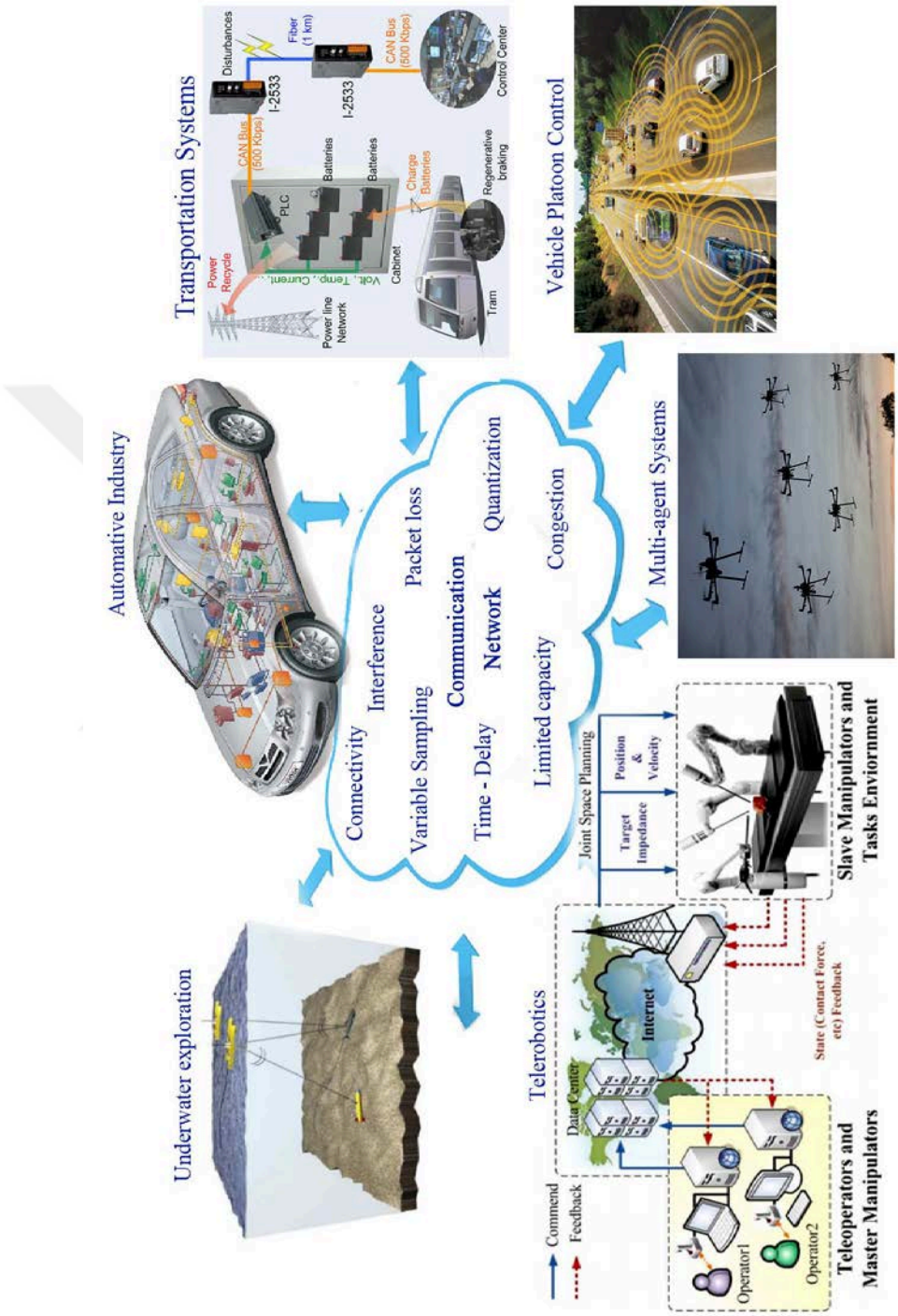


Figure 1.1 A number of constraints in control system applications

Time delay arises from perception, communication, transportation, decision-making in control system applications. Further, the sources of delay phenomena can be summarized as follows:

- The time required for transferring energy, information, and mass.
- The time required for processing and implementing for complicated control algorithm.
- The time required for data processing, noninstantaneous communication, and computational limitations.
- The time required for the transmission of control signals to actuators.

The aforementioned delay makes the control of systems difficult and potentially leads performance degradation and even instability. However, the detection of the delay not only promotes a better understanding of the system dynamics, but it also becomes the preliminary step for compensating or using that delay.

Since the 1950s, various studies have been dedicated to understanding the effects of time delay and investigating theoretical control approaches to avoid the detrimental effects of delays to dynamical behaviour of the system. One of the first tools to deal with delays is known as Smith predictor (Smith, 1959). On the other hand, an interesting phenomenon discovered is the so-called stabilizing effect of delays (Smith, 1957), inducing delays in the control loop may lead to a stable closed-loop system, which can be lost when the delay becomes zero (Sipahi et al., 2012). The interesting feature of time delay has become the motivation of many theoretical and experimental studies in the literature, in particular for the last 50 years (Sipahi et al., 2012). Thus, a number of modified Smith predictor structures from classical to optimal intelligent schemes (Mataušek and Ribić, 2012; Bolea et al., 2014; Jesus and Barbosa, 2017) are addressed with experimental applications.

Time Delay Systems (TDS) are described by Delay Differential Equations (DDE). They have the infinite number of characteristic roots, which make their analysis and control challenging issue. In the first case, delay causes a physical constraint which does not allow reacting until periods of time after the change in the value of the state (Niculescu, 2001; Normey-Rico and Camacho, 2007; Normey-Rico et al., 2009). In another case, the time-delay may deteriorate the closed-loop response by decreasing the phase margin of the system. Furthermore, delays give a rise to a quasi-polynomial characteristic equation, which has infinitely many roots (Kolmanovskii et al., 1999; Michiels and Niculescu, 2007; Hernández-Díez et al., 2017). In such cases, the analysis and control of time delay system are challenging, since the closed-loop system has infinite Eigen spectrum. The effects, if not taken into account, may cause significant problems such as undesirable poor performance, or even instability. It is worth mentioning that, a stable feedback system may become unstable for some delay value yet, a proper selection of a delay may increase the control performance, and this paradox makes the time delay system is very attractive.

Furthermore, some studies revealed that delays could, in some cases, present an opportunity for performance enhancements (Khan et al., 2008; Ulsoy, 2015; Ramirez et al., 2016; López et al., 2018; Ramirez and Sipahi, 2018; Roy et al., 2018). Delay systems have been very attractive for control system technologists, since the well-rounded theory of classical feedback control cannot keep pace with the control design issues for systems having time-delay. These properties make the time delay systems very attractive to analyse and control, hence there have been numerous papers over the last decades dedicated to overcoming these problems (Sipahi et al., 2012).

1.2. Research Objectives and Contributions

Time delay has a major influence on the stability of dynamical systems, thus it is crucial to take into account them in the mathematical description with

delay differential equations. The effects of delay can be explained twofold, first, delay can be destructive to the stability of the system, second, in contrast to this opinion, a number of studies argued that delays can, in some cases, be beneficial for closed-loop dynamics (Sipahi et al., 2011; Ulsoy, 2015). The present research investigates both detrimental and beneficial effects of time delay phenomenon on system performance. The elaborated algorithms are experimentally applied to an industrial air heating process and electromechanical system. The objectives are to

- Describe the terminology used in the field of delay systems and its effects.
- Provide an overview of various stability analysis methods and control strategies for time-delay systems from a different perspective.
- Develop and validate system model with a number of modelling and identification techniques.
- Develop an interactive system identification tool for modelling and identification of elaborated systems.
- Develop effective control methodologies for control systems in the presence of uncertainties, parameter changes, delay variations, internal/external disturbances.
- Design fractional order controller based internal model control strategies.
- Propose and application of a second-order sliding-mode based Smith predictor for SOPDT systems.
- Propose and application of intelligent gain-scheduling control algorithms for time-delay systems.
- Investigation of beneficial effects of time-delay for control systems.
- Design a proportional integral delay controller for a second-order system.
- Propose and application of a proportional-integral proportional delay controller for a second-order linear time-invariant system.

- Evaluate performance of the proposed control methods with experimental applications.
- Explore the interplay between the various control methods; and exploits the connections revealed to produce enhanced or improved control design techniques for the control of dead-time processes.

The original contributions of the present research can be summarized as follows:

- Real-time identification of a time-delay system is achieved with a number of continuous and discrete techniques. A set of system model with the different order is obtained.
- Experimental application of fractional order proportional integral control based Smith predictor structures for a FOPDT process.
- A sliding-mode controller with the proportional integral derivative sliding surface is combined with Smith predictor. The presented control strategy is experimentally investigated with a temperature air heating process in real-time.
- A second-order sliding-mode controller is designed with a Smith predictor in order to enhance the control system performance. The proposed algorithm has been highlighted with experimental applications to a time delayed control system.
- A novel intelligent Smith predictor configuration is proposed to improve the control system performance in the presence of delay variation, internal/external disturbance, model uncertainties, and parameter changes. The performance of the proposed controller is compared experimentally with the sliding-mode controllers selected from the literature.
- Time-delay utilization in controller design is addressed from a different perspective. Concerning the matter, a proportional integral delayed controller is implemented experimentally on an electromechanical system.

- A novel control scheme namely proportional integral proportional delayed controller is proposed for a second-order linear time-invariant system. Performance of the proposed controller is evaluated using an electromechanical plant and the results are compared with well-known proportional integral derivative controllers.
- Classical and proposed methods are experimentally applied to an electromechanical system and air heating system.

The framework of the research is depicted in Figure 1.2. There are two different branches; on the one hand, a number of delay elimination methods are addressed because of the negative effects of the time-delay such as degrading the phase margin, bringing infinitely many roots of quasi-polynomial, limiting the application of the control signal. On the other hand, delay utilization methods are presented to investigate the positive effect of the time-delay such as eliminating the use of a derivative term, minimizing the effect of noise, improving the disturbance rejection capability, decreasing the computational complexity.

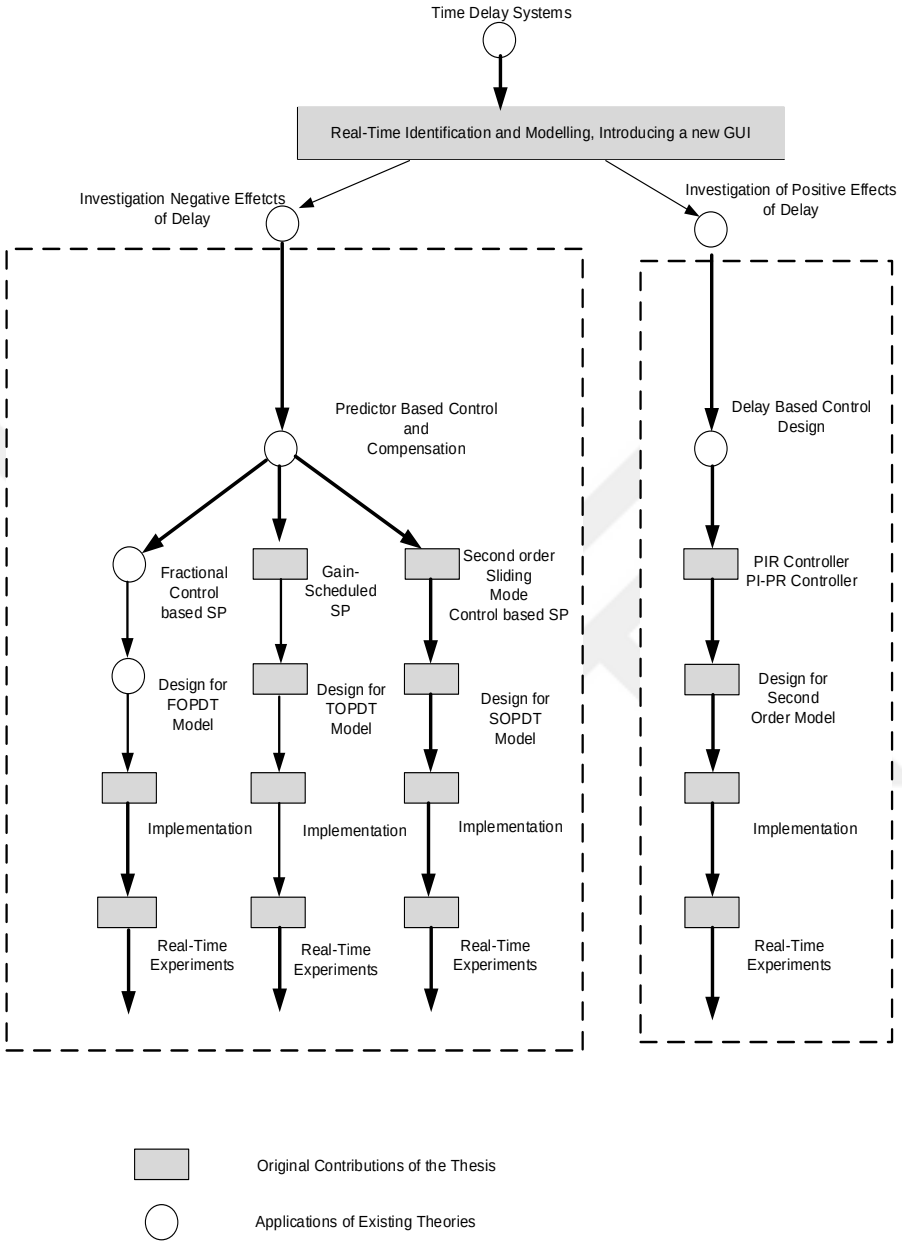


Figure 1.2 Framework of the research

1.3. The Organization of the Thesis

This thesis is organized as follows:

Chapter 1: Introduction

A brief introduction to delay phenomenon in control theory is presented in the first chapter. Theoretical background and main motivation of the thesis is addressed. A general overview of solution techniques for time delay systems is presented. Stability analysis methods and stabilization techniques are explained. Further, stabilizing and destabilizing effects of time-delay are discussed. The research objectives, contributions, and outline of the thesis are presented in the present chapter.

Chapter 2: Time Delay and Control Methods

The second chapter introduces the delay problem in control systems. A number of constraints with delay phenomenon are presented in this section. Literature survey for the various stability and control methods for delay systems is provided. Detrimental and beneficial effects of time delay on control system performance are outlined. Predictor based control strategies are discussed as the delay elimination techniques. From a different perspective delay based controller design techniques are highlighted.

Chapter 3: Proposed Control Methods

The third chapter presents the theoretical background of the proposed control techniques. The applied controllers are detailed in four parts. First, a number of fractional order control based predictor structures are presented. The methodology and application of each method are presented. The theoretical findings of aforementioned design strategies have not been strengthened by real-time applications. In terms of contributions, a comparative study of a number of fractional order control based SP structures are proposed and experimentally tested on real-system presented with first order plus dead time model.

Second, a number of robust control based Smith predictor structures are presented. A short overview of the variable structure control based Smith predictors is briefly presented and discussed. In this sense, the stability of the second-order sliding-mode controller is addressed. Next, the stability of variable

structure based Smith predictor structures with constant and varying time delays are also investigated. A first-order sliding-mode control with PID sliding surface is combined with Smith Predictor first and then, a second-order sliding-mode control based Smith predictor is introduced. As a contribution, the combination of sliding-mode control with Smith predictor is addressed. The compensation results of the modelled system under different operating conditions. The physical limitations of the real system are taken into account through the experimental applications. Further, control parameter effects on stability and control performance are investigated.

Third, optimal gain-scheduled smith predictor structures are addressed. A modified intelligent variable gain Smith predictor structures is presented to enhance closed-loop system performance in the presence of model uncertainties, parameter changes, and disturbances. Since the PI-PD control is an effective controller for different types of time delay systems, it is the core of the proposed control scheme as the structure for gain-scheduled implementation. However, the main contribution of this chapter is to propose a novel optimal fractional order intelligent controller. Further, the realization of the fractional operators is investigated.

Fourth, delay effect on the control systems is investigated from a different perspective. More specifically, positive effects of time delay such as stabilizing effect, using in spite of derivative term, noise suppression, are discussed. Hence, delay term is utilized in the controller of a feedback system that is called delay-based control. Concerning the matter, stability analysis of each technique presented systematically.

Chapter 4: Experimental Set-up and Preliminaries

The experimental setup and preliminaries are given in Chapter 4. Mathematical models of the air-heating process and electromechanical systems are described. Further, application of system identification techniques for elaborated systems is presented with a novel interactive computer-aided identification tool.

Theoretical background of each method is highlighted. Technical details of the equipment such as Data Acquisition Card (DAQ) and personal computer, which are used through the experiments, are presented.

Chapter 5: Experimental Applications

Chapter 5 presents experimental applications and results of proposed control methods given in Chapter 3. The results of experimental applications and performance comparison are elaborated in fourfold. First, performance results of fractional order control based SP structures are presented with some quantitative criteria.

Second, the simulation results and experimental tests of robust control techniques with tabulated time domain measures showed that performance enhancement of the closed-loop system enables more robust behaviour, better disturbance rejection capability, and good noise suppression ability while less energy consumption in comparison with the first-order SMC based SP scheme. It is also shown that the present controller provides better time domain specifications compared with the classical SMC in both tracking and disturbance rejection.

Third, in order to enhance the closed loop system performance, the proposed optimal gain-scheduled control techniques are experimentally tested with different types of model approximations.

Fourth, the delay-based control is addressed and experimentally implemented on an electromechanical system. Then, a novel control strategy, namely, proportional integral proportional delayed control is implemented. In addition, performance results based on some performance criteria are given.

Chapter 6: Conclusions and Future Works

Chapter 6 gives some concluding remarks, summarizes the main contributions, and discusses future directions of the present research.

Finally, the bibliography and personal information of the author are presented.

1.4. Conclusions

In this part of the thesis, basic features of the research including the research goal, problem definition, main motivations, and contributions are presented.

2. TIME DELAY AND CONTROL METHODS

2.1. Introduction

This section presents delay phenomenon as well as its effects on stability and control performance of a closed loop system. Control systems, which comprises time-delay are also called hereditary, dead-time or aftereffect systems.

In time-delay systems, the variation of system state depends not only its present value but also its past, since processes take effect after a certain amount of time elapses, which follows the input.

2.2. Importance of Delay Phenomenon

It is to be noted that delay, which may arise from perception, communication, and transportation may have counter effects on the stability and performance of a dynamical system. Further, most of the control algorithms and their real-time applications have always a time delay. It is worth mentioning that the paradox about the effects of delay makes time-delay systems highly active research field with a large amount of research effort over the half-century. Thus, analysis and control of time delay systems are one of the main research issues in control engineering framework.

The popularity of the issue in control society can be presented in Figure 2.1, wherein the number of published manuscript and related citations are given in the last decade.

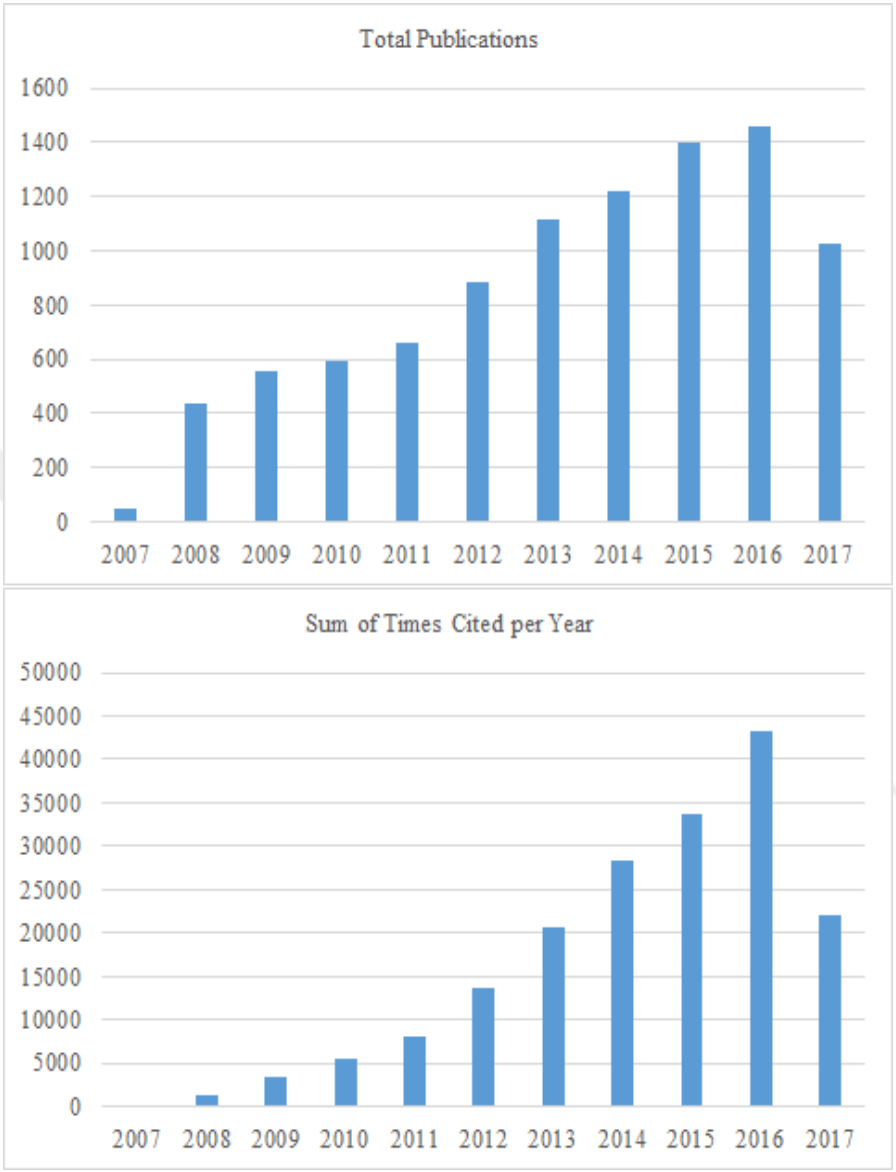


Figure 2.1 Publications dedicated to time-delay systems

2.3. Overview: Delay Effects, Stability Analysis, and Control Issues

Time delay systems have been encountered in various applications across different areas such as; robotics, electrical networks, wireless transmission of sensor data, congestion control in communication networks, traffic-flow and car

following models, distributed and cooperative control for the coordination of unmanned vehicles, adaptive combustion control, haptics interfaces and motion synchronization, and biological systems as cell/virus dynamics etc. Bearing this in mind, the following chapter mainly focuses on the delay problem in process control applications and networked control applications.

2.3.1. Time Delay in Process Control Applications

The time-delay is one of the important problems that need to be carefully considered in process control. From the application point of view, there may be a significant time delay value, which deteriorates the closed-loop system performance.

Stability analysis and stabilization of processes comprise long delay value is an important problem in control society during the last decade. More precisely, a computational delay may be neglected. However, in a physical process, there may be significant time delay value, which deteriorates the performance of the system:

- Fluid travel times,
- Recycle loops in chemical processes
- Long computation times

The main difficulties to control a time-delayed process using standard control strategies are explained as:

- The effect of the control action takes some time to be felt in the controlled variable,
- The effect of the disturbances is not felt until a considerable time has elapsed,
- The control action that is applied based on the actual error tries to correct a situation that originated sometime before.

Further, the time delay may vary from the congestion of pipes, changing of filters, or variation in the properties of the chemicals in the process being controlled. Hence, a performance degradation can occur. Further, the model uncertainties is an even greater problem if the time delay is large enough to affect the system dynamics. For this reason, unknown disturbances and varying time delays in process control systems are problems that require ongoing research.

2.3.2. Time Delay in Networked Control Applications: A perspective on Industry 4.0

Networked control phenomenon enables us control of a group of system components simultaneously over a multi-purpose shared network medium. The present section mainly focuses on the delay problems in networked control applications (Zhang et al., 2013).

A Networked Control System (NCS), wherein the system components, such as sensors, actuators, controllers, and plants are connected to a common network medium, allows the execution of several tasks by introducing a cyber space. More explicitly, an NCS is operated through a shared communication network, where system components, i.e., sensors, actuators, quantizers, controllers and plants are connected through that common network medium (D.Hristu-Versakelis & W.Levine, 2005). The shared communication network medium can be either an industrial control network such as Control Area Network (CAN), Profibus, Modbus, Fieldbus etc., or wireless even Internet, which are general purpose data communication networks (Mahmoud, 2016).

From an industrial perspective, the widespread applications and incredible efficiency of NCSs for different tasks motivate the researchers to investigate analysis and design techniques, which play a crucial role in the system performance. A significant amount of research has been carried out to develop stability analysis methods and control design strategies, which are aware of network-induced constraints such as time delay, variable sampling, data disorder

and dropout, data quantization, scheduling, bandwidth limitation arising from limited capacity of computation and communication resources.

A simple scheme of an NCS is depicted in Figure 2.2. From a control engineer's point of view, the main objective is to meet the desired control performance while data are exchanged through an unreliable communication network. For that purpose, the controller has to deal with digital and analogue, cyber and physical heterogeneities in order to enable success.

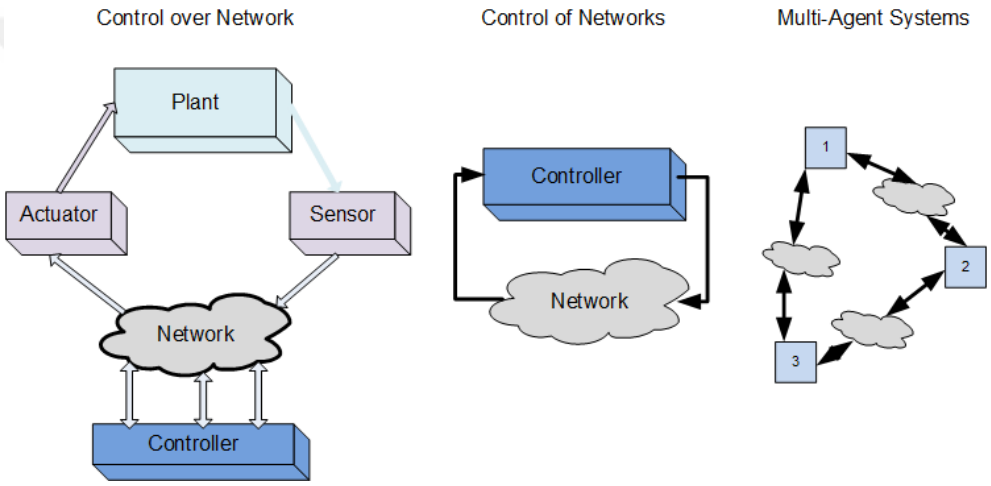


Figure 2.2 Networked control phenomenon

Delays, which may arise from perception, communication, transportation, and decision-making, is one of the most important problems in networked control applications (Sipahi et al., 2011). Further, the overall network-induced delays are commonly categorized as, transmission delay, network access delay, and computational delay, which can be modelled and analysed with various methods.

The network-induced delays may possess different characteristics such as constant, randomly varying, or varying with a known probability distribution etc. To mention but a few examples, the network-induced delay can be constant if a CAN protocol is employed as a medium access. Further, when we use a buffer in

the controller that reads the data periodically, the constant delay can be observed. However, the main drawback is that the delay has to be enlarged for controller design. If the delay is longer than a sampling period, one may receive zero, one, or more than one control signal in a sampling period. Concerning to this matter, an analytical stability region analysis and the relation between sampling h and delay τ can be found in (Wei et al., 2001).

Figure 2.3 presents the aforementioned delays, where τ_p is the plant delay,τ_k^c is the computational delay, $\tau_k^{wait_c}$ and $\tau_k^{wait_s}$ are network access delays, τ_k^{ca} and τ_k^{sc} are transmission delays (Tipsuwan and Chow, 2003; Zhang et al., 2017). The computational delay may occur in system components due to the computational limitations of digital devices. The network access delay has arisen in network queue due to the fact that data are transmitted through a network in a packet form and a queued network packet may need to wait sometime before being sent out. In addition, the transmission of a data packet through a network cannot be achieved instantaneously; it takes a finite amount of time, so transmission delays, which are the most significant delay, are unavoidably introduced. The transmission delay heavily depends on network conditions such as network channel quality, bandwidth, network traffic congestion, and transmission protocols. However, in most cases, the computational delay and the network access delays are small enough to neglect compared with the transmission delays (Ge et al., 2017).

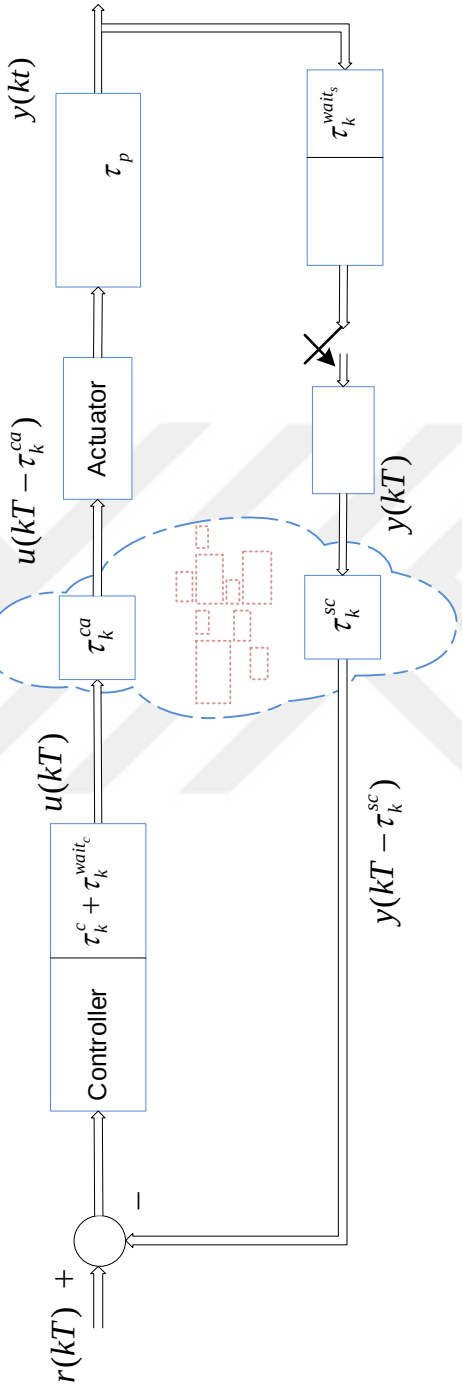


Figure 2.3 Delay in networked control application

A number of promising results are presented concerning the stability analysis of an NCS with network-induced delay. Gao (Gao and Chen, 2007; Gao et al., 2008) present a discrete-time version of the NCS with random delay and the mean-square asymptotic stability conditions are derived. Tang et al. investigate the application of model predictive control (MPC) for a class of NCSs in the presence of network-induced delays. In their research, a time-varying control law is designed with the aid of a novel augmented model. Further, the sufficient conditions are presented based on Lyapunov stability theory (Tang et al., 2015). Bonala et al. propose a robust control method by utilizing a digital Smith predictor structure for NCSs with time-varying delay and packet dropouts (Bonala et al., 2017). The compensator is implemented in digital form with a time-driven controller and event-driven actuator configuration. Lucia and Tedesco address a novel robust receding horizon control strategy for Linear Parameter Varying (LPV) system with polytopic uncertainties and network-induced time-varying delay (Lucia and Tedesco, 2015). These studies present the importance of delay problem in NCS applications.

Apart from these research, predictor based control strategies for NCSs comprising different types of time delay have been presented in the literature. For instance, Gamal et al. present delay compensation using Smith predictor for wireless control systems (Gamal et al., 2016). A number of simulations have been presented by using a true-time toolbox. Yet another SP is addressed for a hardware-in-the loop-docking simulator (Qi et al., 2016).

Further, delay robustness improvement using digital SP for the networked control system is addressed in (Bonala et al., 2017). Batista and Jota propose an adaptive SP structure for improving the performance of the NCS closed over the internet (Batista and Jota, 2018). Another application of SP is investigated in (Santos et al., 2018) for controlling an omnidirectional mobile robot subject to time-varying delay and noise.

2.4. Stability Analysis Methods for Time Delay Systems

Stability analysis of time-delayed systems can be classified in different perspectives. Concerning the matter, consider a closed-loop system with the plant transfer function $e^{-\tau s}(b/(s+a))$, wherein τ, b, and a denote the time delay, the system gain, and the pole of the system, respectively. Furthermore, a proportional controller $C(s)=k$ (Sipahi et al., 2011). The stability chart, which reveals the effect of a delay parameter on stability and how the controller gain *k* can be tuned, is depicted in Figure 2.4.

More precisely, if a time-delay system is stable for any delay values belonging to positive real numbers R^+, the system is said to be delay-independent stable. If a time-delay system is stable for all delay values belonging to a subspace $D \in R^+$ then the system is said to be delay-dependent stable (Briat, 2008). It is well known that delay-dependent conditions are based on model transformations and bounding of the resulting cross terms.

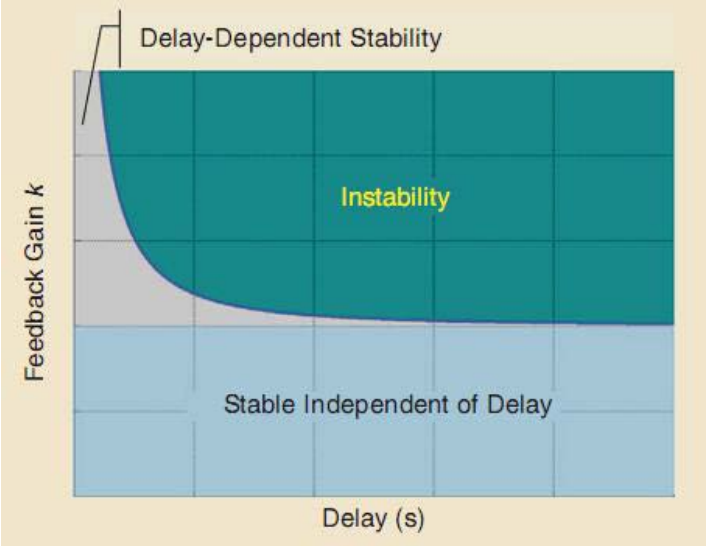


Figure 2.4 Stability with respect to the delay (Sipahi et al., 2011)

The stability of time-delay system can be classified into two main frameworks to analysis the frequency-domain and time-domain analysis. Current developments of frequency domain approaches, which deal with characteristic quasipolynomial of the system, are based on frequency sweeping and matrix-pencils (Michiels and Niculescu, 2007). Some important stability analysis methods are summarized in Table 2.1.

Table 2.1. Methods for stability analysis methods

Frequency domain Methods	**Time domain methods**
Some frequency tests	Model transformations, additional dynamics
Small-gain theorem	Lyapunov-Razumikhin functions (Fridman, 2014) • Delay-Independent • Delay-Dependent
Finite spectrum assignment (Mondie and Michiels, 2003)	Lyapunov-Krasovskii functionals (Fridman, 2014) • Delay-Independent • Delay-Dependent
Pseudo-Delay technique (Niculescu, 2001; Richard, 2003)	
Pontrygain theorem	
Arstein reduction method	
Matrix pencil techniques (Michiels and Niculescu, 2007)	

It is to be noted that frequency methods need sufficient conditions for delay-dependent and delay-independent stability. On the other hand, time domain approaches often consider state-space domain and matrices (Fridman, 2014).

However, time domain approaches have two main advantages, first one can easily handle nonlinearity and time-varying uncertainties; second, on the basis of time domain stability criteria, one can easily address issues about controller synthesis and filter design for time-delay systems (Han, 2009).

2.4.1. Frequency Domain Techniques

In classical control, frequency domain methods provide the most sophisticated approach to analysing the stability of a system with no delay (Wu et al., 2010). Consider the characteristic quasi polynomial as given in (2.1). The necessary and sufficient condition for the stability of a system is $\lambda(A + A_d) \leq 0$, when $\theta > 0$

$$f(\lambda) = \det\left(\lambda I - A - A_d e^{-\theta\lambda}\right) = 0 \tag{2.1}$$

which has negative real parts. Furthermore, λ, A, A_d, and θ denote eigenvalues, the system matrix, the delayed system matrix, and the corresponding time delay, respectively (Wu et al., 2010). More precisely, the frequency methods explore the necessary and sufficient conditions with regard to locations of the roots of its characteristic function. Note that if the system has uncertainties and time-varying delay, the stability analyses will be a tedious task (Vyhlídal et al., 2014).

2.4.2. Time Domain Techniques

Time-domain stability analysis methods are mainly based on Lyapunov theorems; Lyapunov- Krasovskii theorem and the Lyapunov-Razumikhin theorems. The central notion is to find a sufficient condition for the stability of time delay system by constructing an appropriate Lyapunov-Krasovskii functional or an appropriate Lyapunov-Razumikhin function (Wu et al., 2010).

Fortunately, computationally powerful computers and software such as Matlab toolboxes make the Lyapunov methods easy to implement, since then, significant results have obtained (Sipahi et al., 2011). Two sufficient conditions have received an important attention, first one is delay-independent type and its members are called delay-independent conditions and second one deal with the length of the delay, which is called delay-dependent conditions:

$$V_1(x_t) = x^T(t)Px(t) + \int_{t-h}^{t} x^T(s)Qx(s)ds \tag{2.2}$$

where $P = P^T > 0$ and $Q = Q^T > 0$ are known Lyapunov matrices and x_t denotes the translation operator acting on the trajectory, $x_t(\theta) = x_t(t+\theta)$ for some non-zero interval defined by $[-h, 0], (\theta \in [-h, 0])$ where $h \in R^+$. It is to be noted that P is a positive definite matrix and Q is a positive definite matrix in proper dimensions. The integral term on the ride side of (2.2) is computed by a fixed model transformation. It transforms a system with a discrete delay into a new system with distributed delay. Calculating the derivative of $V_1(t)$ along the trajectories of the systems and providing it to less than zero yields the delay-independent stability condition of a time-delay system (Wu et al., 2010).

$$\begin{bmatrix} PA + A^T P + Q & PA_d \\ * & -Q \end{bmatrix} < 0 \tag{2.3}$$

wherein the inequality is linear with respect to the Lyapunov matrices *P* and *Q*.

The time-domain approaches are better than frequency domain approaches with the following properties:

- One can easily cope with the nonlinearity and time-varying uncertainties in time-domain
- One can overcome the complexity problem of controller synthesis and filter design issues for time delay systems based on time-domain stability criteria.

Further, recent directions have shown that time-domain stability methods have become a very important tool for stability analysis of time-delay systems including uncertainties and nonlinearities (Fridman, 2014; Fridman, 2014).

2.5. Delay Effects on Stability and Control Performance

As indicated previously, the time delay may be profitable or destructive for stability and performance of a control system. This paradox is very attractive to investigate for scientist and researchers in the last decades (Sipahi et al., 2011).

2.5.1. Detrimental (Unstabilizing) Effects of Time Delay

The example of a delay differential equation can be presented as:

$$\frac{dx(t)}{dt} = A_0 x(t) + \sum_{i=1}^{N} A_i x(t-\tau_i) \tag{2.4}$$

where $x(t)$ is the state variable with n dimensional, A_i , $i = 0, \dots, N$, is an nxn dimensional matrix with real elements, and N is a positive integer. In (2.4) $\tau > 0$ is the delay.

Consider a unit feedback system consisting of the plant $G_p(s) = \frac{1}{s}e^{-\tau s}$ and the proportional control $G_c(s) = k > 0$ in the forward path. It can be shown by Nyguist criteria that closed loop system is stable if and only if $\tau < \frac{\pi}{2k}$, especially,

the system is stable for arbitrary $k > 0$ if delay $\tau = 0$. Therefore, time delay has destabilizing effect in this case.

2.5.2. Coping With Detrimental Effects of Delay: Predictor Based Control Strategies

Delay may have a major influence on the stability and performance of a dynamical system (Normey-Rico and Camacho, 2007). To mention a few, it causes a physical constraint which does not allow reacting until periods of time after the change in the value of the state, and thus the delay can damage the closed-loop stability of the system. In addition, time delay, quite often, may deteriorate the closed-loop response by decreasing the phase margin of the system. Further, the delay gives rise to a quasi-polynomial characteristic equation, which has infinitely many roots. In such cases, the well-rounded theory of classical feedback control cannot keep pace with the control design issues for systems having time-delay (Normey-Rico and Camacho, 2008; Sipahi et al., 2011).

PID controllers are frequently encountered in many control applications. However, the control performance may not be satisfied when the time delay in system dynamics is sufficiently large. During the last few decades, a number of control techniques have been presented to overcome detrimental effects of delay. Among these techniques, Smith Predictor, wherein the controller is designed by considering the delay-free model of the system, seemed to be very attractive in the early period of studies. Therefore, an efficient way is to remove time delay from the characteristic equation of the closed loop system mathematically. Then, the designer may construct control strategy as if the process is delay free.

Smith predictor, which uses a model of the plant and time delay, increases the overall system performance. However, the classical SP has a number of disadvantages. For instance, it requires a precise model of the controlled plant, which we hardly ever have. Further, the closed loop system is highly sensitive to

model uncertainties and delay variations that lead to performance degradation or even cause instability.

The Smith predictor has since been modified and applied to various systems (Normey-Rico and Camacho, 2008). A survey of dead-time compensators elaborating various SP schemes is reported in (Normey-Rico and Camacho, 2008). For instance, a further modification for ease of tuning and increase in robustness can be reported in (Albertos and García, 2009). However, these methods require a well-known model of the plant and time delay, so work has been done to improve control systems while estimating parameters online or providing an adaptive control mechanism. An adaptive Smith predictor is compared to a non-adaptive robust predictive controller in (Niculescu and Annaswamy, 2003) where the benefit of the adaptive controller is evident under an unknown time delay, however, no analysis of the adaptive scheme is given. More advanced neural network approaches have been used for systems with unknown time delays, however, the controllers are more complex and not necessarily intuitive for a classical control designer.

The block diagram of classical predictor structure is presented in Figure 2.5.

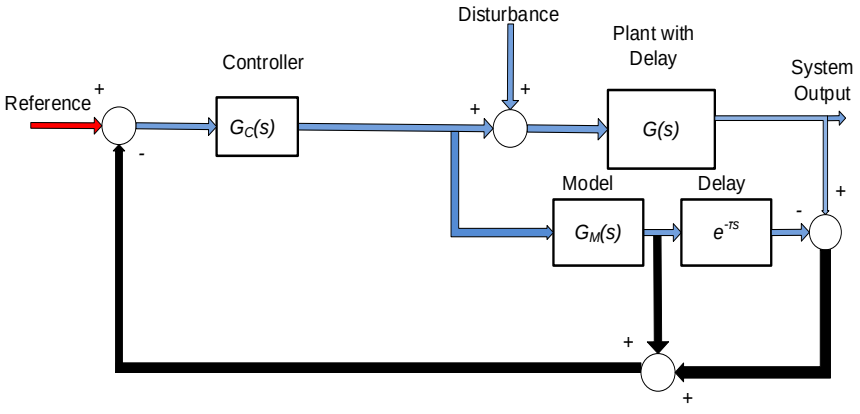


Figure 2.5 General structure of Smith predictor

where the closed loop transfer function of SP, which is depicted in Figure 2.5, can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G(s)}{1+G_C(s)[G_M(s)+G(s)-\tilde{G}(s)]} \tag{2.5}$$

where $Y(s)$ $R(s)$ $G_C(s)$ $G_M(s)$, and $\tilde{G}(s)$ denote the system output, the reference, the controller, the delay free model of the system, and the system model with time delay, respectively. The closed-loop transfer function can be written as

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_M(s)e^{-\tau_M s}}{1+G_C(s)G_M(s)} \tag{2.6}$$

by assuming a perfect modelling of the process $\tilde{G}(s) = G(s)$. In the present research, the main point is to control time-delayed systems, which may have model uncertainties, parameter changes, disturbances, and varying delay. It is evident that the classical Smith predictor structure should be modified for a number of reasons. For instance, classical SP may show unsatisfied control performance in the presence of model uncertainties. On the other hand, measurement noise is another source of performance degradation for SP structure; hence, filters structures will be beneficial for closed-loop control performance. A two degree of Smith predictor is addressed by (Normey-Rico and Camacho, 2008). The structure of the predictor is presented in Figure 2.6, wherein a forward controller *F*(*s*) is added to the reference of the system in order to obtain satisfactory performance for disturbance rejection and reference tracking simultaneously.

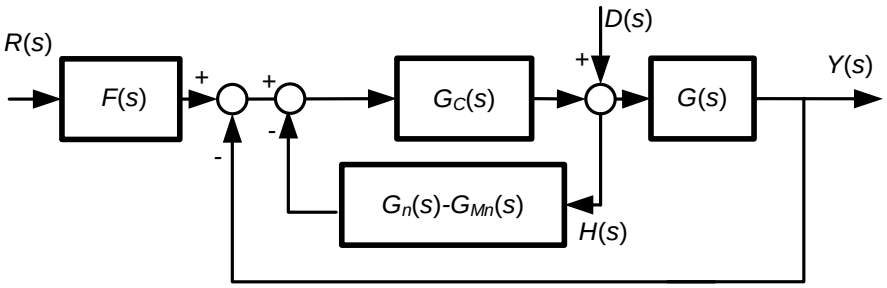


Figure 2.6 A two degrees of freedom Smith predictor

where $F(s)$, $D(s)$, $H(s)$, $G_n(s)$, and $G_{Mn}(s)$ represent the filter to improve the tracking performance, the disturbance, the feedback path, the nominal model of the system, and the model of the system. Assuming the real-system and nominal model match exactly, the closed-loop transfer function of the output $Y(s)$ to $R(s)$ and $Y(s)$ to $D(s)$ can be written

$$\frac{Y(s)}{R(s)} = \frac{F(s)G_C(s)G(s)}{1+G_C(s)[G_M(s)+G(s)-\tilde{G}(s)]} \tag{2.7}$$

$$\frac{Y(s)}{D(s)} = \frac{G(s)[1+G_C(s)G_M(s)(1-e^{-\tau_M s})]}{1+G_C(s)G_M(s)} \tag{2.8}$$

As seen from (2.7) and (2.8) the characteristic equation of the system has not a delay, hence, the controller parameters in $F(s)$ and $G_C(s)$ can be tuned by using delay free system.

Liu et al. present an internal model control with a two-degree-of-freedom structure, which exhibited substantial control performance enhancement for both trajectory tracking and disturbance rejection (Liu et al., 2005). Yet another two-degree-of-freedom modified SP structure, which shows satisfactory disturbance

rejection and trajectory tracking performance for a class of unstable processes with time delay, is presented in (Yin et al., 2014). García and Albertos. address a robust SP structure for providing a considerable performance enhancement and simplicity in the controller tuning (García and Albertos, 2013).

Yet another modification, so-called Filtered Smith predictor is depicted in Figure 2.7, wherein $F_r(s)$ is filter to compensate the delay variations.

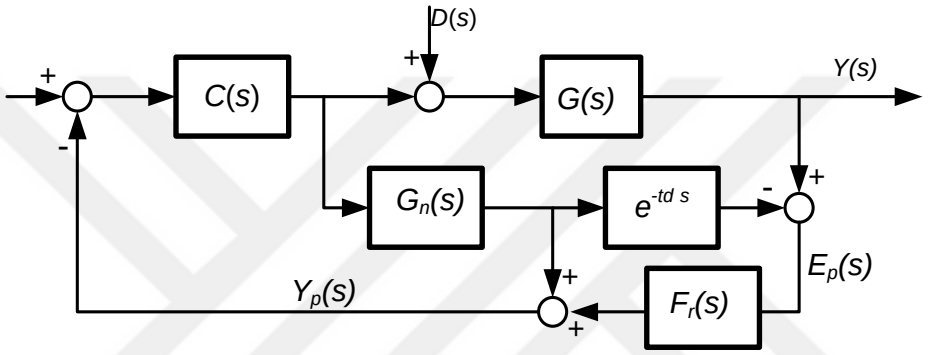


Figure 2.7 Filtered predictor

Further, it is stated that the PI-PD control scheme can improve the closed loop performance of systems having large time constants or integrator (Kaya, 2015; Zou and Li, 2017). However, parameter variations, model uncertainties, and unknown load disturbances still cause suffering (Kaya, 2003).

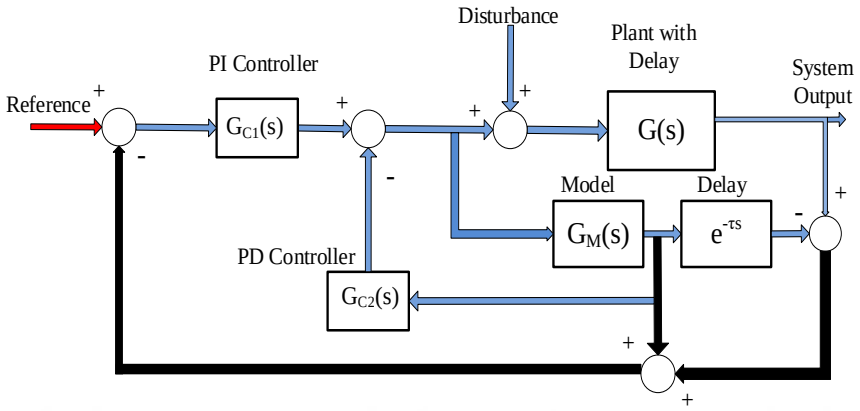


Figure 2.8 Smith predictor based PI-PD control

The closed-loop transfer function of the system given in Figure 2.8 is

$$\frac{Y(s)}{R(s)} = \frac{G_M(s)[1+G_M(s)(G_{C_1}(s)+G_{C_2}(s)-G_{C_1}(s)e^{-\tau_m s})]e^{-\tau_m s}}{[1+G_M(s)(G_{C_1}(s)+G_{C_2}(s))][1+G_M e^{-\tau_m s}]} \quad (2.9)$$

where, PI and PD controllers are denoted by $G_{C_1}(s)$ and $G_{C_2}(s)$, respectively.

2.5.2.1. Smith Predictor Based Fractional Order Control Strategies

Recently, fractional order control strategies have attracted a great deal of attention across industry sectors and academics. In fact, fractional order control has a number of advantages over the integer order counterpart especially in the application of modelling and control of complex dynamical systems (Monje et al., 2010). It offers flexible design strategy by increasing the number of degrees of freedom. Moreover, a high-order transfer function can be expressed by fractional operators more compactly (Efe, 2011). For instance, in classical control system theory, a real and rational transfer function has asymptotes of 20 dB/dec for every real zero and 20 dB/dec for every real pole (Efe, 2011). A fractional operator can be given as follows (Monje et al., 2010):

$$ {}_{a}D_{t}^{v} = \begin{cases} \dfrac{d^{v}}{dt^{v}} & v > 0 \\ 1 & v = 0 \\ \int_{a}^{t} (d\tau)^{(-v)} & v < 0 \end{cases} \tag{2.9} $$

where $v \in R$ denotes the fractional order, and ${}_{\alpha}D_{t}^{v}$ is the fractional derivative or integral operator depending the value of v. The integral bound of the operator is defined by a and t. Equation (2.9), which is known as a general definition of the fractional operators, includes the derivative and integrator operators for integer order systems. A number of definitions for fractional order integrodifferential operator have been reported in the literature. Caputo and Riemann-Liouville are the two well-known definitions of fractional order integrodifferential operator (Chen et al., 2009; Monje et al., 2010). A fractional order PID controller is represented in Figure 2.9.

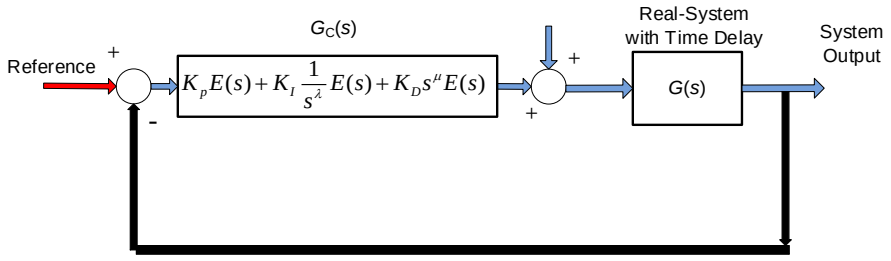


Figure 2.9 A fractional order PID controller

Fractional order control based SP scheme has been gaining a large amount of interest due to their flexible structure as well as superior control performance by further increasing the robustness of the control system (Feliu-Batlle et al., 2009; Feliu-Batlle et al., 2009). A number of advanced fractional order control approaches have been addressed for systems with unknown time delays, however, the elaborated control schemes are not easy to apply experimentally. Because a

real-time control scheme should be designed to ensure robust stability while still meeting performance requirements for a particular application. Further, (Vu and Lee, 2014) elaborate SP based fractional-order proportional-integral controller which is designed based on Bode's ideal transfer function. Yet another design procedure, which is based on time-domain specifications, is presented in (Safaei and Tavakoli, 2017).

These observations show that the research of the SP based fractional order control design is still a hot topic in control system society. It should be pointed out that a few studies elaborate real-time experimental application performance of Smith predictor base fractional controllers. A study proposes a novel fractional order controller for controlling a heat flow system (Al-Saggaf et al., 2016). In the study, however, the measurement delay is approximated by three different rational approximation methods. Thus, the effect of time delay has not been directly examined.

It is to be stated that one should obtain integer order approximation of fractional operators; at this point, no study compares the performance of different approximation techniques experimentally (Li et al., 2016).

2.5.2.2. Smith Predictor with Robust Control Strategies

Real systems have always uncertainties and modelling mismatches, further effects of the aforementioned uncertainties and disturbances can lead to reducing the performance of the predictor as well as control at the output of the system. The strategy to improve the performance of dead time compensator is combining a robust controller with the predictor. A number of sliding mode control techniques are combined with Smith predictor in the literature. The control structure is given in Figure 2.10.

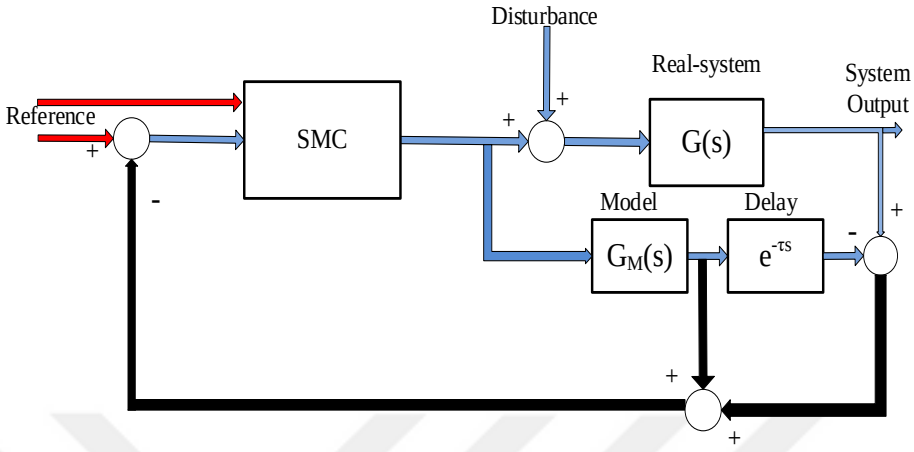


Figure 2.10 Sliding mode control with predictor structure

SMC for long time delay systems has been elaborated in (Camacho and De La Cruz, 2004). The elaborated system is a first-order plus dead time (FOPDT) model. First order Taylor series is used for approximating the process dead time. A second order SMC for a time delay system is addressed by (Gang et al., 2009), wherein the time-delay is approximated by first, second, and third order Padé approximation.

To overcome the delay approximation problem in those methods, the Smith Predictor (SP) was adopted to eliminate dead time together with SMC to achieve the robust controller. Mehta and Rojas present SMC with SP scheme for open-loop unstable processes (Mehta and Rojas, 2015). Yet another study addresses optimal tuning of an SP based SMC technique (Mehta and Kaya, 2017).

2.5.2.3. Gain-Scheduled Smith Predictor

One possible solution to the control of the time-delayed system is the gain-scheduled Smith predictor, which is very effective if the approximated model not exactly matched with the real system. Although these techniques have been successfully applied in simulations, a few studies based on real-time experimental applications are reported in the literature. A gain-scheduled SP for a linear

parameter varying system is addressed in (Bolea et al., 2011). The SP is integrated with the real-time estimated parameters to handle the unknown portion of the delay. The corresponding results are presented in (Bolea et al., 2014), wherein the authors highlight a gain-scheduled PID algorithm integrated into SP for controlling an open-flow canal problem. Benitez Gonzales et al. propose a fuzzy gain-scheduling SP control scheme (Benitez Gonzalez et al., 2016). A number of simulation results are presented for a temperature control in an industrial steel slab-reheating furnace.

A further research direction to be explored is to integrate computational intelligent techniques into fractional order control schemes, wherein this new type controller possesses tremendous potential especially in the field of industrial control. Several studies have presented that the intelligent based fractional control enlarge the potentialities of both intelligent and fractional controller at performs. Among these studies, the fractional controller has been quite often combined with fuzzy logic (Efe, 2011; Das et al., 2013; Pan and Das, 2016; Sharma et al., 2016). The robustness capability of a fuzzy logic control strategy can be further enhanced by fractional order control methods.

An inspiring study is addressed by Das et al. (Das et al., 2013), where the authors highlight a new fractional-order fuzzy PID control strategy and perform a number of simulation tests for a naturally unstable nonlinear dead time process. Pan and Das (Pan and Das, 2016) illustrate an application of fractional order fuzzy scheme for controlling a hybrid power system. It is reported that the elaborated controller outperforms then conventional control strategies. A further study demonstrates a Takagi-Sugeno type fractional order fuzzy PID control with self-tuning capabilities (Mishra et al., 2015). The controller is tested on a binary distillation column process containing various model uncertainties and nonlinearities. In (Sharma et al., 2014), a performance investigation of fractional fuzzy PID scheme is highlighted for controlling of a robotic manipulator, where control parameters are optimized by using cuckoo search algorithm (CSA). Yet

another study presents a nonlinear adaptive fractional order fuzzy PID scheme in control of a 2-link manipulator with different payloads by (Kumar and Kumar, 2017; Kumar and Rana, 2017). A robust fractional fuzzy P + fuzzy I + fuzzy D controller is addressed for an uncertain nonlinear system (Kumar et al., 2016). Beddar et al. present an experimental application of fuzzy fractional order PI+I control strategy for controlling of a grid-connected variable speed wind energy conversion system, in which a particle swarm optimization (PSO) algorithm is used to tune the controller parameters (Beddar et al., 2016).

A number of optimal design methodologies combine fuzzy logic with the Genetic Algorithm (GA) based optimization strategies. For instance, Jesus and Barbosa address fuzzy fractional PD+I controller with genetic optimization (Jesus and Barbosa, 2015; Jesus and Barbosa, 2017). Kaya and Nalbantoglu propose an optimal cascade control structure for different process applications (Kaya and Nalbantoğlu, 2016). Haji Haji and Monje present a comparison of various evolutionary optimization algorithms for fractional order fuzzy PID controller in control of cycle-power plant (Haji Haji and Monje, 2017).

Furthermore, a lot of effort has been dedicated to the design of fractional type-1 and type-2 fuzzy control system, which are optimized by nature-inspired optimization techniques. A number of bio-inspired optimization techniques are applied in (Castillo et al., 2014) for autonomous mobile robot application. An experimental study of type-1/type-2 fuzzy cascade controller based on GA and PSO is addressed in (Oh et al., 2011).

2.5.3. Stabilizing and Favourable Effects of Time Delay on Control System Performance

Consider a unit feedback control system consisting of the plant $G_p(s) = \frac{1}{s^2 + w_0^2 e^{-s\tau}}$, the system can be stabilized by a controller, $G_c(s) = k$, only

if $\tau > 0$. Thus, the system can never be stabilized by such a control if $\tau = 0$. The mitigation of the roots of characteristic quasi-polynomial is depicted in Figure 2.11.

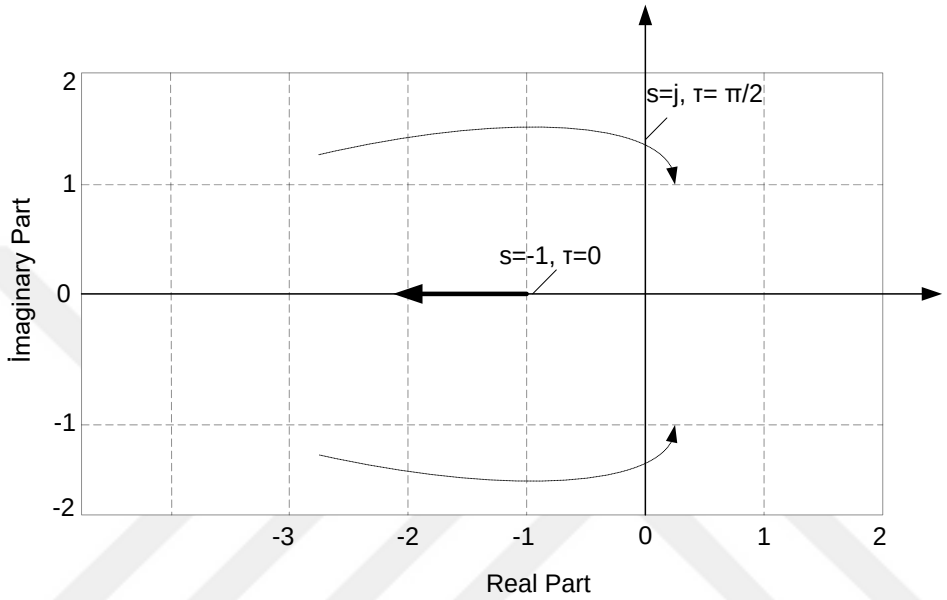


Figure 2.11 Delay effects on stability (Sipahi et al., 2011)

The delay-based control is an interesting perspective and new research avenue for delay researchers in control community. Concerning the matter, (Khan et al., 2008) addresses positive effects of time delay such as improving robustness, reducing noise effect, for type-I systems. A number of important results have been presented a few decades ago; however, stability analysis and experimental applications of the controller have not been presented. Some preliminary results for overcoming uncertainties were given by Youcef-Toumi and Ito (Youcef-Toumi and Ito, 1990), wherein a direct estimation of unknown dynamics is obtained by using the time delay.

In a recent work, Ulsoy presented some advantages of delay based control for a single input-single output system (SISO) (Ulsoy, 2015). Delay differential

equations are solved by employing the Lambert *W* functions. Moreover, some improvements in terms of robustness are provided in that study. Delayed resonators can be used by delayed position feedback in order to enhance vibration observer performance (Renzulli et al., 1999; Hosek and Olgac, 2002). Yet another benefit of utilizing delays allows the designer to replace derivative terms (Kokame et al., 2001). Some studies used time delay in state feedback controller (Kwon and Pearson, 1980). A further example highlights delayed output feedback control scheme for NCSs with randomly varying network-induced delay condition (Zhang et al., 2014), in which the network-induced delay is compensated by using the recently presented singular Markovian jump linear system framework. The output delayed feedback strategy is utilized to generate the control input packet.

Parallel to studies given, an intentional delay in the controller may provide simple and effective technique, which is known as a delay-based control or retarded control that can be proposed as an alternative option of conventional PID type low-order controller. The main advantage is that designer does not use any additional filter through the realization, which preserves simplicity and improves the energy consuming properties of the controller. Moreover, satisfactory performance can be obtained in the presence of low noise level (Villafuerte et al., 2013; Ramirez et al., 2015; Ramirez et al., 2016). A number of studies on the analysis and design of retarded type controllers are proposed in the literature. In (Suh and Bien, 1979), Suh and Bien address a proportional minus delay controller, which attenuates high-frequency noise by performing an averaged derivative action over a finite period. Furthermore, it is shown that the performance of the closed loop system is better in responding to noise like disturbances (Suh and Bien, 1980). An example of the analytical design and stability analysis is given in (Lee and Edgar, 2002), wherein an improved PI control comprising a filtered integral term is highlighted. The tuning strategy is addressed by an approximated delayed transfer function by using Padé approximation.

A delayed PID controller was presented comprising delayed integral and derivative terms (Zhong and Li, 2002). Villafuerta et al. address the stability analysis and tuning strategy of a Proportional Retarded (PR) control scheme (Villafuerte et al., 2013), wherein simple tuning rules for assigning the dominant poles of second-order system are addressed via a PR controller. According to the results, the PR controller outperforms classical Proportional Derivative (PD) controller in terms of tracking performance and control signal quality. A benefit of the PR control strategy is that its numerical realization is computationally more efficient than other classical control techniques such as PID controller. An example of PR control application to a mechatronic system is presented in (Ortega-Montiel et al., 2017), in which the authors present a pendulum control performance without using differentiators. The closed-loop stability analysis of voltage buck using proportional-delayed controller was presented in (Hernández-Díez et al., 2017). The work is also based on the geometric approach that allows partitioning of the parameters space into regions with a constant number of unstable roots. In the work of Hernandez-Diez et al., a transparent bilateral control scheme for a local teleoperation system is realized by using a proportional-delayed controller (Hernandez-Diez et al., 2016), wherein stability analysis problem is presented based on *D*-partition curves. Further, fragility analysis, which is based on computing of the maximum controller parameters deviation without losing the closed-loop stability, is carefully elaborated. A different PID type dead-time controller is highlighted in (Shinskey, 2001), wherein a delay is added to the integral loop of the PID controller. Ramirez et al. address a Proportional Integral Retarded (PIR) control scheme, wherein the stability analysis is derived in the sense of the algebraic geometric analysis (Ramirez et al., 2016; Ramírez et al., 2017).

In addition to aforementioned research studies, it is worth to be noted that a remarkable performance improvement can be achieved by using time delay for a nonlinear dynamical system, such as chaotic motion. A number of studies highlight

the utilization of delay in nonlinear systems. However, alongside the aforementioned favorable features, it is to be noted that the parameter tuning and stability analysis issues are tedious tasks.

2.5.3.1. Control Design Methods for Favourable Effects of Delay: Delay-Based Control Strategies

The control performance can be enhanced by a proportional integral delay controller, which has a proportional gain, an integral action, and a delayed proportional gain while avoiding derivative terms. The structure of proportional integral delay controller is depicted in Figure 2.12.

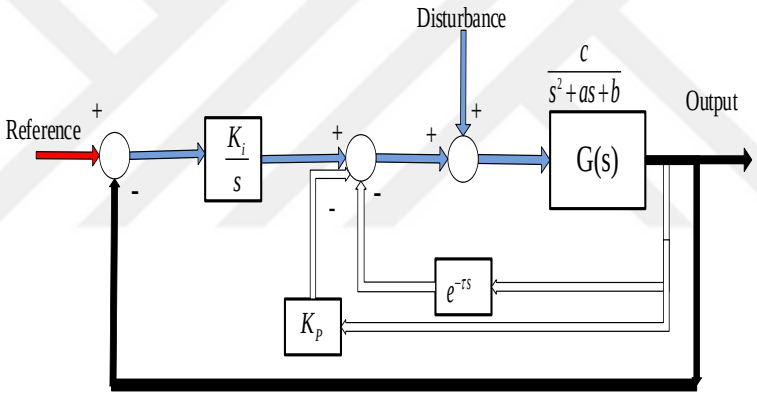


Figure 2.12 A proportional integral delay controller

The PIR controller in Figure 2.12 was introduced in (Ramirez et al., 2016), wherein stability analysis and parameter tuning is investigated deeply. The tuning of a delay-based controller can be investigated by a detailed characterization of the maximum achievable exponential decay rate of the closed-loop system (Ramirez et al., 2016; Ramírez et al., 2017). The key idea of the parameter tuning is to assign a triple real dominant root for the closed-loop system. It is achieved by using spectral analysis, which provides designer more flexible information about the dominant poles.

One of the advantages of the delay-based control is that the control system does not need any filter to attenuate noisy measurements. The elaborated control strategy is compared with a classical PID type controller, both simulated and tested experimentally on a real control set-up.

Even though delay-based controllers may enhance the noise attenuation and improve the robustness capability of the system, it is not easy to obtain controller gains (Ramírez et al., 2017). Hence, a few research article addresses delay-based control strategies. Moreover, most of the research studies are based on simulation results. Thus, experimental applications of the aforementioned control strategies may be another contribution for control theory and applications in the present research.

2.6. Conclusion

The basic aim of this chapter is to give some definitions and terminologies used in the field of delay systems and to review control methods from different perspectives.

3. PROPOSED CONTROL METHODS

3.1. Smith Predictor Based Fractional Order Control Techniques

Fractional order dynamical systems are presented by differential equations where the orders of derivatives can take any real number, not necessarily integer number (Baleanu et al., 2010; Padula and Visioli, 2015). The central philosophy of fractional calculus is to generalize integral and derivative operations to any possible real order (Padula and Visioli, 2015). Thus, the fractional calculus is considered as a superset of integer-order calculus.

Fractional-order mathematical operators provide a strong tool for the description of memory and hereditary properties of different substances (Podlubny, 1999). From the control theory point of view, one of the main motivation is to expand the classical integer-order control techniques into fractional order control, which has attracted a great deal of interest across industry sectors and research fields (Li et al., 2016). Fractional order control has a number of advantages over the integer order counterpart especially in the application of modelling and control of complex dynamical systems (Monje et al., 2010). For instance, it has more flexibilities than using a classical controller in adjusting the gain and phase characteristics for controlling an integer order system. Moreover, the fractional controller provides similar robustness achievable by using very high-order integer-order controllers. Furthermore, it is known that fractional order PI controller is less sensitive to changes in process parameters and the controller parameters itself. Hence, the fractional order control has the potential in designing robust control system than that of integer-order control (Sabatier et al., 2007; Chen et al., 2009; Balachandran and Kiruthika, 2011). In classical control system theory, a real and rational transfer function has asymptotes of 20 dB/dec for every real zero and -20 dB/dec for every real pole (Efe, 2011). However, the fractional order realizations remove this limitation such that high-order transfer functions can be presented by fractional operators more compactly (Efe, 2011).

Apart from these, the fractional calculus has gained importance due to its capability to complete characterization and to describe various physical systems such as transmission lines, diffusion and wave propagation, electromagnetism, and dielectric polarization more accurately (Barbosa et al., 2004). From the above points, it is evident that the fractional order operators will be frequently encountered in several engineering applications.

This chapter presents a number of analytical methods and design techniques for fractional order controller integrated into Smith predictor and its modifications to make the control system more robust to disturbances as well as parameter changes. The main objectives of the chapter can be presented as follows:

- To design a number of fractional order controllers to control an air heater with experimental applications.
- To perform a comparative study of SP based fractional order proportional integral controllers.
- To determine the advantages and drawbacks of the elaborated feedback strategies.

The second section of the present chapter gives the theoretical background of a number of SP based fractional order control techniques with some fundamentals of fractional calculus and fractional order control. Then, a comparative evaluation of control applications with real-time control experiments is presented. Finally, concluding remarks and future works are presented in the last section.

3.1.1. Introduction to Fractional Calculus

Recently, fractional calculus has various application tools with a strong mathematical background (Padula and Visioli, 2015). As already known, some

early attempts adapt the fractional order operators to frequency-domain analysis techniques. For instance, Manabe introduces the frequency response of fractional order integral and its applications to the control systems (Manabe, 1961; Manabe, 2003). However, the computational constraint and theoretical limitation make the application of fractional order control tedious task. Later on, Oustaloup makes a major contribution for the applications of fractional order control algorithms for controlling dynamical systems and demonstrates the better response of CRONE method (Commande Robuste d'Ordre Non Entier, meaning Non-integer-order Robust Control) over classical PID controller (Oustaloup, 1991; Oustaloup et al., 2000). It is to be noted that the study in the time domain has been generally avoided, however, some effective and easy-to-use tools for the time domain analysis and synthesis of fractional order $PI^{\lambda}D^{\mu}$ controller involving an integrator of order λ and differentiator of order μ is presented in (Podlubny, 1999), given in Figure 3.1. A recent work about the application of fractional order PID control is reported in (Barbosa et al., 2003).

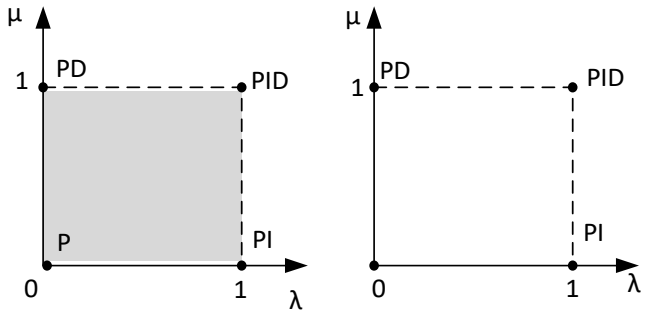


Figure 3.1 Fractional order PID vs. integer order PID

The main concern about the integer or fractional order PI and PID controller design is to tune its parameters to meet the desired performance specifications and design criteria. Apart from this, a number of research studies investigate the robustness properties of fractional order controllers (Feliu-Batlle et

al., 2013; Feliu-Batlle and Rivas-Perez, 2016) for different types of systems. Further, some studies address different optimization methods for the tuning of FOPID controller parameters (Sikander et al., 2017; Zamani et al., 2017). For instance, (Al-Dhaifallah et al., 2018) propose a novel tuning strategy for FOPID controller parameters based on minimizing the Integral Absolute Error (IAE) with a constraint on the maximum sensitivity. Yet another study highlights a robust design method for unstable systems (Chen et al., 2018). However, a few research studies present experimental applications of fractional order controllers (Lino and Maione, 2013; Muresan et al., 2015; Roy and Krishna Roy, 2016).

A fractional order integrodifferential operator can be represented as (Monje et al., 2010):

$$ {}_aD_t^v = \begin{cases} \dfrac{d^v}{dt^v} & v > 0 \\ 1 & v = 0 \\ \int_a^t (d\tau)^{(-v)} & v < 0 \end{cases} \tag{3.1} $$

where $v \in R$ denotes the fractional order and ${}_aD_t^v$ is the fractional derivative or integral operator depending on the value of v. Further, a and t denote the lower and upper terminal, respectively. Equation (3.1), which is known as a general definition of the fractional operators, includes the derivative and integrator operators for integer order systems. Moreover, a number of mathematical definitions can represent fractional order integrodifferential operators. For instance, Caputo and Riemann-Liouville are the two well-known definitions of fractional order integrodifferential operator (Chen et al., 2009). The Riemann-Liouville (RL) definition represents a fractional differentiation as (Sabatier et al., 2007; Monje et al., 2010; Padula and Visioli, 2015):

$$ {}_aD_t^{v} f(t) = \frac{1}{\Gamma(n-v)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{v-n+1}} dt, \quad n-1 < v < n \tag{3.2} $$

where, $\Gamma(.)$ denotes Euler Gama function. Further, fractional integration is represented as:

$$ {}_0D_t^{-v} f(t) = \frac{1}{\Gamma(v)} \int_0^t (t-\tau)^{v-1} f(\tau) d\tau, \quad 0 < v < 1 \text{ and } t < 0 \tag{3.3} $$

and a Grünwald-Letnikov definition based fractional order derivative is given as (Sabatier et al., 2007; Monje et al., 2010; Padula and Visioli, 2015):

$$ {}_aD_t^{v} f(t) = \lim_{h \to 0} h^{-v} \sum_{i=0}^{\frac{t-a}{h}} (-1)^i \binom{v}{i} f(t-ih) \tag{3.4} $$

where h denotes the interval, $(-1)^i \binom{v}{i}$ presents the binomial constants. A further definition is known as Caputo fractional order differentiation as:

$$ {}_aD_t^{v} f(t) = \frac{1}{\Gamma(v-n)} \int_a^t \frac{f^n(\tau)}{(t-\tau)^{v-n+1}} dt, \quad n-1 < v < n, \; n \in \mathbb{N} \tag{3.5} $$

It is known that frequency based methods facilitate analysis and design issues in fractional order control systems. Towards this goal, Laplace transform of the above functions can be represented as (Sabatier et al., 2007; Monje et al., 2010; Padula and Visioli, 2015):

$$L\left\{ {}_{a}D_{t}^{v} f(t)\right\} = \int_{0}^{\infty} e^{-st} {}_{a}D_{t}^{v} f(t)dt = s^{v}F(s) - \sum_{k=0}^{n-1} s^{k}(-1)^{j} {}_{a}D_{t}^{v-k-1} f(t)|_{t=0} \quad (3.6)$$

where n belongs to the set of integers $n \in Z$ and $n-1 < a < n$. The Laplace transform of (3.1) is defined as follows when the initial conditions are as $f(0) = f^{(1)}(0) = f^{(2)}(0) = ... = f^{(n-1)}(0) = 0$:

$$L\left\{ {}_{0}D_{t}^{\pm v} f(t)\right\} = s^{\pm v}F(s) \quad (3.7)$$

Further, the Fourier transform of a fractional derivative can be expressed as:

$$F\left\{ {}_{0}D_{t}^{\pm v} f(t)\right\} = (j\omega)^{\pm v}F(j\omega) \quad (3.8)$$

The frequency response of fractional order system is obtained as exact values if $s^{\pm v}$ is written as $j\omega^{\pm v}$. This feature actually provides an advantage for the usage of classical frequency domain methods for fractional order control systems. A number of assumptions are considered for the analysis and design of fractional order control systems (Sabatier et al., 2007; Monje et al., 2010; Padula and Visioli, 2015):

1. If $f(t)$ is the analytical function of t, then the fractional derivative of the function ${}_{0}D_{t}^{v}$ is the analytical function of a and t.
2. The fractional operator ${}_{0}D_{t}^{v}$ acts as an integer operator if $v = n$ and $n \in Z$

3. The fractional operator ${}_0D_t^v$ is used as a unit function when $v=0$, ${}_0D_t^0 f(t) = f(t)$
4. Fractional order derivative and fractional order integral are linear operations: ${}_0D_t^v kf(t) + {}_0D_t^v m\,\mathrm{g}(t) = k\,{}_0D_t^v f(t) + m\,{}_0D_t^v \mathrm{g}(t)$
5. The sum of exponents of $f(t)$ under the appropriate conditions can be presented as: ${}_0D_t^y\,{}_0D_t^y f(t) = {}_0D_t^y\,{}_0D_t^v f(t) = {}_0D_t^{v+y} f(t)$
6. The commutative property fractional derivative provides the following equation if $t=a$:

$$\frac{d^n}{dt^n}({}_aD_t^v f(t)) = {}_aD_t^v f(t)\left(\frac{d^n f(t)}{dt^n}\right) = {}_aD_t^{v+n} f(t) \tag{3.9}$$

3.1.1. Stability of Fractional Order Systems

It is well-known that the stability of a linear time-invariant (LTI) system is guaranteed if the roots of the characteristic polynomial are negative or have negative real parts if they are complex conjugate (Luo and Chen, 2012). However, the stability condition of a fractional order system is different from an integer order system, since a stable fractional order system may have right half plane roots. It is showed that a fractional order system is stable if the following condition is satisfied:

$$\left|\arg(eig(A))\right| > q\frac{\pi}{2} \tag{3.10}$$

where $0<q<1$, and $eig(A)$ represents the eigenvalues of the state matrix A in proper dimension. The Matignon's stability theorem says that the fractional

transfer function is stable if and only if the following condition is satisfied in σ-plane:

$$\left|\arg(\sigma)\right| > q\frac{\pi}{2}, \forall \sigma \in \mathbb{C}, P(\sigma) = 0 \tag{3.11}$$

where σ is defined as $\sigma := s^q$. When $\sigma = 0$ is a single root of $P(s)$, the system cannot be stable. For $q = 1$, this is the classical theorem of pole location in the complex plane: no pole is in the closed right half plane of the first Riemann sheet (Chen et al., 2009). It is to be noted that only the denominator is meaningful in stability assessment and the numerator does not affect the stability of fractional order transfer function (Luo and Chen, 2012).

Figure 3.2 demonstrates the stable and unstable regions on the complex plane.

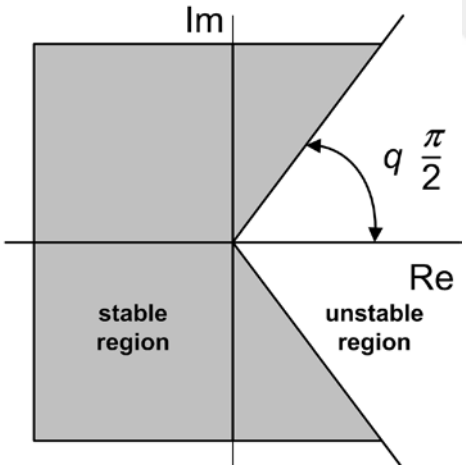


Figure 3.2 Stability of LTI fractional system with order $0 < q < 1$

Now consider a fractional order system in the form (Chen et al., 2009):

$$D^q \omega = f(\omega) \tag{3.12}$$

where $0 < q < 1$ and $\omega \in R^n$. The equilibrium points of (3.12) are obtained by solving the $f(\omega) = 0$. Further, the equilibrium points are asymptotically stable if all the eigenvalues of the Jacobian matrix $J = {\partial f}/{\partial \omega}$, evaluated at the equilibrium, satisfy the following condition:

$$\left|\arg(eig(J))\right| = \left|\arg(\lambda_j)\right| > q\frac{\pi}{2}, \; j = 1, 2, ..., n \tag{3.13}$$

where λ_j is the j^{th} eigenvalue of the state matrix. Thus, it can be noted that stability characteristic of fractional order control is different from the integer order counterpart.

3.1.2. Bode's Ideal Transfer Function

The design of fractional order control techniques are mainly based on the Bode's ideal transfer function (Barbosa et al., 2004), wherein the controller can be analytically derived for integer and fractional order models and can be easily applied to various process models.

Assume that the closed loop reference model can be presented as follows:

$$f(s) = \frac{1}{1 + \left(\frac{s}{\omega_c}\right)^{\mu}}, \quad \mu \in R \tag{3.14}$$

This particular form (3.14) has very important properties since the phase margin remains constant independently of the value of the system gain (Bettayeb et

al., 2017). Hence, the closed-loop system behaves more robust against the process gain variations and disturbance. Additionally, step response exhibits iso-damping property (Al-Saggaf et al., 2016).

An ideal open loop transfer function can be represented as:

$$H(s)=\left(\frac{\omega_c}{s}\right)^{\mu} \tag{3.15}$$

where ω_c is the gain crossover frequency of $H(s)$ and μ is the slope of the magnitude curve. In the Bode diagrams of $H(s)$, the amplitude curve is the straight line of constant slope $-20\mu dB/dec$ and the phase curve is a horizontal line at the frequency of $-\mu\pi/2\ rad$ (Bettayeb et al., 2017).

The transfer function plays a central role in the design of the fractional order controller and is given as:

$$f(s)=\frac{1}{1+T_c s^{\lambda+1}},\quad 0<\lambda<1 \tag{3.16}$$

It is to be noted that the performance of the closed-loop is specified in the frequency domain, where T_c and λ are deduced from the gain crossover frequency ω_c and the phase margin φ_m by (Al-Saggaf et al., 2016; Bettayeb et al., 2017):

$$\lambda=\frac{\pi-\varphi_m}{\pi/2}-1 \tag{3.17}$$

and

$$T_c = \frac{1}{\omega_c^{\lambda+1}} \tag{3.18}$$

Another useful formula for characterizing the time response of $f(s)$ is presented by (Barbosa et al., 2004), wherein the fractional order can be calculated based on the overshoot of the step response denoted by $M_p\%$:

$$\lambda \cong -6.75M_p^2 10^{-5} + 0.016M_p + 0.066 \tag{3.19}$$

3.1.3. A Review of Smith Predictor Based Fractional Order Control Techniques

It is known that various industrial processes exhibit an inherent delay, and the control-engineering framework offers different techniques in order to cope with the delay phenomenon. For instance, fractional order filtered PID controller is proposed for systems having relatively small delays (Maamar and Rachid, 2014). However, these controllers cannot be effectively applied to processes with long delays due to the additional phase lag of delay (Zheng and Li, 2018). Smith predictor (SP) (Smith, 1959), wherein the controller is designed by using delay free model of the process, seemed to be very effective to deal with delay constraint (Kaya, 2003). However, the SP highly relies on the accuracy of the plant model (Wang et al., 2000). Thus, the closed-loop control performance can be degraded sharply in real-time practical applications due to the parameter uncertainties, internal/external disturbances, and delay variations etc. (Visioli and Zhong, 2011). In order to deal with these challenges, several modifications of dead time compensators such as; adaptive fuzzy Smith, 2DOF SP, Filtered SPs etc., have been presented (Normey-Rico and Camacho, 2008).

Further, SP based fractional order control strategies have been gaining a large amount of interest due to their flexible design parameters as well as better

control performance by further increasing the robustness of the control system. Concerning the matter, some studies can be reported as follows. A robust fractional order control technique is proposed in (Feliu-Batlle et al., 2009). A direct synthesis of the fractional order proportional integral control technique is addressed in (Vu and Lee, 2014) for stable time-delay systems. The controller is designed based on Bode's ideal transfer function. In that work, sufficient conditions are derived to ensure the system to be robustly stable. Another study presents the tuning of $PI^{\alpha}D^{\mu}$ controller parameters (Dziwinski et al., 2015). The controller is optimised by an IAE minimization technique. Yet another robust fractional order PI control for a stable FOPDT system is addressed in (Luo and Chen, 2012). An application of Hermite-Biehler theorem for characterizing stability regions is elaborated in (Hafsi et al., 2013). A tuning method for fractional order PID controller is highlighted in (Hafsi et al., 2015), wherein the controller is designed by using the Hermite-biehler and pontrygain theorem. The performance of the fractional order PID control is tested on a nonlinear twin-rotor helicopter system in (Azarmi et al., 2015). An SP structure, which is combined with a fractional order PID filter, is addressed in (Bettayeb et al., 2017). A comparison of SP based fractional order controllers is presented in (Maamri N et al., 2013). A state feedback control, which is constituted by a fractional integral, is investigated in (Al-Saggaf et al., 2015). A fractional order controller for controlling a heat flow system is elaborated in (Al-Saggaf et al., 2016), wherein the measurement delay is approximated by three different rational approximation methods. A further design procedure, which is based on some time-domain specifications, is highlighted in (Safaei and Tavakoli, 2017). These observations show that the research of the fractional order control for delay systems is still a hot topic in control system society. Furthermore, it is to be noted that the control of fractional order systems with long time delay is addressed in a few research studies. Although the method has been reported in the literature for integer order systems, the experimental applications have not been investigated in

detail. The most of the aforementioned studies have been presented simulation studies with their perspective. Thus, the present chapter is filling this gap.

3.1.3.1. Approximations of Fractional Order Operators

The implementation issue is still one of the main problem for the control applications of fractional order systems. Fractional order systems are presented by an infinite dimensional discrete transfer function, which necessitates infinite memory in contrast to integer order systems. Hence, one has to obtain a rational approximated model in order to implement fractional order controller. Towards this goal, a number of integer order approximations of fractional order operators have been presented in the literature. It is to be noted that the performance of the fractional order controller strictly depends on the approximation methods and selected bounds. The Oustaloup approximation method is utilized through the study. The corresponding approximated transfer function derived by Oustaloup is presented as:

$$s^{v} \cong k \prod_{n=-N}^{N} \frac{s+\omega_{Z_n}}{s+\omega_{P_n}} \tag{3.20}$$

where v is the real number power of s. Furthermore, ω_{Z_n} and ω_{P_n} denote the zeros and poles of numerator and denominator of (3.20).

$$\omega_{P_n} = \omega_l \left(\frac{\omega_h}{\omega_l} \right)^{\frac{n+N+(1/2)(1+v)}{2N+1}} \tag{3.21}$$

$$\omega_{Z_n} = \omega_l \left(\frac{\omega_h}{\omega_l} \right)^{\frac{n+N+(1/2)(1-v)}{2N+1}} \tag{3.22}$$

Toward obtaining an accurate approximation, the corresponding frequency range ω_l and ω_h are chosen between 0.01 and 100. Further, ***N*** is chosen as 5 commonly used through process control applications. These parameters give the best approximating performance of the fractional order controller. Further, the choice of approximation parameters significantly affect the performance of the fractional order controller.

An example of integer order approximation for $s^{0.7649}$.

$$s^{0.7649} = \frac{6.141s^5 + 13.86s^4 + 4.38s^3 + 0.2098s^2 + 0.00168s + 1.614e-06}{s^5 + 9.801s^4 + 13.074s^3 + 2.695s^2 + 0.07895s + 0.0002969} \quad 3.23)$$

A fractional order proportional integral controller can be represented as:

$$u(t) = K_P e(t) + K_I D_t^{-\varsigma} e(t), (\varsigma > 0) \quad (3.24)$$

where the transfer function of the controller is given:

$$G_C(s) = K_P + \frac{K_I}{s^{\varsigma}} \quad (3.25)$$

In (3.25) the proportional gain, integral gain and fractional order of integral action are expressed by K_P, K_I, and ς respectively. Further, by substituting $s = j\omega$ into (3.25) one can get:

$$G_c(j\omega) = K_P + \frac{K_I}{(j\omega)^{\varsigma}} \quad (3.26)$$

The fractional power of $j\omega$ can be presented as follows:

$$(j\omega)^{\varsigma} = \omega^{\varsigma} j^{\varsigma} = \omega^{\varsigma}[e^{j[\frac{\pi}{2}+2\pi n]}]^{\varsigma} = \omega^{\varsigma}[e^{j[\frac{\pi}{2}\varsigma+2\pi n\varsigma]}] \tag{3.27}$$

where $n = 0, \pm\frac{1}{\varsigma}, \pm\frac{2}{\varsigma}, ..., \pm\frac{m}{\varsigma}$, then (3.27) can be rewritten as

$$(j\omega)^{\varsigma} = \omega^{\varsigma} j^{\varsigma} = \omega^{\varsigma}[\cos(\xi_I) + j\sin(\xi_I)], \quad \xi_I = \frac{\pi\varsigma}{2} \tag{3.28}$$

and substituting (3.28) into (3.26) gives (Vu and Lee, 2014):

$$G_C(j\omega) = \left(K_P + \frac{K_I \cos(\xi_I)}{\omega^{\varsigma}}\right) - j\frac{K_I \sin(\xi_I)}{\omega^{\varsigma}} \tag{3.29}$$

3.1.4. Fractional Order Controller Design Techniques

The classical SP is very sensitive to the uncertainties and modelling errors that may cause destructive effects or even cause instability. However, we always have modelling errors as well as uncertainties, which may cause performance degradation or even instability. Due to the fact that various modifications of SP have been proposed (Bolea et al., 2014; Normey-Rico and Camacho 2008). This section presents a number of fractional order control techniques integrated into Smith predictor (Vu and Lee, 2014; Muresan et al., 2015; Bettayeb et al., 2017). The block diagram of the SP based fractional order control structure can be given in Figure 3.3.

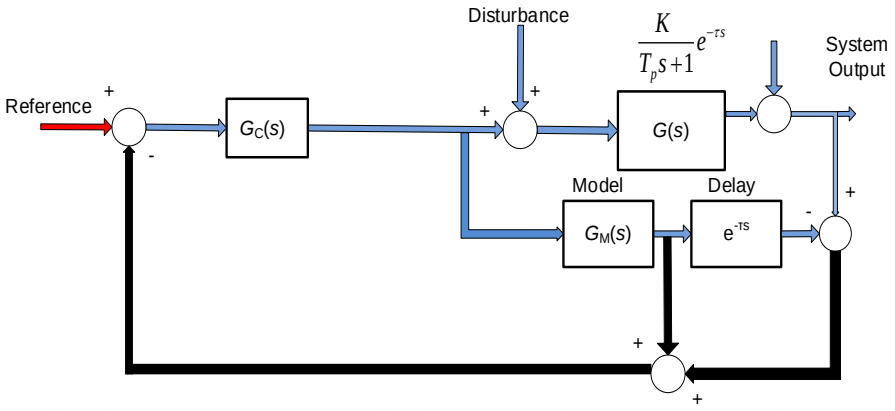


Figure 3.3 Smith predictor based control structure

where $G_C(s)$ is the controller, $G(s)$ is the real process, $\tilde{G}(s)$ is the model of the time delayed process, and $G_M(s)$ is the delay-free model of the real-system. The closed loop transfer function can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G(s)}{1+G_C(s)[G_M(s)+G(s)-\tilde{G}(s)]} \tag{3.30}$$

By assuming a perfect modelling of the process $\tilde{G}(s) = G(s)$, then the closed-loop transfer function can be written as

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_M(s)e^{-\tau s}}{1+G_C(s)G_M(s)} \tag{3.31}$$

A modified Smith predictor is presented in Figure 3.4.

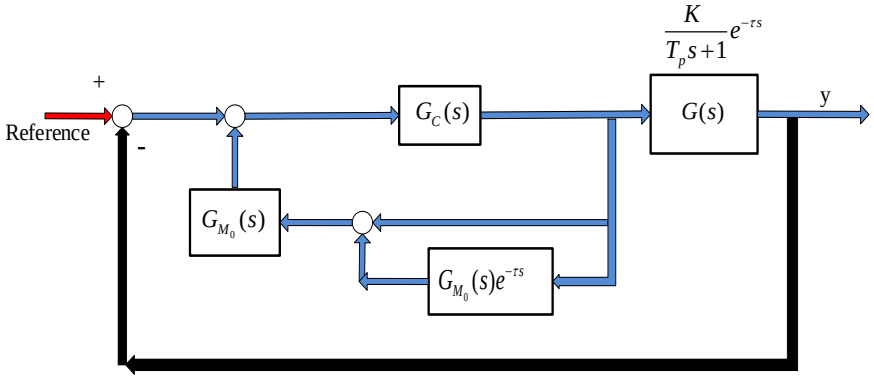


Figure 3.4 Modified Smith predictor

Having these facts in mind, the main motivation is to design and experimentally validate SP based fractional order controllers (Tepljakov et al., 2016). It is to be noted that the Smith predictor method can be successfully applied to stable processes having long time delays. However, the closed-loop performance can be poor in the case of the inevitable mismatch between the model and the actual process. Several modified Smith predictors were then proposed. A modified of Smith predictor is addressed by Wang et al. (Wang et al., 2000), wherein a simple primary controller and a deliberately mismatched model are used in order to improve the performance of the control system.

Consider Figure 3.4 and assume that the delay-free model of the system can be represented as follows.

$$G_M(s) = G_{M_0}(s)G_{M_1}(s) \tag{3.32}$$

where $G_{M_0}(s)$ is a first order transfer function

$$G_{M_0}(s) = \frac{K_m}{1+T_m s} \tag{3.33}$$

where K_m and T_m represent the gain and the time constant of the delay free model of the system. These parameters are optimized so that $G_{M_0}(s)$ fits at best $G(s)$. Further, $G_{M_1}(s)$ can be given as

$$G_{M_1}(s) = \frac{1}{(1+T_m s)^{n-1}} \tag{3.34}$$

where *n* is the order of $G_M(s)$.

3.1.4.1. SP Based Fractional Order Filter PI-PID Controller Design

The method proposed by Bettayeb et al. (Bettayeb et al., 2017) is based on the Bode's ideal transfer function as indicated previously.

Theoretical background, design steps, and stability: Now assume that the plant is modelled as:

$$G_M(s)e^{-\tau_m s} \tag{3.35}$$

where the delay free system is considered in rational form as $\frac{N(s)}{D(s)}$, where *N*(*s*) and *D*(*s*) are rational polynomials if an integer order system is elaborated. In this case, the controller $G_C(s)$, which is a fractional order integrator cascaded with a PI controller, can be represented by

$$G_C(s) = \frac{1}{T_c s^{\lambda}} \frac{T_m}{K_m} \left(1 + \frac{1}{T_m s} \right) \tag{3.36}$$

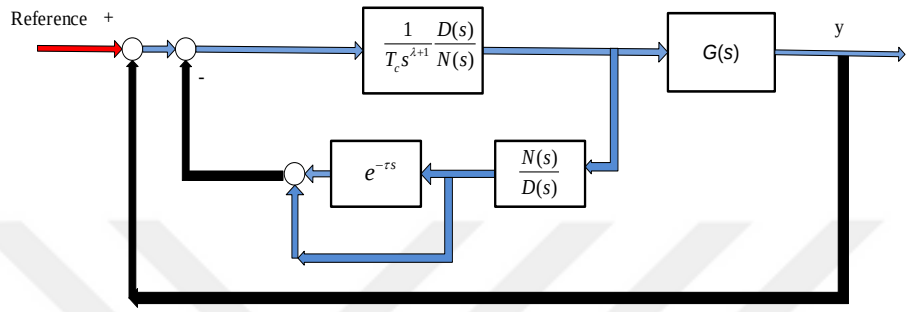


Figure 3.5 Modified Smith predictor based fractional controller

Figure 3.5 shows that the fractional controller. The tuning of the controller requires only the desired gain crossover frequency and phase margin specification.

Stability of the fractional order controller $G_C(s)$ in (3.36) is characterized by the stability of the fractional filter, which is given as:

$$L(s) = \frac{1}{T_c s^{\lambda+1} + 1 - e^{-\tau_m s}} \tag{3.37}$$

is stable if and only if the time constant T_c verifies the following condition:

$$T_c > \frac{2 \sin\left(\frac{\lambda \pi}{2} \right) \tau_m^{\lambda+1}}{\left[(2 - \lambda) \pi \right]^{\lambda+1}} \tag{3.38}$$

It is to be noted that the stability theorem is based on the analysis of the roots of the quasi-polynomial, $p(s, \theta) = T_c s^{\lambda+1} + 1 - e^{-\tau s}$ (Titouche et al.,

2015). In order to establish the proof, the method given in (Walton and Marshall, 1987) is employed.

The controller parameters are tuned according to the presented strategy in proper time-domain and frequency domain specifications. In order to obtain a good control performance the fractional order of the controller is obtained according to the proper overshoot value. The other controller parameters are chosen by using the model of the system. The detail about the parameter tuning for the experimental applications is presented in Chapter 5.

3.1.4.2. SP Based Fractional Order PI Controller Design

The second design technique is known as a direct design of the fractional controller which is elucidated in (Vu and Lee, 2014)

Theoretical background, design steps, and stability: In this context, the controller can be directly designed by using the desired closed loop response $\left[Y(s)/R(s) \right]_d$. Thus, one can express the controller as:

$$G_C(s) = \frac{1}{G_M(s)} \left[\frac{\left(\frac{Y(s)}{R(s)} \right)_d}{e^{-\tau s} - \left(\frac{Y(s)}{R(s)} \right)_d} \right] \tag{3.40}$$

Further, assume that one has the closed loop system represented in Figure 3.6; hence, one can present the desired closed loop transfer function with

$$\left[\frac{Y(s)}{R(s)}\right]_d = \frac{H(s)}{1+H(s)} = \frac{1}{1+\left(\frac{s}{\omega_{cg}}\right)^{\xi}} \tag{3.41}$$

where, the well-known Bode's ideal transfer function in (3.41) can be presented as follows:

$$H(s) = \left(\frac{\omega_{gc}}{s}\right)^{\xi} \tag{3.42}$$

where, ω_{gc} and ξ denote the gain crossover frequency and the slope of the magnitude, respectively.

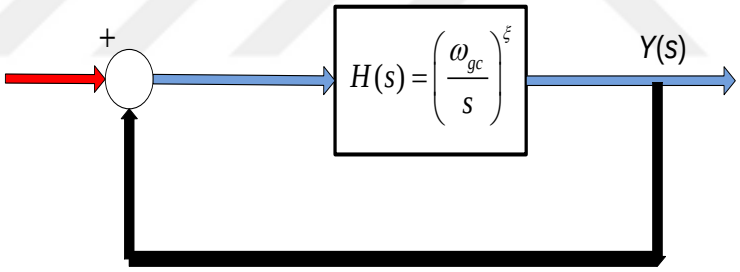


Figure 3.6 Representation of Bode's ideal transfer function

It is to be noted that $H(s)$ represents a fractional order transfer function, where one has a differentiation for $\xi < 0$ and an integration for $\xi > 0$. Then, the fractional order reference model is presented as:

$$\left[\frac{Y(s)}{R(s)}\right]_d = \frac{e^{-\tau s}}{1+\left(\frac{s}{\omega_{cg}}\right)^{\xi}} \tag{3.43}$$

Further, substituting (3.43) into (3.40) can ensure the desired set-point regulation:

$$G_C(s) = \frac{1}{G_M(s)\left(\frac{s}{\omega_{cg}}\right)^{\xi}} \tag{3.44}$$

Substituting a FOPDT model of the system into (3.44), the controller is obtained as follows:

$$G_C(s) = \frac{1}{K}\left[\frac{T_p s + 1}{\left(\frac{s}{\omega_{cg}}\right)^{\xi}}\right] \tag{3.45}$$

Then, substituting $s = j\omega$ into (3.45) and reconsidering the power of the $(j\omega)^{\xi}$ fractional order operator, the controller is obtained in the frequency domain as follows:

$$G_C(j\omega) = \frac{\cos(\theta) + T\omega\sin(\theta)}{K\left(\frac{\omega}{\omega_{cg}}\right)^{\xi}} + \frac{T\omega\cos(\theta) - \sin(\theta)}{K\left(\frac{\omega}{\omega_{cg}}\right)^{\xi}} j \tag{3.46}$$

where

$$e^{-j\tau\omega} = \cos(\varphi) - j\sin(\varphi), \quad \varphi = \tau\omega \tag{3.47}$$

$$\left.\begin{aligned}\left(j\frac{\omega}{\omega_{cg}}\right)^{\xi} &= e^{j\pi\xi/2}\left(\frac{\omega}{\omega_{cg}}\right)^{\xi} \\ &= \left(\frac{\omega}{\omega_{cg}}\right)^{\xi}\cos(\theta) + j\left(\frac{\omega}{\omega_{cg}}\right)^{\xi}\sin(\theta),\ \theta = \frac{\pi\xi}{2}\end{aligned}\right\} \tag{3.48}$$

Then, by considering (3.46) and (3.29), analytical tuning rules of K_I and K_P can be represented as (Vu and Lee, 2014):

$$K_I = \frac{\left[\sin(\theta) - T_p\omega\cos(\theta)\right]\omega^{\varsigma}}{K\left(\frac{\omega}{\omega_{cg}}\right)^{\xi}\sin(\xi_I)} \tag{3.49}$$

$$K_P = \frac{\left[\cos(\theta) + T_p\omega\sin(\theta)\right]}{K\left(\frac{\omega}{\omega_{cg}}\right)^{\xi}} - \frac{K_I\cos(\xi_I)}{\omega^{\varsigma}} \tag{3.50}$$

The fractional order PI controller presented in (3.45) should have frequency dependent parameters as given in (3.49) and (3.50) to achieve the desired closed-loop response perfectly. Further, the maximum value of the sensitivity function over frequency is used to ensure the robustness of the controller:

$$M_s = \max_{\substack{0<\omega<\infty \\ 0<\omega_{cg}<\infty \\ 1<\xi<2}} \left|\frac{1}{1 + G_c(j\omega)G_M(j\omega)}\right| \tag{3.51}$$

Thus, the frequency variables ω and ω_{cg} are considered decision variable to define the controller parameters as well as the closed loop control performance.

Tuning Procedure: The tuning procedure of the controller parameters is presented in this section. First, a number of tests have been conducted on the selection of the fractional integral operator, which is the most critical parameter affecting the performance of the closed loop system. An appropriate fractional order, which shows the smallest value of ISE. Then, the integral term as well as proportional gain are tuned by using ω, ω_{cg},and ς in order to obtain satisfactorily good tracking and disturbance rejection performance. More discussion about the parameter tuning can be found in Chapter 5.

3.1.4.3. SP Based Fractional Order Internal Model Control Design

In this subsection, the experimental realization of the fractional order internal mode control strategy is explored (Muresan et al., 2015).

Theoretical background and design steps: The general structure of the control strategy is portrayed in Figure 3.7 (Muresan et al., 2015).

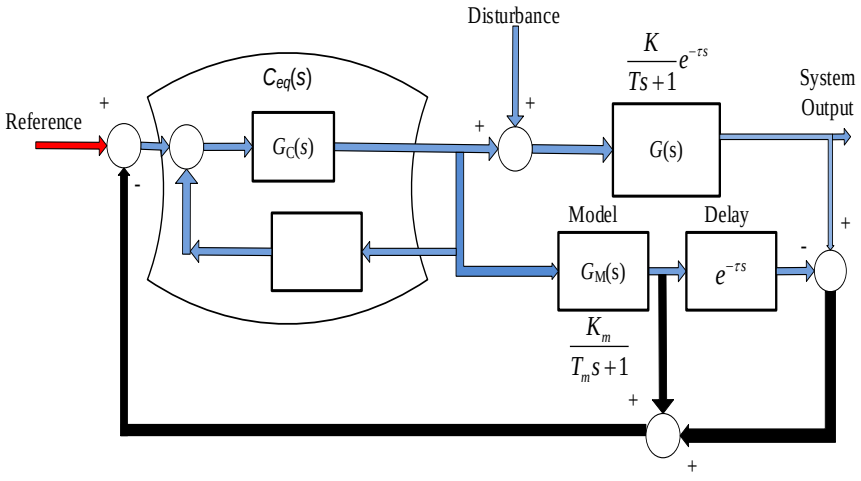


Figure 3.7 SP based internal model control

The equivalent controller of internal model control technique can be expressed as follows:

$$C_{eq}(s)=\frac{G_C(s)}{1-G_C(s)G_M(s)} \tag{3.52}$$

The open loop transfer function can be given as:

$$G_{Open-loop}=C_{eq}(s)G_M(s) \tag{3.53}$$

The internal model controller can be designed by considering the inverse system model (Muresan et al., 2015):

$$G_C(s)=\frac{T_m s+1}{K_m}\frac{1}{\alpha s^{\varsigma}+1} \tag{3.54}$$

At this point, the delay value is approximated by a series expanded method, in which we may obtain approximately $e^{-\tau s}=1-\tau s$. Accordingly, the equivalent controller is given as (Muresan et al., 2015):

$$C_{eq}(s)=\frac{G_C(s)}{1-G_C(s)G_M(s)}=\frac{T_m s+1}{K_m(\alpha s^{\varsigma}+\tau s)} \tag{3.55}$$

and the open loop transfer function is rewritten as:

$$G_{open-loop}(s)=C_{eq}(s)G(s)=\frac{1}{\alpha s^{\varsigma}+\tau_m s}e^{-\tau_m s} \tag{3.56}$$

Tuning procedure: For shaping the closed loop response of a system, the designer has two important time domain specifications, which can be considered as the time constant (α) and the overshoot. However, it is not easy to determine the overshoot directly in internal model control (Garcia and Morari, 1982; Muresan et al., 2015). Concerning the matter, the elaborated control strategy enables us to obtain the overshoot directly by using the fractional order of integral action of the controller. The settling time specification can be obtained by using the gain crossover frequency ω_{gc} in the frequency domain. At this point, one can determine the overshoot of the system by considering the phase margin of the system. Further, the time constant (α) can be directly obtained from modules condition of gain crossover frequency of the open loop model:

$$\angle G_{open-loop}(j\omega_{gc}) = -\pi + \phi_m \tag{3.57}$$

The modified phase margin specification is given as:

$$\frac{\varsigma\pi}{2} = \pi - \phi_m \tag{3.58}$$

Further, the time constant of the internal model filter is obtained:

$$\alpha\omega_{gc}^{\varsigma} = 1 \rightarrow \alpha = \frac{1}{\omega_{gc}^{\varsigma}} = \omega_{gc}^{-\varsigma} \tag{3.59}$$

3.2. Smith Predictor Based Robust Control Techniques

3.2.1. Introduction

Smith Predictor (SP) based robust control is one of the important control techniques for time delay systems. The main purpose is to improve closed-loop

control system performance of time delay systems in the presence of uncertainties, noise, and disturbance. Combination of SP and second-order sliding mode control (SMC) technique is addressed in the present chapter to control single-input–single-output (SISO) time-delayed process subject to disturbances and uncertainties. Further, the first-order sliding mode is applied to compare the system performance.

The stability of the closed-loop system is proved to be asymptotical stable with Lyapunov stability theorem. The proposed controller comprises robust capabilities that make it suitable for experimental applications.

From a practical point of view, an experimental application has a number of constraints with actuators, sensors as well as implementation platforms. Thus, this research highlights a set of experimental applications of new techniques for controlling an industrial process. The objectives of the present chapter can be summarized as below:

- To design a SP based first-order SMC with proportional-integral-derivative sliding surface for a second-order time delay system.
- To design a SP based second-order SMC to control an air heater with experimental applications.
- To test the elaborated control strategies on a real experimental set-up.
- To perform a comparative study between elaborated control techniques.
- To determine the advantages and drawbacks of each control technique.

The contributions of the chapter are twofold. First, the combination of SP and SMC techniques is presented. Second, the simulation as well as the experimental application of the controllers are addressed and the comparative analysis of the elaborated techniques are presented.

The performance of the present control strategies is tested with a number of experimental applications on a second-order time delay process. Even though an

approximate second order model is employed through the study, it is seen that the control techniques satisfactorily cope with the model uncertainties and internal/external disturbances, measurement noise. Further, a quantitative comparison is performed by taking into account the tracking precision, robustness against uncertainties and disturbances, chattering reduction, sliding mode convergence, control signal variations, and control costs.

3.2.2. Literature Background of Smith Predictor Based Robust Control

The classical SP has a number of drawbacks, which may cause possible instability and poor control performance due to the existence of model mismatches, measurement noise, and perturbations (Liu et al., 2005). In other words, although the SP may stabilize the nominal system, a performance degradation may occur or the closed-loop system may become unstable in the presence of disturbances and small variations in the system dynamics. The main reason is that the closed-loop control system is highly sensitive to uncertainties, parameter changes, and disturbances. More precisely, if the controlled plant has poorly known model, parameter changes, uncertainties, and subject to disturbances, conventional SP based control techniques such as Proportional-Integral (PI), Proportional-Integral-Derivative (PID) show insufficient closed-loop performance.

In view of the foregoing, the design of robust control techniques with SP structure for dealing with modelling uncertainties and mismatch are very attractive in control society. A number studies have been addressed the robustness of the SP when the approximated model of the system cannot be obtained exactly. For instance, a simple tuning rule for SP in the face of delay uncertainties is presented in (Santacesaria and Scattolini, 1993). Further, Kravaris and Wrigt address the usage of SP for nonlinear systems (Kravaris and Wright, 1989). An H_∞based robust controller is integrated into SP to improve the control performance (De Oliveira and Karimi, 2013). A further SP structure with a robust H_∞based speed controller is addressed by Zhu et al.(Zhu et al., 2017). In this study, H_∞based

robust control design is transformed to an optimization problem comprises Linear Matrix Inequalities (LMIs). Then, the proposed robust controller is embedded in SP to enhance the control performance of the system with time delay.

SMC is widely applied for both linear and nonlinear control applications, because of its higher robustness capability in the presence of parameter uncertainties of the controlled system as well as internal/external disturbances (Utkin, 1977; Young et al., 1999). In this context, a possible solution to improve the robustness of SP is to use a robust control technique in the controller part of the predictor.

The central notion, the theoretical background, and the detailed discussion on recent SP based SMC techniques have been presented in (Fridman et al., 2012). For instance, the application of SMC for long time delay systems has been elaborated in (Camacho and De La Cruz, 2004), while the system is considered as a first-order plus dead time (FOPDT). A further modification of SP, which employs a variable structure algorithm to design the controller, is highlighted in (Camacho et al., 2007). However, the rational approximation of the delay term is obtained by using the first order Taylor series in this study. In (Chen and Peng, 2005), a robust SMC is presented in controlling of a chemical process. In the research, a delay ahead predictor is adapted to compensate the time-delay. Further, an optimal sliding surface is designed for a SOPDT model. A second order SMC for a time-delay system, in which the time-delay is approximated by first, second, and third order Padé approximation is presented in (Gang et al., 2009). Musmade and Patre address a modified SMC in control of time-delay processes (Musmade and Patre, 2014). An identified second-order plus-dead time process is employed with a state predictor for the controller synthesis. Further, the control parameters are tuned by using the reachability condition (Musmade and Patre, 2014).

Yet another research addresses SMC technique with a proportional-integral sliding surface to improve the regulation as well as tracking control performance of uncertain systems (Kadu et al., 2018). The controller parameters are tuned by using

Linear Quadratic Regulator (LQR). Furthermore, stability conditions are derived by considering the matched uncertainty. Output delay model is applied to use the delay free states and a state observer is employed to obtain the system states. The aforementioned methods are mainly based on the approximation of the actual plant in their design. However, it is to be noted that the approximation of the delay is not exact solution if the time delay sufficiently large. Thus, to eliminate the disadvantages of the approximation methods and to handle systems with long time delay, SP based SMC technique is adopted in a number of studies. For instance, a SP based SMC for open-loop unstable processes is addressed in (Mehta and Rojas, 2015). Optimal tuning of a SP based SMC technique is presented in (Mehta and Rojas, 2015).

3.2.3. System Description and Main Motivations

Temperature control problem (Özbek and Eker, 2016; Özbek and Eker, 2018) is extremely important in industrial applications because of the potential effect the production efficiency and quality. Thus, several techniques have been addressed for controlling heating processes. From a linear system point of view, Haugen addresses a comparison of different types of PI control methods for a heating system (Haugen, 2010). A further study is elaborated fault tolerant control of the air-heating process by using set-valued observers (Rosa et al., 2016). However, it is to be noted that the controller design problem for such a process suffers from a number of constraints such as nonlinearities, overheating problem, transport delay variations, hysteresis effect, saturation, disturbances, and uncertainties.

The control objective is to obtain the desired output temperature by manipulating the input voltage of the heater coil. However, it is to be noted that control design issues for such processes bring a number of challenges. For instance, the changes in heat transfer dynamics due to the speed variation of the blower fan make the process more complicated. From practical points of view, the speed

variations of the air blower, which may cause fluctuation of air mass flow rate in the air tube, acts as a load disturbance. In addition, the temperature sensor is not located at a close position to the heater in industrial thermal process. Due to the fact that, a long transport delay is introduced between the temperature sensors and the heater. Furthermore, there may be a number of sensor positions, where the controller is designed to control the temperature of the process according to the feedback signal comes from these different sensor positions. The thermistor can be located at three diverse measurement points in the tube enabling several transport lags. From these findings, the controller should be able to deal with different constraints as well as unexpected situations, so that the classical control schemes can lead to poor control performance for these types of applications. Hence, it is necessary to design a control scheme to cope with unknown disturbances, parameter variations as well as model uncertainties. A controller that exhibits the lowest sensitivity to changes in the system dynamics, as well as internal/external disturbances will be suitable for this application.

The aforementioned features of SMC and the difficulties of experimental application of SP motivate us to investigate the combination of SMC techniques with SP for long time-delay systems in order to cope with the drawbacks.

The second order plus dead time model is extensively used for modelling because of its simplicity and the ability to represent the system dynamics more precisely than first order plus dead time model. So far, a number of identification methods have been addressed to estimate SOPDT model parameters, and various control schemes have been designed based on SOPDT model. Roughly speaking, the SOPDT model of the system is generally identified by running the system in closed loop or open loop, and then the obtained model is employed directly to design and tune the controller. It is to be noted that experimental applications may consist uncertainties because some part of the real-plant is unknown or poorly known. Therefore, to achieve satisfactory control performance when the system subjects to disturbances and uncertainties is a tedious task for control techniques

that need exact plant models. Thus, providing high robustness against uncertainties as well as disturbances is the main motivation for control designers. From this perspective, the present chapter concerns such challenges to demonstrate the performance of SP based robust control schemes.

A second order system can be presented as (Eker, 2012):

$$\ddot{y}_m(t) = -a_n\dot{y}_m(t) - b_n y_m(t) + c_n u(t) + d(t) \tag{3.60}$$

where $y_m(t)$, $u(t)$, and $d(t)$ represent the model output, the control signal, and the disturbance, respectively. a_n, b_n, c_n are the nominal plant parameters, which can be obtained from the identification process.

Assuming that the system has uncertainties as Δa, Δb, and Δc, then the dynamical system can be presented by

$$\ddot{y}_m(t) = -(a_n + \Delta a)\dot{y}_m(t) - (b_n + \Delta b)y_m(t) + (c_n + \Delta c)u(t) + d(t) \tag{3.61}$$

where the bounded model uncertainties are assumed to be $\Delta a \in [\Delta a_l, \Delta a_h]$, $\Delta b \in [\Delta b_l, \Delta b_h]$, and $\Delta c \in [\Delta c_l, \Delta c_h]$. The lower and the upper bound of uncertainties are represented by the subscripts *l* and *h* (Eker, 2006).

The main purpose is to generate a control input $u(t)$ to track the reference signal with a good level of precision when the system subjects to disturbances. The error is given as $e(t) = y_r(t) - y_m(t)$.

3.2.4. Controller Design

It is known that model uncertainties, parameter changes, and internal/external disturbances may reduce the output tracking accuracy in control applications. Thus, so as to enhance the control performance, the SMC is embedded in SP to compensate the difference between the approximate and the real

time-delayed system. It is evident that robust control techniques such as sliding mode control increase the system performance since their robustness features (Utkin, 1977).

SMC is widely applied in real-time experiments as it provides better control performance as compared to the classical control techniques due to its special characteristics such as invariance to model uncertainty and disturbances. To mention a few, it is well-accepted that SMC provides higher robustness on linear and nonlinear systems subject to uncertainties or disturbances. More precisely, SMC approach enables us a systematic design for the problem of ensuring stability and providing a consistent control performance in case of modelling imprecision.

The control scheme, wherein the time delay is eliminated by a SP structure, while disturbances and uncertainties are compensated with SMC, is depicted in Figure 3.8.

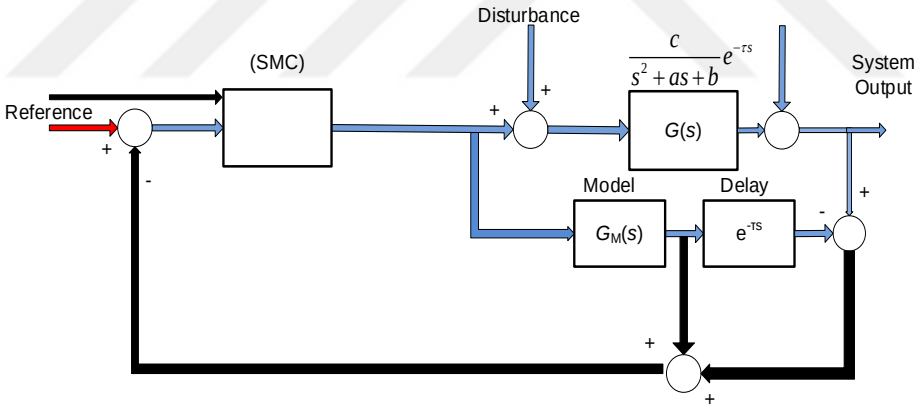


Figure 3.8 Smith predictor based sliding mode control

A standard calculation gives the transfer function of closed loop system as:

$$T_1(s) = \frac{G_M(s)C_1(s)}{1+G_M(s)C_1(s)}e^{-\tau_M s} \tag{3.62}$$

where $C_1(s)$ denotes the sliding mode controller, $G(s)$ presents the real plant, and $G_M(s)$ represents the approximated delay free model of the system (Azar and Zhu, 2015).

The main feature of the SMC is that if the system remains on the sliding manifold, then the closed loop system behaves as an invariant set even if the system subjects to disturbances and uncertainties (Derbel et al., 2017). It is to be stated that the insensitivity property of the SMC with respect to parameter changes and perturbations can be ensured when the invariance condition is satisfied (Utkin, 1977).

The system given in (3.60) can be rearranged as

$$\dot{x}(t) = (a + \Delta a)x(t) + Bu(t) + d(t) \tag{3.63}$$

where $x(t) \in R^n$ denotes the system state, $u(t) \in R$ represents the control input, $a \in R^{nxn}$ is the system matrix, $\Delta a \in R^{nxn}$ is the uncertainty of the system matrix, $b \in R^n$ is the input vector and $d(t)$ presents the disturbance.

The invariance property of the SMC is guaranteed if matching conditions are verified with respect to external disturbances and parametric variations (Khalil, 1996; Derbel et al., 2017). Further, Δa and $d(t)$ verify the matching conditions if there exists $\Delta\bar{a} \in R^{nxn}$ and $\Delta\bar{d} \in R^n$ such as:

$$\Delta a = b\Delta\bar{a} \tag{3.64}$$

$$d(t) = b\Delta\bar{d} \tag{3.65}$$

More precisely, the sliding mode behaves as an invariant set if external disturbances and parametric uncertainties belong to the space generated by *b* (Derbel et al., 2017),

$$\Delta a \in \text{Span}(b),\ d(t) \in \text{Span}\{b\} \tag{3.66}$$

In essence, the SMC technique uses the uncertainty bounds and determine the closed loop system behaviour by the sliding function.

The behaviors of the states can be considered as two main separate parts. First is the so-called reaching phase, which is from the initial state to the sliding surface yet the other is the sliding phase that is from the intersection of the sliding surface to the origin. These parts are depicted in Figure 3.9 (Khalil, 1996; Derbel et al., 2017).

It is to be noted that to ensure the reaching phase to sliding surface, the reaching condition can be ensured by $\dot{\sigma}\sigma < 0$ (Derbel et al., 2017) where σ denotes the sliding surface. Further, to guarantee a finite sliding time, the condition becomes:

$$\dot{\sigma}\sigma < 0 \tag{3.67}$$

The closed-loop system behaviour is represented as $\sigma = 0$ and $\dot{\sigma}\sigma < 0$ (Eker, 2006) through the sliding phase.

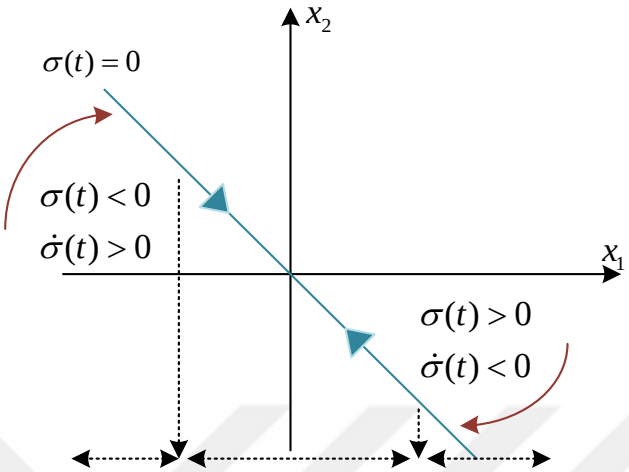


Figure 3.9 Reaching and sliding phase of the SMC

Two main phases are conducted in the synthesis of SMC. First is to design an equivalent control signal to steer the state variables of controlled systems onto the sliding surface. Second is to augment a nonlinear switching control signal for keeping the state variables on the predefined sliding surface within specified boundary layer around the surface.

The synthesis of the SMC is achieved by satisfying the reaching condition (Derbel et al., 2017). The control form to ensure the reaching condition can be chosen by different forms:

$$u = u_{eq} + u_{sw} \tag{3.68}$$

where u_{eq} the equivalent control signal and the term u_{sw} is a nonlinear switching control input as:

$$u_{sw} = -ksign(\sigma) \tag{3.69}$$

where k is a positive gain, $k > 0$. A possible solution for chattering alleviation is to use a smooth signum function through continuous approximation methods. Further, the signum function can be replaced by a sigmoid function, $sign(.)$ denotes the sign function as:

$$sign(\sigma) \cong \frac{\sigma}{(|\sigma| + \varepsilon)} \tag{3.70}$$

where ε denotes the sharpness around $\sigma = 0$. Hence, the chattering phenomenon may be avoided during the implementation. Furthermore, various techniques have been addressed to enhance the SMC performance as well as to avoid chattering phenomenon. An in depth guide is presented in (Yu and Efe, 2015).

The equivalent approach with PID sliding surface was successfully implemented to an electromechanical system (Eker, 2010). The equivalent part of the control signal is evaluated by equating the first derivative of sliding function to zero. The switching part is selected as the function of tangent hyperbolic instead of signum function to overcome chattering. The stability of the proposed algorithm is guaranteed by Lyapunov theory. Furthermore, the experimental results showed that the proposed scheme has faster convergence time and better time-domain specifications with respect to classical SMC.

3.2.4.1. Smith Predictor Based Sliding Mode Control

The error in system dynamics is $e(t) = y_r(t) - y_m(t)$ where y_r is the reference, y_m is the measured output. The sliding surface is given as (Eker, 2010)

$$\sigma = k_p e + k_i \int_0^t e + k_d \dot{e} \tag{3.71}$$

Considering the nominal system such that $\Delta a = 0$, $\Delta b = 0$, $\Delta c = 0$, and the disturbance $D(t) = 0$, then the first time derivative of (3.72) can be given as:

$$\dot{\sigma} = k_p \dot{e} + k_i e + k_d \ddot{e} \tag{3.72}$$

The main goal of the SMC technique is to force the error function $e(t)$ to reach the specified sliding surface and then move it to the origin along the sliding surface. Then, in order to remain on the sliding surface, $\dot{\sigma} = 0$ should be satisfied.

3.2.4.2. SP Based First Order Sliding Mode Control with PID Sliding Surface

One needs to obtain the second time derivative of the error function, $\ddot{e}(t)$, which can be presented in terms of the plant parameters as (Eker, 2010)

$$\ddot{e}(t) = \ddot{y}_r(t) + a_n \dot{y}_m(t) + b_n y_m(t) - c_n u(t) - D(t, u(t)) \tag{3.73}$$

where $D(t,u(t))$ is disturbance and should satisfy $\left|D(t,u(t))\right| < D_{\max}$. Then, substituting (3.73) into (3.72) gives

$$\begin{aligned} \dot{\sigma}(t) = {} & k_p \dot{e}(t) + k_i e(t) + k_d [\ddot{y}_r(t) + a_n \dot{y}_m(t) + b_n y_m(t) - c_n u(t)] \\ & - D(t, u(t)) \end{aligned} \tag{3.74}$$

An important note should be pointed out that the controller parameters namely k_p, k_i, k_d should be chosen such that the characteristic polynomial of (3.72) is strictly Hurwitz. This condition satisfies $\lim_{t\to\infty} e(t) = 0$ and stability is

provided. Then, the equivalent control signal u_{eq} can be obtained by the solution of $\dot{\sigma} = 0$,

$$u_{eq}(t) = \frac{1}{k_d c_n}\left[k_p \dot{e}(t) + k_i e(t) + k_d \ddot{y}_r(t) + k_d a_n \dot{y}_m(t) + k_d b_n y_m(t) \right] \quad (3.75)$$

Furthermore, the equivalent control signal can be represented if the uncertainty is taken into account

$$u_{eq}^{*}(t) = u_{eq}(t) + \frac{1}{c_n} D(t, u(t)) \quad (3.76)$$

The elaborated SP based first-order SMC technique is depicted in Figure 3.10.

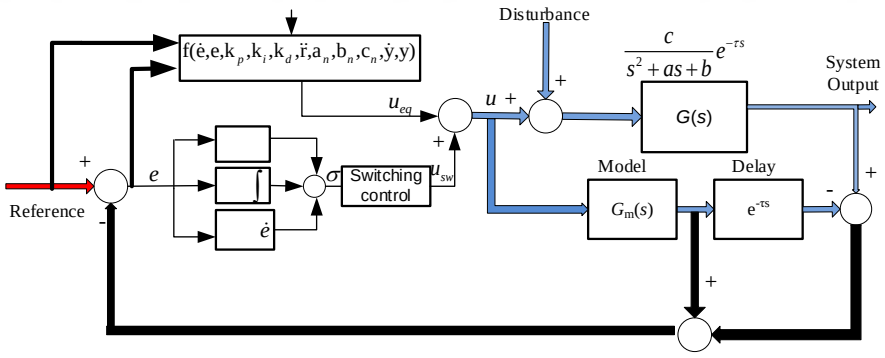


Figure 3.10 SP based first-order SMC

The stability of a control system is often extremely important safety issue in engineering systems. In other words, from the safe operation points of view, a control system has to provide all the necessary and sufficient stability conditions. Towards this goal, the stability analysis is derived based on Lyapunov stability

theory, which is a system-dependent, and its construction currently is more an art than a science. Now consider the Lyapunov function candidate as:

$$V(\sigma) = \frac{1}{2}\sigma^2 \tag{3.77}$$

A sufficient condition to ensure the translation of error trajectories from reaching phase to sliding phase is known as reaching condition (Eker, 2010). In other words, if the time derivative of the Lyapunov function candidate satisfies $\dot{V} = \sigma\dot{\sigma} < 0$, then all initial conditions of the error is guided toward the loci characterized by $\sigma = 0$. To maintain $\sigma\dot{\sigma} < 0$ the control signal is chosen as (Utkin, 1977):

$$u(t) = u_{eq}(t) + u_{sw}(t) \tag{3.78}$$

where, the switching signal $u_{sw}(t)$ is determined by the following condition

$$\begin{aligned}\dot{V}(t) \le & \left|\sigma(t)\right|\{k_d[\left|\Delta a - c^{-1}a\Delta c\right|\left|\dot{y}_m\right| + \left|\Delta b - c^{-1}b\Delta c\right|\left|y_m\right|] \\ & + \left|c^{-1}a\Delta c\right|(k_p\left|\dot{e}\right| + k_i\left|e\right| + k_3\left|\ddot{y}_r\right|)\} - \sigma(t)k_d(c+\Delta c)u_{sw} - \sigma(t)k_d D(t,u(t)) \\ & < 0\end{aligned} \tag{3.79}$$

It is observed that the negative definiteness of the first time derivative of the Lyapunov function candidate can be guaranteed if (3.79) is satisfied. Further, to ensure (3.79) is less than zero, $u_{sw}(t)$ can be written as:

$$\begin{aligned}u_{sw}(t) = & \operatorname{sgn}(\sigma)[k_d(c+\Delta c_l)]^{-1}[k_d(\Delta a_h - c^{-1}a\Delta c_l)\left|\dot{y}_m\right| \\ & + k_d(\Delta b_h - c^{-1}b\Delta c_l)(y_m) + c^{-1}\Delta c_h(k_p\left|\dot{e}\right| + k_i\left|e\right| + k_d\left|\ddot{y}_r\right|)] + k_d D(t,u(t))\end{aligned} \tag{3.80}$$

It is evident that substituting (3.80) into (3.79) provides $\dot{V}(t)$, wherein the hitting control achieves a stable sliding mode control system. Due to a number of constraints, the switching signal is introduced as follows:

$$\begin{aligned} u_{sw}(t) &= -k_s sign(\sigma(t)) \\ &= -k_s \frac{\sigma(t)}{|\sigma(t)| + \varepsilon} \end{aligned} \tag{3.81}$$

where ε defines the thickness of the boundary layer. A remedy to this is to smooth the sign function by introducing a boundary layer and its thickness is another parameter influencing the performance. Further, to improve the switching control effort, a tangent hyperbolic function is introduced as follows

$$u_{sw}(t) = -k_s \tanh\left(\frac{\sigma(t)}{\varepsilon}\right) \tag{3.82}$$

The slope of (3.82) ε is a key parameter determining the convergence of error to zero. The SMC systems are quite vulnerable to noise as the switching mechanism is based on the sign of a quantity that is very close to zero.

3.2.4.3. SP Based Second-Order SMC for Long Time-Delay Process

A number of research studies have been investigated to alleviate the chattering phenomenon. Some of these studies can be summarized as follows. A boundary layer technique is addressed in (Burton and Zinober, 1986). Tseng and Chen indicate that the boundary layer design may becomes ineffective, if there exists high measurement noise (Tseng and Chen, 2010). Thus, they present a filtered SMC, which is designed by low-pass filtering of the control signal. A recent technique to alleviate the chattering is fractional order SMC (Corradini et

al., 2015). However, apart from these techniques, high-order sliding mode control (HOSMC) technique, which consists not only the sliding variable, but also its time derivatives up to a certain order $r-1$ (Bartolini et al., 1998; Bartolini et al., 2003; Levant, 2007; Eker, 2010; Ding and Li, 2017). HOSMC techniques have been extensively applied to various systems because of the continuous nature of the control action (Cruz-Zavala and Moreno, 2017; Incremona et al., 2017). A control diagram of the second-order SMC is presented in Figure 3.11.

In the following, the application of SP based second order sliding mode control will be presented for a temperature air-heating process with SOPTD identified model.

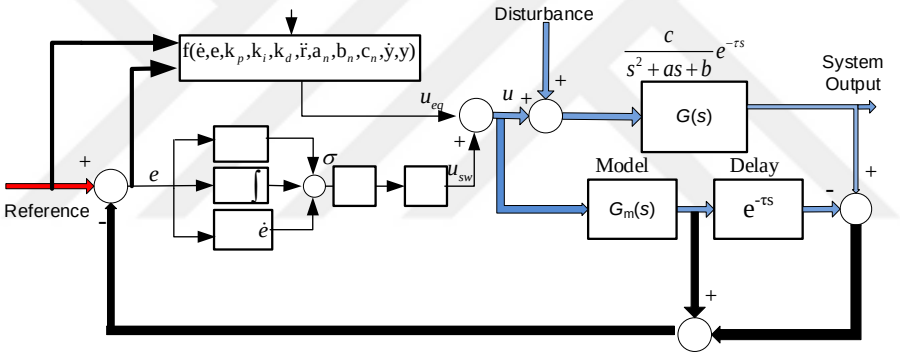


Figure 3.11 SP based second-order SMC

A sliding mode is said “rth order sliding mode” if and only if $\sigma(t)=\dot{\sigma}(t)=...=\sigma^{(r-1)}(t)=0$. In this aspect, the objective is to steer to zero not only the sliding surface $\sigma(t)$, but also its first-order time derivative as $\sigma(t)=\dot{\sigma}(t)=0$ (Eker, 2010). In view of this, a sliding surface can be introduced as:

$$\dot{\sigma}(t)+\lambda\sigma(t)=k_p e(t)+k_i\int_0^t e(\tau)d\tau+k_d\dot{e}(t) \tag{3.83}$$

where k_p, k_i, k_d, $\lambda \in R^+$ are representing controller gains of proportional, integral, derivative actions, and the sliding gain that contributes the damping of $\sigma(t)$, determining the rate of decay for $\sigma(t)$, R^+ denotes positive real numbers (Eker, 2010).

It is well known that chattering phenomenon, which leads to undesirable loads on control actuators, is a natural result of switching type control mechanisms. In view of this, various strategies indicating new directions and improvements for SMC are reported. Among them, the SOSMC has a better accuracy than classical SMC.

The second time derivative of (3.83), can be given as

$$\ddot{\sigma}(t) + \lambda\dot{\sigma}(t) = k_p\dot{e}(t) + k_i e(t) + k_d\ddot{e}(t) \tag{3.84}$$

The tracking error will converge to zero exponential, if the system is trapped on the sliding surface, namely $\sigma(t) = \dot{\sigma}(t) = \ddot{\sigma}(t) = 0$, further, if the roots of $k_p\dot{e}(t) + k_i e(t) + k_d\ddot{e}(t) = 0$ lie in the open left half of the complex plane.

$$\begin{aligned}\ddot{\sigma}(t) + \lambda\dot{\sigma}(t) = k_p\dot{e}(t) + k_i e(t) + k_d(\ddot{y}_r(t) \\ + a_n\dot{y}_m(t) + b_n y_m(t) - c_n u(t) - d(t,u(t)))\end{aligned} \tag{3.85}$$

The equivalent control signal can be calculated by using $\ddot{\sigma}(t) = 0$. It is to be noted that the disturbance function $D(t,u(t))$ is not taken into account for the equivalent control since the nominal plant parameters are assumed known.

$$u_{eq}(t) = \frac{1}{k_d c_n}\left[k_p\dot{e}(t) + k_d\ddot{y}_r(t) + k_d a_n\ddot{y}_m(t) + k_d b_n y_m(t) + k_i e(t) - \lambda\dot{\sigma}(t)\right] \tag{3.86}$$

where, the equivalent control signal with the uncertainty can be written as

$$u_{eq}^{*}(t) = u_{eq}(t) + c_n^{-1} d(t, u(t)) \tag{3.87}$$

If the switching control signal is chosen as

$$u_{sw}(t) = \delta_1 \sigma(t) + k_s sign(\dot{\sigma}(t)) \tag{3.88}$$

where $\delta_1, k_s \in R^{+}$ with $\delta_1 > \frac{1}{k_d c_n}$, $k_s > \frac{D_{\max}}{c_n}$ with $D_{\max} = \sup_{\forall t,\sigma,\dot{\sigma}=0} \{D(t, u(t))\}$.

By substituting (3.86) and (3.88) into (3.85) one has

$$\ddot{\sigma}(t) = -k_d d(t, u(t)) + k_d c_n \delta_1 \sigma(t) - k_d c_n \, sign(\dot{\sigma}(t)) \tag{3.89}$$

Now let us use the following Lyapunov function candidate

$$V(t) = \frac{1}{2}\sigma^2(t) + \frac{1}{2}\dot{\sigma}^2(t) \tag{3.90}$$

where $V(t)$ satisfies $V(0) = 0$ and $V(t) > 0$ for $\sigma(t) \neq 0, \dot{\sigma}(t) \neq 0$. The stability can be guaranteed if the reaching condition is ensured

$$\dot{V}(t) < 0, \ \sigma(t) \neq 0, \ \dot{\sigma}(t) \neq 0 \tag{3.91}$$

Then the first time derivative of $V(t)$ can be written as

$$\begin{aligned}\dot{V}(t) &= \sigma(t)\,\dot{\sigma}(t) + \dot{\sigma}(t)\ddot{\sigma}(t) \\ &= \sigma(t)\,\dot{\sigma}(t) + \dot{\sigma}(t)(-k_d d(t,u(t)) + k_d c_n \delta_1 \sigma(t) - k_d c_n \,\mathrm{sign}(\dot{\sigma}(t))) \\ &= \sigma(t)\,\dot{\sigma}(t) - k_d c_n \delta_1 \sigma(t)\dot{\sigma}(t) - \dot{\sigma}(t) k_d d(t,u(t)) - k_d c_n k_s |\dot{\sigma}(t)| \\ &\le |\dot{\sigma}(t)|(|\sigma(t)| - k_d c_n \delta_1 |\sigma(t)| - k_d d(t,u(t)) - k_d c_n k_s) \\ &= -|\dot{\sigma}(t)|(|\sigma(t)|(k_d c_n \delta_1 - 1) + k_d c_n k_s - k_d d_{\max}) < 0\end{aligned} \tag{3.92}$$

where, $k_s > \frac{D_{\max}}{c_n}$ is to dominate the matching uncertainties (Eker, 2012). In (3.92), since the system is in the reaching phase with $\delta_1 > \frac{1}{k_d c_n}, |\sigma(t)| > 0,\ |\dot{\sigma}(t)| > 0$ then negative definiteness of $\dot{V}(t) < 0$ is ensured (Eker, 2012). Then, the switching signal is selected as to get approximate function of sign

$$u_{sw}(t) = \delta\sigma(t) + k_s \tanh\left(\frac{\dot{\sigma}(t)}{\varepsilon}\right) \tag{3.93}$$

where ε denotes the thickness of the boundary layer.

3.3. Smith Predictor Based Gain-Scheduled Control

3.3.1. Introduction

In spite of the alternatives available in the literature, the structure of the control system, the fractional calculus, the role of fuzzy inference mechanism and the availability of adaptation mechanism make the proposed control scheme an efficient and highly suitable for real-time experimental applications of time delay systems. The present research considers a combination to obtain better tracking capability, strong robustness, improved noise rejection capabilities, and more suitable control signal than those utilizing traditional integer order operators. Further, the structural properties provide more choice to the control engineer for

the controller variables. To the best of the author's knowledge, until now, no work has been reported in the literature to design of the SP based FFPI-PD control for a process comprising time-delay.

The choice of the controller parameters is a critical issue in the design phase of the control applications. It is known that analytical solutions can be provided to decide the controller parameter values for simple linear systems (Pan and Das, 2013). To mention a few, the controller design problem has been solved by using analytical formalisms like the pole placement method, Ziegler-Nichols method, Cohen Coon's method etc. Further, LMI techniques have also become very popular since various control design problems can be recast as an LMI problem which can be solved by efficient interior point methods offering the advantage of guaranteed convergence within a finite time (Boyd et al., 1994). However, for complex systems with nonlinearities such as saturation, hysteresis, and backlash in the control loop, it is a challenging problem to obtain analytical tuning of controller parameters. Thus, many practical engineering design problems comprise nonlinearities use intelligent gradient free algorithms as an effective alternative to solve the controller-tuning problem (Pan and Das, 2013).

The present research discusses further modifications of the recently developed fractional order fuzzy control strategy integrated into SP. It is found in literature search; this topic has been widely investigated neither in simulation nor in real-time experiments. Although a number of papers (Efe, 2008; Pan and Das, 2016; Haji Haji and Monje, 2017) address the problem of fractional fuzzy control algorithms which are focusing on typical industrial examples such as robots (Kumar and Rana, 2017), the distillation column (Mishra et al., 2015). It is found that the proposed controller, has not been developed and implemented for any linear or nonlinear process. Furthermore, the applications of fractional fuzzy control algorithms have been discussed mostly by simulations (Das et al., 2012; Pan and Das, 2016; Sharma et al., 2016; Kumar and Kumar, 2017). Thus, it seems

that the experimental validation has been problematic up to now, and the absence of experimental application on a real system is the main motivation of the research.

The proposed fractional fuzzy PI-PD controller is a new form of SP structure which has not seen in the literature (Kaya, 2003; Normey-Rico and Camacho, 2008). The present control scheme has the characteristic of a gain-scheduling, wherein the parameters of the controller are updating at runtime. Moreover, non-integer differentiator and integrator are utilized in the controller. The controller gains are optimized by using a genetic algorithm strategy.

The main objectives of the present chapter can be summarized as follows:

- The first objective is to address a control scheme for robust temperature tracking, which ensures the temperatures be close to the reference temperature values in the presence of parameter variations and uncertainties.
- The second is to optimize the proposed controller with a prescribed performance index.
- The third objective is to compare the closed-loop control performances of integer and fractional order fuzzy controllers with experimental applications.

3.4. System Description and Main Motivations

Control of temperature, which needs to be finely achieved with the consideration of equipment and environmental safety, is a crucial issue as flow rate and motor speed control in industrial applications. The temperature profile tracking, particularly, is necessary for an efficient control of critical systems such as a batch chemical reactor. Moreover, three main control tasks have been seen such as regulation of the temperature, tracking of a variable temperature profile,

and the temperature uniformity control has been frequently elaborated in various applications (Ahn et al., 2009).

It is observed that the classical PI and PID type control schemes are commonly used for controlling thermal processes in literature. However, a number of challenges such as parameter variations, nonlinearities, unpredictable disturbances, uncertainties, and unknown dynamics can easily lead to performance degradation. Furthermore, the thermal process is nonstationary, because of parameter changes during the warming-up of the heater and air transmission line. The changes in heat transfer dynamics due to the speed variation of the blower fan make the process more complicated. The speed variations of the air blower may cause fluctuation of air mass flow rate in the air tube, and thus it acts as a load disturbance and parameter variations. The temperature sensor is not located at a closed position to the heater, and thus a long transport delay is introduced between the sensor and the actuator. Hence, the aforementioned delay makes the system an infinite dimensional problem. Furthermore, the overheating of the duct has a crucial impact on the system model. These situations have a direct impact not only on the actuation but also on the model of the process. Concisely, a process including all the aforementioned challenges is complex and has some vulnerabilities. (Ahn et al., 2009; Rosa and Silvestre, 2014; Rosa et al., 2016). Further, the aforementioned variations can cause an important effect on the system performance.

Thus, the designed control scheme should be able to cope with unknown disturbances, parameter variations, and model uncertainties. There exists a need to obtain satisfactory control performance for the real-time heating process running under different operating conditions.

The dynamics of the full-order heat conduction model contains temperature dynamics, power dynamics, and mass air flow dynamics (Yesil et al., 2007). Some reasonable assumptions simplify the model to get: i) The dynamics of the air flow are much slower than the pressure dynamics, which is omitted; ii) The volumes

associated with the air gas recirculation are considered small. Further, for the sake of simplicity, most of the studies in literature present the low order control-oriented model of the system.

3.4.1. Fundamental of Fractional Calculus and Implementation Issues

A number of definitions for fractional order integrodifferential operator have been reported in the literature. Among them, Caputo and Riemann-Liouville are the two well-known definitions of fractional order integrodifferential operator (Das and Pan, 2012). In the present study, the fractional order integrodifferential is defined by using Riemann-Liouville (RL) definition:

$$ {}_aD_t^{v} f(t) = \frac{1}{\Gamma(n-v)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{v-n+1}} dt, \quad n-1 < v < n \tag{3.94} $$

where (3.94) represents a fractional order functional operator ${}_aD_t^{v}$, further a and t are the limits of fractional operation. There, D is the fractional operator, $f(t)$ is a function, v represents the fractional order, $\Gamma(.)$ denotes a gamma function. The definition given in (3.94) can be extended to fractional order integral as (Podlubny, 1999):

$$ {}_aD_t^{-v} f(t) = \frac{1}{\Gamma(v)} \int_a^t (t-\tau)^{v-1} f(\tau) dt, \quad v > 0 \tag{3.95} $$

Now, considering all the initial conditions to be zero within $v \in [0,1]$, the Laplace transform of the fractional functional operator can be presented as (Sabatier et al., 2015):

$$L\{{}_aD_t^{\pm v} f(t)\} = s^{\pm v} F(s) \tag{3.96}$$

An example of fractional order system can be expressed as:

$$\sum_{i=0}^{n} a_i D_0^{v_i} y(t) = \sum_{j=0}^{m} b_j D_0^{\upsilon_j} u(t) \tag{3.97}$$

where the control signal and system output are denoted by $u(t)$ and $y(t)$ respectively. Further, the transfer function of the system can be expressed as follows:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_m s^{\upsilon_m} + b_{m-1} s^{\upsilon_m - 1} + \ldots + b_0 s^{\upsilon_0}}{a_n s^{v_n} + a_{n-1} s^{v_{n-1}} + \ldots + a_0 s^{v_0}} \tag{3.98}$$

where v_i and υ_j are arbitrary positive real numbers.

Fractional order transfer function shows infinite dimensional characteristic. In this aspect, the experimental application of a fractional order controller is still a challenge, due to the physical constraints of actuators, sensors as well as implementation platforms (Tepljakov et al., 2011). An integer order model approximation should be obtained for the fractional order of s. So far, several integer order approximation methods such as Caputo, Oustlaoup have been dedicated. In the present work, the Oustaloup's approximation method is employed because of its ability for real hardware implementation with the use of higher-order infinite impulse response (IIR) type analog or digital filters for each fractional order differentiator integrator in the design of the controller (Sharma et al., 2014). The approximated transfer function provided by Oustaloup is shown in (3.20), (3.21), and (3.22).

A critical step, which determines the performance of the fractional order approximation, is the choice of ***N***. More clearly, high values of ***N*** ensure much more realistic approximation, however, it leads heavy computational complexity (Das et al., 2013; Sharma et al., 2014). By considering the previous experimental knowledge, ***N*** is selected as 5 and frequency range ω_l and ω_h are selected as $\left[10^{-2},10^{2}\right]$ through the study. The above parameters are selected after several experiments.

Frequency domain representation of Fractional Order Proportional Integral (FOPI) controller and Fractional Order Proportional Derivative (FOPD) controller can be given as

$$G_{PI}(j\omega) = K_C + \frac{K_I}{(j\omega)^{\lambda}} \tag{3.99}$$

$$G_{PD}(j\omega) = K_p + K_d(j\omega)^{\mu} \tag{3.100}$$

where, K_c, K_i, and λ denote the proportional gain, integral gain and fractional order of integral, K_p, K_d, and μ denote the proportional gain, derivative gain and fractional order of derivative.

3.5. Controller Design

The conventional fixed-gain PID type control scheme is used in a wide range of industrial applications, however, the performances of these types of controllers may suffer from various factors such as parameter variations caused by flow changes, temperature variations, and internal/external disturbances caused by heat exchange. These methods cannot deal with nonlinear or ill-defined processes, especially, when the disturbances are unpredictable. Furthermore, the

aforementioned challenges make it hard to apply conventional control strategies for accurate control with small errors in the presence of variable ambient conditions. Thus, the classical control approaches cannot exhibit satisfactory performance for a wide range of temperature variations.

Fuzzy control enables us more flexibility in control of such systems by adapting the experiments into the linguistic notations. Although the fuzzy logic controller contains static non-linearity between its inputs and outputs, it can be tuned easily by means of heuristic manner without delving into the exact mathematical description of the controlled system (Das et al., 2012). In view of foregoing, by utilizing a synergetic combination of fractional fuzzy PI-PD (FFPI-PD) strategy with SP, the most challenging issues can be solved. More clearly, SP compensates the time delay while the FFPI-PD controller copes with the challenging issues such as parameter variations, model uncertainties, and unpredictable disturbances. Since the controller can be tuned on-line by fuzzy logic to improve the control performance of a time-delay thermal process.

The PI-PD control scheme can improve the closed loop performance of systems having large time constants or integrator (Kaya, 2015; Zou and Li, 2017). However, parameter variations, model uncertainties, and unknown load disturbances still cause suffering (Kaya, 2003). To overcome these drawbacks, a fractional order fuzzy-gain scheduled structure is combined with PI-PD based SP structure as shown in Figure 3.12.

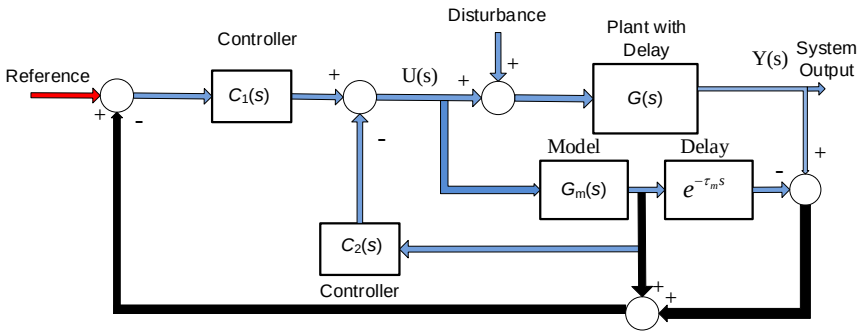


Figure 3.12 Smith predictor based PI-PD control

The transfer function can be presented as:

$$\frac{Y(s)}{U(s)} = \frac{G_m(s)[1+G_m(s)(C_1(s)+C_2(s)-C_1(s)e^{-\tau_m s})]e^{-\tau_m s}}{[1+G_m(s)(C_1(s)+C_2(s))][1+G_m e^{-\tau_m s}]} \quad (3.101)$$

where two controllers $C_1(s)$ and $C_2(s)$, represent PI and PD controllers, respectively (Kaya, 2015).

The controllers, $C_1(s)$ and $C_2(s)$ are designed using fractional fuzzy gain-scheduling algorithm. A theoretically sound and practically useful design method is necessary to reduce both the cost as well as time for the development of the fuzzy control system.

A fuzzy controller is composed of different interrelated nonlinear components (e.g., input and output fuzzy sets, fuzzy rules, AND and OR operators, fuzzy inference, and a defuzzifier). The fuzzy logic based controller is a nonlinear controller and its local behaviour can be adjusted to the rules defining the local functions (Eker and Torun, 2006). The underlying philosophy is to incorporate the experiences of an expert into the design that is mostly based on the physics of the process, utilising the possibilities available in the domain of linguistic labels. The flow of information through the fuzzy controller undergoes fuzzification and defuzzification stages enabling the designer to make choices from a diverse set of possibilities.

In the present control scheme, fractional order differentiator is used to producing the rate of change of error at the input to the fuzzy logic control. Parallel to this, a non-integer integrator, as well as a non-integer differentiator are used to integrate and differentiate the output of fuzzy logic control in order to obtain fuzzy PI and fuzzy PD control actions. The block diagram based on fractional order is given in Figure 3.13 and the proposed applicable scheme is depicted in Figure 3.14.

The main difference between the fractional fuzzy PI-PD and integer order fuzzy PI-PD is that the FFPI-PD controller employs non-integer differentiator to generate the change of error and non-integer integral and derivative to produce fractional PI and PD control signals (Mishra et al., 2015; Kumar et al., 2016). Due to the aforementioned differences, the proposed control scheme uses different values of controller gains. It should be noted that integer order fuzzy gain scheduling structure can be attained by replacing the non-integer orders with ‘1’ in the present scheme.

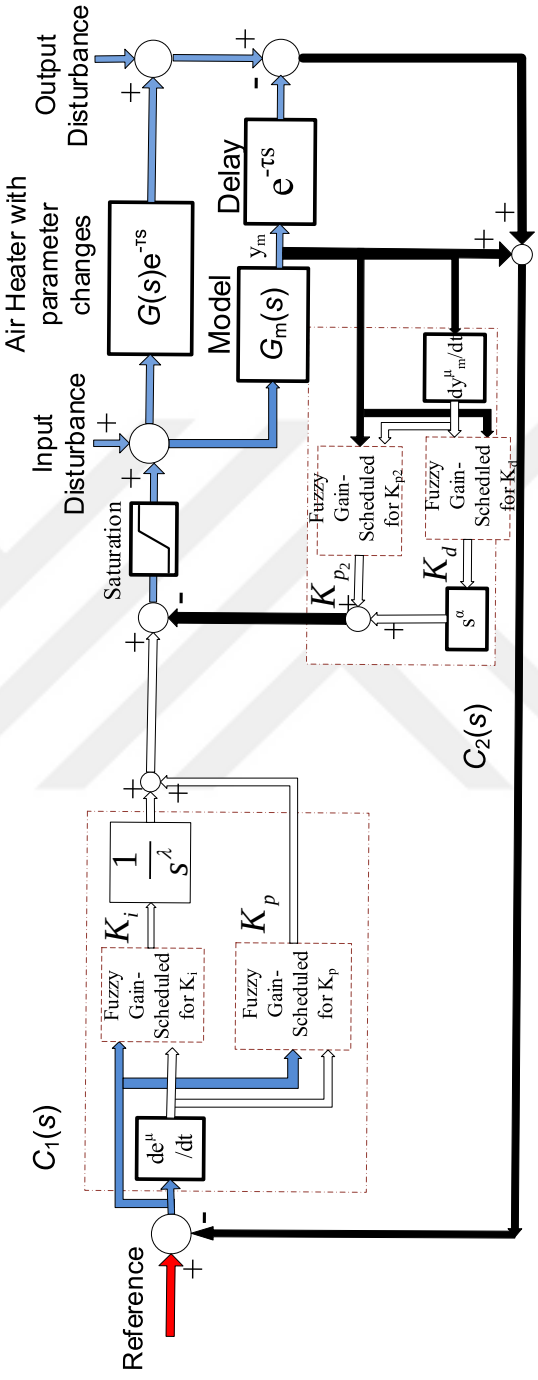


Figure 3.13 The control scheme with fractional parameters

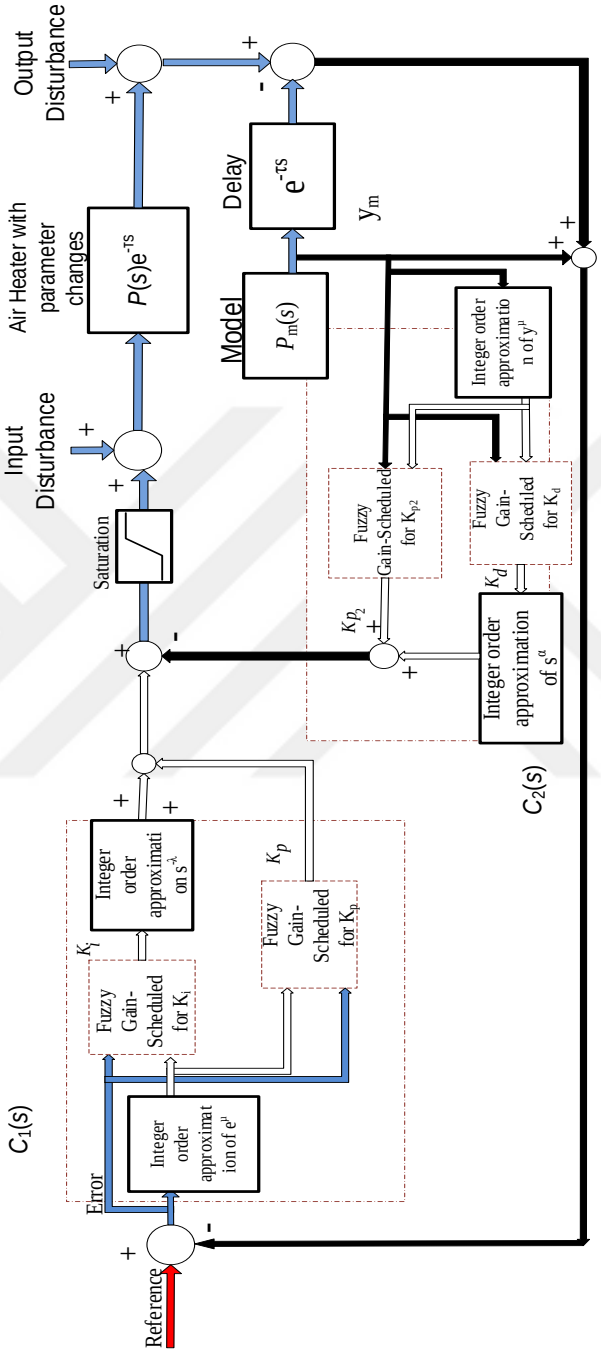


Figure 3.14 The proposed applicable control scheme

Each controller parameter is updated according to the linear transformation such as

$$K_p = (K_{p_{\max}} - K_{p_{\min}})K_p + K_{p_{\min}} \tag{3.102}$$

$$K_i = (K_{i_{\max}} - K_{i_{\min}})K_i + K_{i_{\min}} \tag{3.103}$$

$$K_{p2} = (K_{p2_{\max}} - K_{p2_{\min}})K_{p2} + K_{p2_{\min}} \tag{3.104}$$

$$K_d \in [K_{d_{\min}} - K_{d_{\max}}] \tag{3.105}$$

Where $K_p \in [K_{p_{\min}} - K_{p_{\max}}]$, $K_i \in [K_{i_{\min}} - K_{i_{\max}}]$, $K_{p2} \in [K_{p2_{\min}} - K_{p2_{\max}}]$ and $K_d \in [K_{d_{\min}} - K_{d_{\max}}]$ are predetermined parameter intervals for K_p, K_i, K_{p2}, K_d respectively.

The control of the thermal process, a fuzzy control system comprising 49 rules is implemented. It is well-known that the fuzzification part mainly produces the linguistic equivalents of the crisp values. Thus, the formulation of membership functions (MFs) and the construction of rule-based is the key part, which directly effects the control performance (Sharma et al., 2016). The rule base is generally constructed from a priori knowledge, and expertise of the designer by considering the process dynamics. To clarify how these rules are constructed, following situations can be summarized for K_{i} and K_{p2}. Suppose that we have a constant reference, the error is zero, and fractional derivative of the error is negative. In this case, the output increases which causes an overshoot. To overcome this situation, the control input should be decreased. More specifically, this corresponds to applying a sufficiently small positive value. Thus, the rule base can be defined as ‘if the error is zero and fractional derivative of error is negative law, then output needs a positive medium correction term. In order to prevent sharp response and oscillations and produce smooth control response.

Further, an example for K_p, K_d can be explained as follows (Li et al., 1998). Suppose that error and fractional rate of change of error are negative, in this case, the system output has exceeded the reference and their difference is still increasing. This situation necessitates reducing controller output by a low positive output value. Hereby, the output of the system can track the reference with an acceptable performance. In the second case, suppose that error is negative and fractional rate of change of error is positive. This means that the system output is above the set value although the error is decreasing. So that, the controller output should continue to be reduced but the decrement is should be adjusted properly such that the system output can track the reference. By considering the above approximate human inference, a number of fuzzy rules can be derived. Furthermore, from a system theoretical point of view, a typical performance demand requires less oscillatory step response having as small as possible overshoot and a fast settling. The fuzzy rule-based can be constructed by observing a typical step response of the closed-loop system.

The fuzzy gain-scheduled algorithm for each control parameter is utilized separately. The membership functions are purposely selected as a mixture of different types, namely, triangular and trapezoidal. Further, product inference engine has been used to form the fuzzy rules. The overall input-output relation can be represented as:

$$u = \frac{\sum_{i=1}^{R} y_i \prod_{j=1}^{m} \mu_{ij}(e_j)}{\sum_{i=1}^{R} \prod_{j=1}^{m} \mu_{ij}(e_j)} \tag{3.106}$$

where $\mu_{ij}(e_j)$ is the MF quantifying the i-th rule's j-th input, which is e_j. In the rule base, NH, NM, NL, Z, PL, PM, PH denote the labels `negative high`,

`negative medium`, `negative low`, `zero`, `positive low`, `positive medium`, `positive high`, respectively. Based on the input and output MFs and the related fuzzy rules can be given as:

IF (e_1 is NH) AND ($\dot{e}_1$ is NH) **THEN** ($u = y_1$)

⋮

IF (e_1 is PH) AND ($\dot{e}_1$ is PH) **THEN** ($u = y_{49}$)

In fuzzy control, crisp inputs are mapped to crisp outputs by an appropriately designed inference system as prescribed by the rule base. Fuzzy sets must be somehow mathematically combined to come up with one single number as the output of a fuzzy controller or fuzzy model. Toward this goal, the membership functions computed in fuzzy inference are finally converted into one number by a defuzzifier. Since, actuators can only admit one value as their input signal, whereas measurement data from physical systems being modelled are always crisp. Through this paper, the centroid defuzzifier is utilized.

3.5.1. Tuning and Optimization of the Controller

The closed-loop performance of a control system strictly depends on the tuning of the controller parameters according to the test and performance criteria. The present control is tested with a temperature air heating process for different transportation delay and various throttle position of the airflow duct. In order to evaluate the control performance quantitatively, a number of performance metrics namely, Mean Absolute Error (MAE), IAE given by $IAE = \int |e(t)| \mathrm{d}t$, the Integral Squared Control Input (ISCI) given by $ISCI = \int u^2(t) \mathrm{d}t$, and Error Variance (EV), are utilized as performance measures. So far, various methods have been proposed for tuning of the controller by considering the time response or the frequency

response of the linear system. However, control engineering framework has not been offered a specific method for parameter tuning of intelligent control schemes such as fuzzy logic, which is constructed by the knowledge or experience of the designer. Concerning the matter, various nature-inspired optimization techniques (Melin et al., 2015) such as genetic algorithms (GAs) have widely been investigated for several industrial applications (Castillo et al., 2013). Kumar et al. address a hybridized artificial bee colony-genetic algorithm optimized fractional order fuzzy pre-compensated FOPID control design in control of 2-DOF robot manipulator and the controller parameters are optimized while minimizing Integral Time Absolute Error (ITAE) (Kumar and Kumar, 2017). Yet another SP based on a fuzzy decoupling scheme is addressed for a multiple-input multiple-output process with multiple delays (Hamdy and Ramadan, 2017). In the aforementioned algorithms, the optimal parameters are obtained by considering a number of the time integral performance criteria, such as ISE, IAE or ITAE. Nevertheless, it is to be noted that, no optimization technique shall outperform all other techniques over all the problems.

Genetic Algorithm (GA) is a genetic-based optimization technique for dealing with problems having a large number of decision variables simultaneously. During the last few decades, GA has emerged as a powerful stochastic nature-inspired computational methodology, wherein the population of candidate solutions is produced, evaluated and evolved to the solutions of the optimization problem (Tenreiro machado, 2010). On the contrary to the other classical optimization techniques, GA is not gradient based optimization method, thus it is more suitable to minimize different performance measures. The algorithm is frequently encountered in various applications in control systems such as intelligent transportation systems, strategy planning, and congestion control.

An algorithmic flow chart of GA is portrayed in Figure 3.15. After defining the population (*P*) constructed by chromosomes (Jesus and Barbosa, 2014; Jesus and Barbosa, 2015; Patrascu and Ion, 2016) and genetic representation, then, the

fitness function (*F*), which is defined as $F = 1/J$, is determined, where J is the cost function. A number of quantitative performance indices such as IAE, ITAE, or ISE can be considered as a cost function. In the present article, the IAE criteria is considered as the cost function (*J*). The main philosophy behind the selection of IAE as an objective function is to reduce the error between system output and reference trajectories (Tenreiro machado, 2010; Jesus and Barbosa, 2015). GA starts with a set of randomly generated solutions within search bound in the initialization phase. Individuals in the generation are then determined according to the fitness function. After the fitness test of each member in the generation, the algorithm produces a new generation or is terminated according to the convergence test (Kaya and Nalbantoğlu, 2016). In order to improve the solution, a population of candidate solutions is produced with the repetitive application of selection operators, crossover, and mutation (Tenreiro machado, 2010). The aforementioned operators mainly help to prevent premature convergence. The main objective is to produce a new population, which is to be better than the previous population (Jesus and Barbosa, 2015). Individuals having a larger fitness function value have a greater chance and crossover for passing to the new generation (Kaya and Nalbantoğlu, 2016).

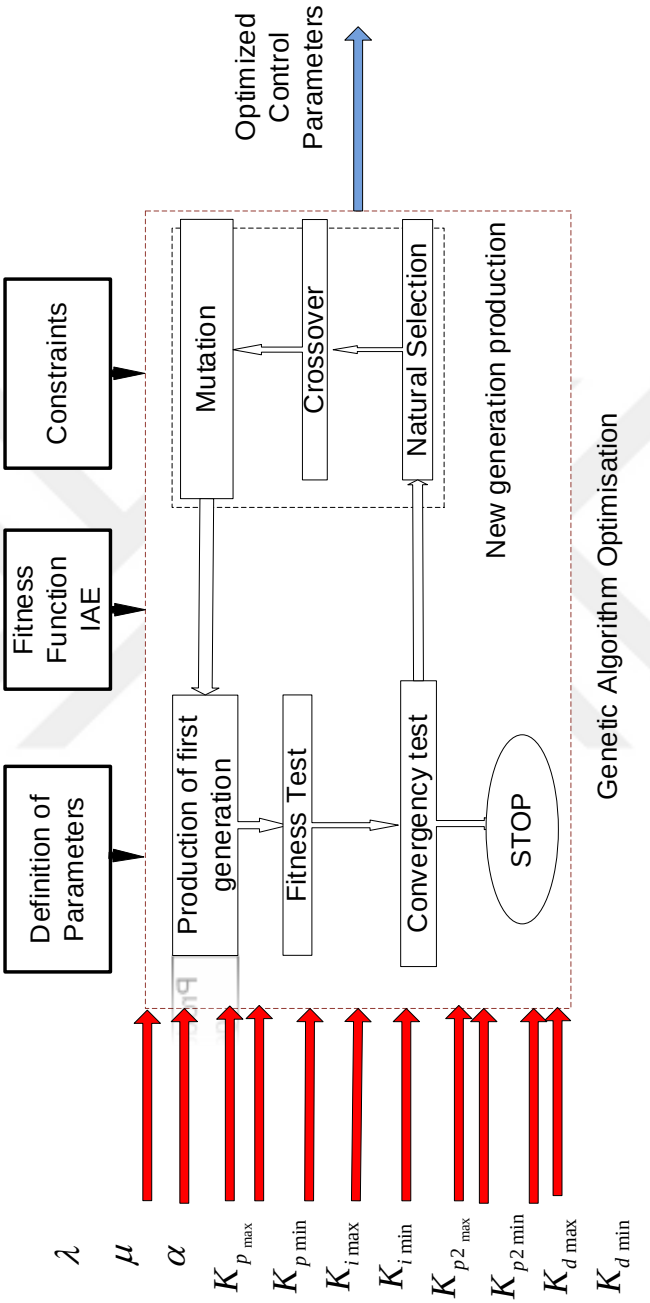


Figure 3.15 Flowchart of the applied GA

Furthermore, to illustrate the design procedure, the pseudo-code of the GA is presented as follow (Tenreiro machado, 2010):

1. Select the initial population: The population consists of individuals, which are controller parameters $\lambda, \mu, \alpha, K_{p\max}, K_{p\min}, K_{i\max}, K_{i\min}, K_{p2\max}, K_{p2\min}, K_{d\max}, K_{d\min}$

2. Evaluate the fitness of each individual in the population

3. Repeat

3.1 Choose the best individuals to reproduce

3.2 Form a new generation by repetitive application of selection operators, crossover, mutation, and give birth to offspring.

3.3 Evaluate the fitness function of the offspring individuals

3.4 Replace the worst ranked part of population with offspring

4. Terminate

In the present study, value encoding with real numbers is applied. Each chromosome comprises of controller parameters, $\lambda, \mu, \alpha, K_{p\max}, K_{p\min}, K_{i\max}, K_{i\min}, K_{p2\max}, K_{p2\min}, K_{d\max}, K_{d\min}$ with value bounds varied depend on the objective function used.

The population in each generation is represented by [maximum generation x 11] matrix, depends on the chromosomes number in population, which each row is one chromosome that comprise the fractional operator values, controller gains,

and the last column added to accommodate fitness value $F = 1/J$ of corresponding chromosomes.

$$\begin{bmatrix} \lambda_1 & \mu_1 & \alpha_1 & K_{p\max 1} & K_{p\min 1} & K_{i\max 1} & K_{i\min 1} & K_{p2\max 1} & K_{p2\min 1} & K_{d\max 1} & K_{d\min 1} & F_1 \\ \lambda_2 & \mu_2 & \alpha_2 & K_{p\max 2} & K_{p\min 2} & K_{i\max 2} & K_{i\min 2} & K_{p2\max 2} & K_{p2\min 2} & K_{d\max 2} & K_{d\min 2} & F_2 \\ . & . & . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . & . & . \\ \lambda_n & \mu_n & \alpha_n & K_{p\max n} & K_{p\min n} & K_{i\max n} & K_{i\min n} & K_{p2\max n} & K_{p2\min n} & K_{d\max n} & K_{d\min n} & F_n \end{bmatrix} \begin{matrix} chromosome\,1 \\ chromosome\,2 \\ . \\ . \\ chromosome\,n \end{matrix} \quad (3.107)$$

3.5.2. Stability Analysis

Stability of the proposed control scheme given in Figure 3.16 is elaborated in this section. Although there have been various well-developed stability tools in control theory, stability analysis is technically more difficult for a fuzzy adaptive system. However, unlike common types of nonlinear, time-varying controllers, the fuzzy controllers are unique owing mainly to their peculiar gain variation characteristics. To mention a few, due to the structural complexity and peculiarity of fuzzy controllers (that is, nonlinear and time-varying), Lyapunov function construction is challenging (Choi et al., 2015; Kumar et al., 2016). However, a number of studies present bounded input bounded output (BIBO) stability of the fuzzy control system (Pang et al., 2015). Among these techniques, BIBO stability is addressed based on the small gain theorem (Chen and Pham, 2000; Eker and Torun, 2006). Furthermore, the local stability and BIBO stability of the fuzzy control systems are addressed in (Kumar et al., 2016). A brief discussion of BIBO stability analysis of a Fuzzy PID controller is presented in (Chen and Pham, 2000). In these studies, the BIBO stability of Mamdani fuzzy PID controller is ensured by region based technique, which divides the input plane into several regions according to the input membership function and magnitude relation between inputs. Then, the sufficient conditions are derived by employing the small-gain theorem. Further, a practical stability example of a fuzzy gain-scheduling PI

control technique is addressed in (Syed et al., 2009). It is worthy to note that the analysis starts with PI-PD controller, and then it is converted to discrete time by using bilinear transformation. Remind that the controller comprises PI and PD based control inputs:

$$u_{PI}(s) = K_p e(s) + \frac{K_i}{s} e(s) \tag{3.108}$$

$$u_{PD}(s) = K_{p2} y(s) + K_d s y(s) \tag{3.109}$$

The control inputs can be rewritten in discrete form by using backward difference formula, then PI and PD control signal can be given as:

$$\Delta u_{PI_{inc}}(nT) = u(nT) - u((n-1)T) = K_p v(nT) + \frac{K_i}{T} e(nT) \tag{3.110}$$

$$u_{PD_{abs}}(nT) = K_{p2} y(nT) + K_d (w(nT)) \tag{3.111}$$

and

$$\left.\begin{aligned} e(nT) &= y_d(nT) - y(nT), \\ w(nT) &= y(nT) - y((n-1)T), \\ \eta(nT) &= w(nT) - w((n-1)T), \\ v(nT) &= e(nT) - e((n-1)T), \\ a(nT) &= v(nT) - v((n-1)T), \end{aligned}\right\} \tag{3.112}$$

where n and T denote the discrete time index and the sampling period, respectively. Further, y is the plant output, y_d is the reference, e is the error, v presents the change of error, w presents the change of y, and a denotes the change of v.

It is to be noted that the stability analysis is carried out from the classical PI-PD control method. The only difference is that fuzzy logic is applied for each control parameter. By considering the control structure, the control signal sent to the actuator can be written as

$$u_{PI-PD}(nT) = \Delta u_{PI}(nT) - u_{PD}(nT) \tag{3.113}$$

where $\Delta u_{PI}(nT)$ and $u_{PD}(nT)$ denote the incremental outputs of fuzzy PI and absolute fuzzy PD controllers, respectively. It can be seen that the PI controller uses the error signal while PD controller is influenced by system output. It is to be noted that PI controller is assumed to be produced incremental output, and PD controller is assumed to be absolute output.

$$u_i(nT) = \Delta u_{PI_i}(nT) - u_{PD_i}(nT) \tag{3.114}$$

In the present control structure, $u_i(nT)$ presents the control input with i^{th} rule of fuzzy controllers. By considering the membership function given in (3.106) output of the fuzzy PI controller can be formed easily. The output of the membership function is given in (3.106) and the membership functions. The output of K_p, K_i, K_d, and K_{p2} are represented by the defuzitication as:

$$K_p = \sum_{i=1}^{N} \bar{\mu}_i(v,e).K_{P,i} \tag{3.115}$$

$$K_I = \sum_{i=1}^{N} \bar{\mu}_i(v,e).K_{I,i} \tag{3.116}$$

$$K_D = \sum_{i=1}^{N} \bar{\mu}_i(y,w).K_{D,i} \tag{3.117}$$

$$K_{p2} = \sum_{i=1}^{N} \bar{\mu}_i(y,w).K_{p2,i} \tag{3.118}$$

where $K_{P,i}, K_{I,i}$, $K_{D,i}$, and $K_{P2,i}$ are i_{th} values of K_P, K_I, K_D, and K_{P2}, respectively, which correspond to the grade μ_i for the i^{th} rule, N is the number of control rules.

The controller parameters are determined by a set of control rules of the fuzzy gain-scheduler (Chaiyatham and Ngamroo, 2017):

$$K_p(v,e) = K_P \varepsilon_i \tag{3.119}$$

$$K_i(v,e) = K_I \rho_i \tag{3.120}$$

$$K_d(y,w) = K_D \kappa_i \tag{3.121}$$

$$K_{p2}(y,w) = K_{p2} \upsilon_i \tag{3.122}$$

Assume that ε_i, ρ_i, κ_i, υ_i are normalized gain-scheduling design parameters. According to the results, consider the system shown in Figure 3.16. Let the subsystems H_1 and H_2 denote the plant under control and the fuzzy PI-PD

controller. α_1, α_2 are the gain of H_1 and H_2, β_1, β_2 are constants, α_1, $\alpha_2 \geq 0$, β_1, $\beta_2 \geq 0$ so that

$$\|y_1\| = \|H_1 e_1\| \leq \alpha_1 \|e_1\| + \beta_1 \tag{3.123}$$

$$\|y_2\| = \|H_2 e_2\| \leq \alpha_2 \|e_2\| + \beta_2 \tag{3.124}$$

Regarding to (3.123) and (3.124) as stability conditions and according to the small gain theorem, that any bounded input pair (u_1, u_2) generates a bounded output pair (y_1, y_2). Then the system subjects to the inputs (u_1, u_2) and outputs (y_1, y_2) are BIBO stable if $y_1 y_2 < 1$.

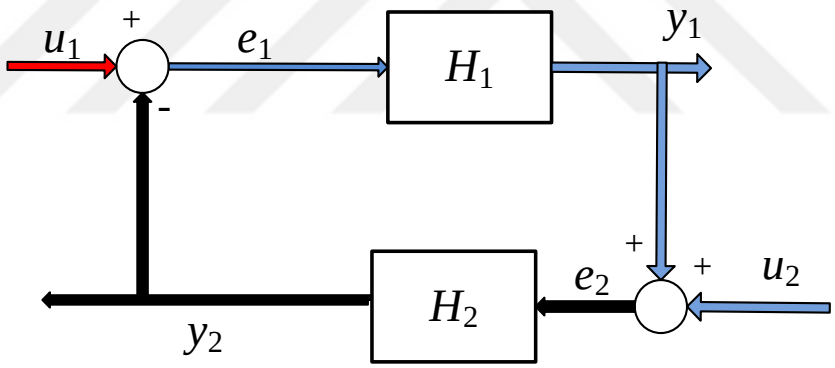


Figure 3.16 Feedback system

In Figure 3.16, H_2 denotes the fuzzy PI-PD controller and H_1 is the system to be controlled. Now assume that:

$$\left.\begin{array}{c} u_1(nT) = y_d(nT), \\ u_2(nT) = 0, \\ e_1(nT) = e(nT), \\ e_2(nT) = u(nT), \\ y_1(nT) = u(nT), \\ y_2(nT) = y(nT) \end{array}\right\} \quad (3.125)$$

The following assumptions are required

$$\left|H_1(e(nT))\right| = \left|K_p v(nT) + K_i e(nT) - K_d w(nT) - K_{p2} y(nT)\right| \quad (3.126)$$

Equation (3.126) can be rewritten using (3.119)-(3.122):

$$\left|K_p v(nT) + K_i e(nT) - K_d w(nT) - K_{p2} y(nT)\right| = \left|K_p \varepsilon_i + K_I \rho_i - K_D \kappa_i - K_{p2} \upsilon_i\right| \quad (3.127)$$

where $\sum_{i=1}^{N} \overline{\mu}_i = 1$ and $0 \le \overline{\mu}_i \le 1$ for all $1 \le i \le N$. If $\left|\varepsilon_i + \rho_i - \kappa_i - \upsilon_i\right|$ is maximum at $i = i^*$ for $1 \le i^* \le N$, then

$$\left|K_p v(nT) + K_i e(nT) - K_d w(nT) - K_{p2} y(nT)\right| = \left|\varepsilon_i + \rho_i - \kappa_i - \upsilon_i\right| \quad (3.128)$$

and

$$\left\|H_1(e)\right\| \le \left|\varepsilon_i + \rho_i - \kappa_i - \upsilon_i\right| . \left\|e\right\| \quad (3.129)$$

By comparing (3.129) and (3.123)-(3.124), one can determine that $\left|\varepsilon_i + \rho_i - \kappa_i - \upsilon_i\right|$ is a candidate for α_1. In addition, if the input membership functions are consistent as in the typical triangular and trapezoidal membership functions, they contain many input pairs that can cause $\bar{\mu}_i = 1$. Thus, both sides of (3.127) are equal when the membership functions are consistent. Then, BIBO stability can be proved.

Similar statements can be expressed in the present study because the proposed FFPI-PD controller and FPI-PD controller have consistent triangular and trapezoidal MFs (Ding, 2003; Choi et al., 2015) and differ by the use of a fractional mathematical operator. The BIBO stability conditions will remain same for fractional order fuzzy controllers (Kumar et al., 2016).

Furthermore, it is to be noted that stability analysis methods such as Kharitonov like fractional order robust stability method, Matignon's stability citation cannot be applied directly for the fractional fuzzy controller because of nonlinear nature of fuzzy control.

It is worth mentioning that the stability criteria in the optimization algorithm can be incorporated by removing the unstable modes that can be found by observing the magnitude of the integral performance index, which gives the GA solution vector in the search space (Das et al., 2013). In other words, the optimization algorithm is formulated to reject controller parameters that will undermine the closed-loop system.

Taking these constraints into consideration, a criterion equivalent to the optimization algorithm has been applied to ensure the closed-loop stability of the system comprises fuzzy and fractional order operators (Das et al., 2012; Pan and Das, 2016).

3.4. Time Delay in Controller Design: Delay-Based Control Techniques

3.4.1. Introduction

It is widely-accepted that delay is frequently a source of oscillations, performance degradation or instability. However, contrary to this idea, an intentional time-delay, in some cases, presents an opportunity to increase the closed loop control performance when appropriately incorporated into the control system. A number of contributions consider the stabilizing properties of time-delays. For instance, the frequency shaping, the Smith predictor, the delayed-control, stabilization of oscillatory systems, and the delayed resonator. Furthermore, it is stated that a remarkable performance improvement can be achieved by using time delay for a nonlinear dynamical system, such as chaotic motion (Sipahi et al., 2011; Pyragas and Novicenko, 2013; Roy et al., 2017). In fact, the counter effect of delay on the stability and performance of dynamical systems is a critical problem that still needs to be carefully answered. Thus, recent attention has been devoted to understanding the effect of time delay on control systems.

This chapter evaluates a set of alternative control structure to achieve better control performance while consuming less energy, fewer computational burden, low design effort with respect to classical controllers. The theoretical background and central notion of the control techniques are discussed carefully. The control techniques are validated by experimental applications. From a practical point of view, real-time experimental application of a number of delay-based control techniques is addressed for an electromechanical system, which is modelled as a second-order linear time-invariant (LTI) system.

The above inspiring ideas bring different perspectives to the delay systems research. More importantly, it opens up a new path to the potential readers of the research. The main contributions of this chapter are,

i) Describing favourable effects of delay and providing an overview of delay-based control techniques,

ii) Describing a novel modified delay-based control strategy and providing the stability analysis,

iii) Performing an experimental implementation to highlight the validity and capability of the proposed control strategy,

iv) Comparing the proposed controller with classical low order control techniques with a number of performance measures.

3.4.2. A Survey: Favourable Effects of Time-Delay

Recently, a number of studies have emphasized that the time delay has a positive effect on the control performance if it is handled carefully. From a linear system point of view, some preliminary investigations are addressed by Suh and Bien. (Suh and Bien, 1979; Suh and Bien, 1980), wherein proportional minus delay controllers are highlighted. A further study presents a direct estimation of unknown dynamics by using an appropriate delay value (Youcef-Toumi and Ito, 1990), wherein the main idea is introducing an appropriate delay value in the control loop, in order to reduce the effect of additive disturbances. Abdallah et al. emphasize that a positive delayed feedback can stabilize an oscillatory system (Abdallah et al., 1993). Yet another study investigates the benefit of utilizing delay instead of derivative terms (Kokame et al., 2001; Villafuerte et al., 2013; Ramirez et al., 2016). As a matter of fact, a deliberate introduction of delay may enhance the performance of a closed loop system without any estimation for derivative terms (Villafuerte et al., 2013; Ortega-Montiel et al., 2017; Ramírez et al., 2017; Ramirez and Sipahi, 2018). Further, it is shown that the control performance of a chain of integrators is improved, when the derivative part of the controller is replaced by a delay term (Niculescu and Michiels, 2004). Parallel to this, a number of studies address the utilization of time delay in state feedback control scheme to approximate integral and derivative terms (Kwon and Pearson, 1980). In a recent

research, Ulsoy (Ulsoy, 2015) proves the positive effect of delay-based control on the disturbance rejection capability and tracking ability of a single input single output (SISO) system. In that research, delay differential equation (DDE) is solved using the Lambert-*W* function. The work of Jankauskiene uses the Lambert-*W* function for the analysis of TDSs (Jankauskienė, 2017).

Apart from these studies, in nonlinear systems area, it is stated that a remarkable performance improvement can be achieved by using time delay for controlling chaotic motion. A favourable effect of time delay is reported on the delayed resonator, which is utilized with a delayed position feedback to enhance vibration absorber performance (Hosek and Olgac, 2002). In (Xiao and Cao, 2007), a bifurcation control problem is investigated for an Internet congestion control problem. The control technique is constructed based on delayed feedback controller. Further, a non-collocated vibration control is investigated by Yang and Mote (Yang and Mote, 1990). Udwadia et al. present a number of favourable effects of time delay for controlling flexible structures (Udwadia et al., 2003). Cai and Chen present the delay based control techniques for controlling flexible structures (Cai and Chen, 2010). In that study, a time delay is selected accordingly much longer than the period of the uncontrolled structure. According to the control results, delayed feedback strategy outperforms classical control techniques (Cai and Chen, 2010).

Additionally, Roy et al. propose a robust time-delayed control scheme for a class of nonlinear uncertain systems (Roy et al., 2017). A recent research investigates the analysis and design of wide- area damping controller with intentionally induced artificial time delay (Roy et al., 2018). A delayed sliding mode controller is addressed by (Efimov et al., 2015; Efimov et al., 2016), wherein the sign function is approximated by a time delay. It is shown that this realization still provides robustness of sliding mode control, while the chattering is reduced. In view of foregoing, delay-based controllers have demonstrated good performance in the presence of noise and disturbance.

Moreover, Ramirez et al. address the design of a delay-based controller for stabilization of network system (Ramírez et al., 2017). Moyne et al. demonstrate a number of favourable effects of time delay on the tracking performance of type-I control systems (Khan et al., 2008). A different look on the delay-based controller is addressed in (Pyragas, 1992) and further investigated in (Pyragas and Novicenko, 2013), wherein a time-delayed feedback control algorithm is applied for a chaotic system. Inspired by that work, van de Wouw et al. present an application for a high-speed milling. The work aims at reducing the chattering phenomenon (Van De Wouw et al., 2015). Further, an inverted pendulum stabilization problem is elaborated with the Pyragas-type controller (Boussaada et al., 2015). The delayed feedback control technique is applied to different types of linear and nonlinear systems in (Atay, 2002) and (Aleksandrov et al., 2015).

The aforementioned studies, which contain the active utilization and intentional introduction of time delay as a design parameter, are known as delayed control. However, alongside the aforementioned favourable features, it is to be noted that the parameter tuning and stability analysis issues are still challenging (Ramirez et al., 2016).

3.5. Delay-Based Control Techniques

The delay-based control techniques contain the active utilization and intentional introduction of time delay as a controller parameter. Moreover, it is showed that a delay-based controller is an effective and simple control technique for a system subjects to uncertainties and modelling errors (Villafuerte et al., 2013; Ramirez et al., 2016; Hernández-Díez et al., 2017; Ozbek and Eker, 2017; Ramírez et al., 2017). This control structure is proposed as an alternative control structure of conventional PID type low-order controller. From a control engineer's perspective, the main advantage of this technique is that designer does not need any additional filter structure through the controller implementation, which preserves simplicity, reduces the energy consumption of the controller. Moreover, satisfactory control

performance can be achieved if the noise levels are low (Ramirez et al., 2015; Ramirez and Sipahi, 2018). A preliminary research is presented in (Suh and Bien, 1979), wherein Suh and Bien address a proportional minus delay controller that attenuates high-frequency noise by performing an averaged derivative action over a finite period (Ozbek and Eker, 2017). Villafuerta et al. address the stability analysis and tuning strategy of a proportional retarded (PR) control scheme (Villafuerte et al., 2013), wherein simple tuning rules for assigning the dominant poles of second-order system are addressed via a PR controller. According to the results, the PR controller outperforms classical proportional derivative (PD) controller in terms of tracking performance and control signal quality. A further benefit of the PR control strategy is that its numerical realization is computationally more efficient than other classical control techniques such as PID controller. An example of proportional delayed control application to a mechatronic system is presented in (Ortega-Montiel et al., 2017), wherein the authors present a pendulum control performance without tweaking differentiators. Yet another study elaborates the closed loop stability analysis of voltage buck using a proportional-delayed controller (Hernández-Díez et al., 2017). This work is also based on the geometric approach, which allows partitioning of the parameters space into regions with a constant number of unstable roots. In the work of Diez et al., a transparent bilateral control scheme for a local teleoperation system is realized by using a proportional-delayed controller (Hernandez-Diez et al., 2016). Stability analysis based on *D*-partition curves is presented. Further, fragility analysis, which is based on computing of the maximum controller parameters deviation without losing the closed-loop stability, is carefully elaborated. In a further study, Ramirez et al. address a proportional integral delayed or retarded (PIR) control scheme, wherein the stability analysis is derived in the sense of the algebraic geometric analysis (Ramírez et al., 2017).

Zalluhoglu et al. propose different types of delayed feedback control schemes for the Rijke tube thermoacoustic instability problem (Zalluhoglu et al.,

2016). In that study, cluster treatment of characteristic roots (CTCR) is utilized to meet the objectives. In (López et al., 2018), a position control problem of servo drives is elaborated by using a cascade proportional integral retarded control. An IAE optimization of a PID controller with delay is addressed by Zitek et al. (Zitek, Fišer, & Vyhlídal, 2016). Last but not least, a geometrical approach for the stability analysis of a proportional delayed controller is highlighted in (Hernández-Díez et al., 2017). A direct integration technique for time-delayed control is addressed in (Wen et al., 2017). Ramirez and Sipahi prove that the using of multiple intentional delays improve the consensus control performance by facilitating fast consensus and reducing the noise in a multi-agent system (Ramirez and Sipahi, 2018).

3.5.1. Proportional Integral Delayed Control

Until recently, various feedback control strategies such as adaptive controllers with intelligent methods, nonlinear control algorithms, and robust control strategies have been investigated to achieve better control performance. Among these strategies, those of PID controller is the most commonly used control algorithm in the industry due to its simplicity, functionality, and applicability. However, it has a number of drawbacks. For instance, in the most of the control applications, the controller gains namely K_p, K_i, and K_d are tuned based on a nominal system model obtained around a desired operating point. Hence, PID controller may show unsatisfactorily control performance in the presence of parameter uncertainties, modelling error, and disturbances (Atherton, 2015; Atherton, 2016; Ozbek and Eker, 2017). The conventional methods cannot deal with nonlinear or ill-defined processes, especially, when the disturbances are unpredictable. Furthermore, the aforementioned challenges make it hard to apply conventional control strategies for an accurate control with small errors in the presence of variable operating conditions. In addition to this, noisy measurements may lead to unexpected performance degradation in particular during the experimental application, if the system does not contain a low-pass filter for the

noisy measurement. Moreover, the tuning of the derivative term, which may amplify the high-frequency measurement noise, is another challenging task. In fact, as indicated in (Segovia et al., 2014), the above arguments advise approximating the derivative term in most applications.

The proportional integral delayed controller contains a proportional (K_p), an integral action with an integral gain K_i, and a delayed term τ with a proportional gain K_r while avoiding derivative term (Ozbek and Eker, 2017). The control structure is depicted in Figure 3.17.

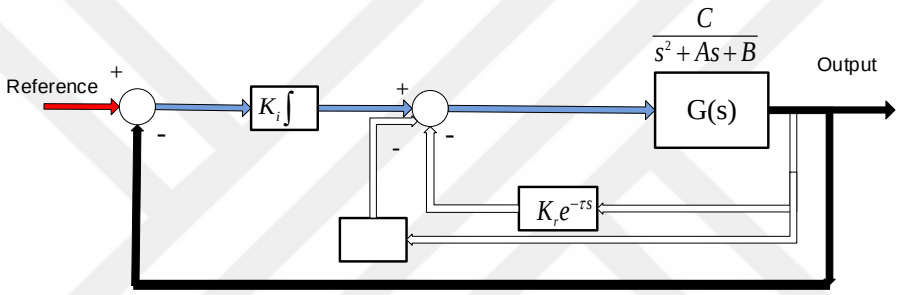


Figure 3.17 Proportional integral delayed controller

The control gains are obtained by a detailed characterization of the maximum achievable exponential decay rate of the closed loop system (Ramirez et al., 2016; Ozbek and Eker, 2017; Ramírez et al., 2017). The aforementioned task needs an explicit analytical tuning strategy containing a dominant triple root assignment with the aim of producing the maximum exponential decay rate of the closed-loop system (Ramírez et al., 2017). More precisely, the main goal is to design a technique to provide algebraic tuning rules for a class of delay-based controllers, ultimately guaranteeing a desired maximum exponential decay rate σ_d while achieving the controller tuning as an explicit function of σ_d and open-loop system parameters (Ramirez et al., 2016; Ramírez et al., 2017).

It is stated that even though the controller may enhance the noise attenuation and disturbance rejection performance, obtaining controller gains is a very challenging problem (Ozbek and Eker, 2017). A further discussion on delay-based control design techniques is represented in (Ozbek and Eker, 2017). That work presents an experimental comparison of PID and PIR controller.

3.5.1.1. Stability Crossing Boundaries: Decomposition of the (τ, k_r)

The section presents the key ideas about the stability characterization of the proportional integral delayed controller. The stability of the closed-loop system is characterized by the location of the roots of the characteristic equation that is defined as:

$$\Delta(s,\tau,K_r) = s^3 + As^2 + (B+CK_p)s + CK_i - CsK_r e^{-s\tau} \tag{3.130}$$

At this point, it is to be noted that $A>0$, $B+CK_p-CK_r>0$ and $CK_i>0$ are necessary conditions for the delay-free ($\tau=0$) closed-loop system to be stable. In this technique, the σ-stability is investigated. Toward this goal, the change of variable $s \to (s-\sigma)$ is applied to (3.130) as a first step, then one can get:

$$\Delta(\sigma,s,\tau,K_r) = p_0(\sigma,s) + p_1(\sigma,s)K_r e^{\sigma h} e^{-s\tau} \tag{3.131}$$

where σ denotes the exponential decay rate of the closed loop system and

$$\Delta_0(\sigma,s) = (s-\sigma)^3 + A(s-\sigma)^2 + (B+CK_p)(s-\sigma) + CK_i \tag{3.132}$$

$$\Delta_1(\sigma, s) = -C(s - \sigma) \tag{3.133}$$

Further, the stability regions are investigated with respect to delay (τ) and proportional gain of delay (K_r). It is to be noted that, there may be a stability switch if some roots cross the imaginary axis. Thus, the crossing points (τ, K_r) can be found with

$$\Delta(\sigma, j\omega, \tau, K_r) = 0 \tag{3.134}$$

The stability crossing points (τ, K_r) must be satisfied (3.134). Corresponding to the singular value $\omega = 0$, one can obtain (Ramirez et al., 2016; Ramírez et al., 2017)

$$K_r = \frac{\Delta_0(\sigma, 0)}{\Delta_1(\sigma, 0)} e^{-\sigma\tau} \tag{3.135}$$

It is to be noted that (3.135) describes an exponentially decaying curve on the (τ, K_r) where on this curve an invariant root exists at $-\sigma$. Further, the stability crossing boundaries can be obtained by the method given in (Ramírez et al., 2017).

3.5.1.2. Parameter Tuning

Remind that one has the following characteristic equation for proportional integral delayed control

$$\Delta(s) = s^3 + As^2 + (B + K_p C)s - K_R B e^{-s\tau} + K_i C \tag{3.136}$$

which is a quasi-polynomial with the parameters A, B and C are defined in modelling section (4.1-4.4). It is to be noted that the stability of the system depends strictly on the location of the roots of the characteristic equation. The computation of the roots of the characteristic quasi-polynomial containing an infinite number of roots is a difficult problem. Concerning the matter, some techniques are developed for the computation of the roots (Zítek et al., 2012; Zítek et al., 2013; Zitek et al., 2016).

The main goal is to determine the parameter set (τ, K_p, K_i, K_r), which provides the maximum exponential decay rate for the controlled process (Kara and Eker, 2004; Furat and Eker, 2014). To do this, a triple real dominant root is placed for the closed loop system (Villafuerte et al., 2013). This design procedure is accomplished by using the spectral analysis, which enables the control designer to obtain more specific information about the dominant poles (Ozbek and Eker, 2017; Ramírez et al., 2017). According to this, the controller parameters are obtained by the following equations (Ramírez et al., 2017).

$$\tau = \frac{1}{3\vartheta\sigma_d}[\gamma - 3\vartheta] \tag{3.137}$$

$$K_p = \frac{1}{2C}[(\sigma_d - A)^2 + 2(\sigma_d{}^2 - b) + \gamma(\vartheta - \gamma)] \tag{3.138}$$

$$K_i = \frac{\sigma_d}{2C}[2\sigma_d{}^2 - 2\gamma(\sigma_d + \gamma) + \gamma(\vartheta - \gamma)] \tag{3.139}$$

$$K_r = \frac{\gamma}{Ch^2\sigma_d{}^2 e^{h\sigma}}[2(\sigma_d + \gamma) - (\vartheta - \gamma)] \tag{3.140}$$

where $\gamma = 3\sigma_d - A$ and $\vartheta = \sqrt{9\gamma^2 + 12\gamma\sigma_d}$

3.5.2. Proportional Integral Proportional Delayed Control

In the last few decades, several modifications of PID control scheme have been addressed in order to overcome the drawbacks mentioned above (Johnson and Moradi, 2005; Aström and Wittenmark, 2011). For instance, a PI-PD control (Kaya and Atherton, 1999; Atherton, 2016), which is one of the modified forms with four parameter controller, can provide better control performance especially for controlling integrating, unstable as well as resonant processes while the classical PID control technique may show poor performance (Tan, 2009; Kaya, 2015; Atherton, 2016). It is to be noted that the transfer function of the PI controller affects both its poles and zeros, however, the PD controller affects only the poles. For further discussion about PI-PD controller, the interested readers are referred to (Atherton, 1998; Kaya et al., 2007; Kaya, 2015).

This section presents a further modification of PI-PD controller, which is depicted in Figure 3.18. There, a proportional gain and a delay term are located in a feedback loop for stabilizing the system and proportional integral controller is located in a forward path to reduce the steady-state error.

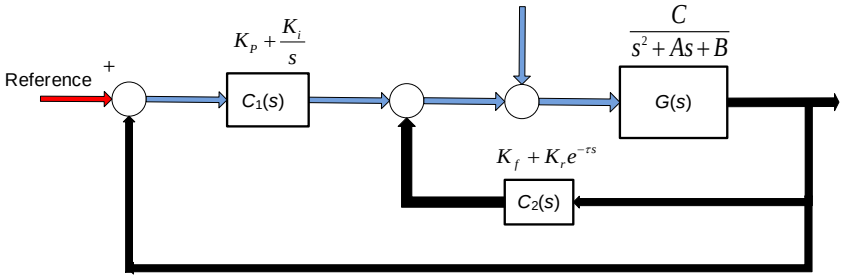


Figure 3.18 Proportional integral proportional delayed control technique

Some advantages of the present control technique can be summarized as follows. First, it provides better transient response and fast convergence of tracking

error. Further, the control signal is smoother than control signal of PI-PD and PID control. Yet another advantage is that the chattering is attenuated in the presence of noisy measurements because there is no derivative term in the control structure. Moreover, this controller requires only memory registers that make it easier to implement. The designer does not need to use any estimation of the derivatives, which is a tedious task for the systems subject to measurement noise and uncertainties. Hence, the computational complexity and the cost of the controller design will significantly reduce.

It is known that a number of tuning methods have been addressed for PI-PD control. For instance, Atherton analysis a step response with standard forms and the controller parameters are given (Atherton, 1998). Further, Tan et al. highlight the stability locus boundaries for obtaining all stability regions and controller parameter (Tan, 2009). By considering the aforementioned studies, the inner control loop is designed based on the proportional delayed control technique (Villafuerte et al., 2013), while the outer PI control is tuned by minimization of predetermined performance indexes such as IAE, ISCI, and the Total Variance (TV).

The PI and Proportional delayed (retarded) controller, which is given in Figure 3.28, can be presented as follows.

$$C_{PI}(s) = K_P + \frac{K_i}{s} \tag{3.141}$$

$$C_{PR}(s) = K_f + K_R e^{-s\tau} \tag{3.142}$$

where $\tau > 0$ is the delay and K_p, K_i, K_f, K_r represent controller parameters. Thus, C_1(s) and C_2(s) presents the conventional PI and proportional delayed controller ($C_{PR}(s)$), respectively. The closed loop system can be presented as:

$$\frac{Y(s)}{R(s)} = \frac{G(s)C_{PI}(s)}{1+G(s)(C_{PR}(s)+C_{PI}(s))} \tag{3.143}$$

Accordingly, the following transfer function is obtained.

$$\frac{Y(s)}{R(s)} = \frac{\left(K_p + \frac{K_i}{s}\right)\left(\frac{C}{s^2+As+B}\right)}{1+\left(\frac{C}{s^2+As+B}\right)\left(K_p + \frac{K_i}{s} + K_f + K_R e^{-s\tau}\right)} \tag{3.144}$$

As stated previously, the proposed control strategy is a variation of the one addressed in (Ramirez et al., 2016), however, a modified delayed output feedback controller is integrated. Considering the facts mentioned above, the characteristic equation of the system can be given as:

$$\Delta(s) = s^3 + As^2 + Bs + CK_p s + CK_i + CK_f s + CK_R e^{-s\tau} s \tag{3.145}$$

which is a quasi-polynomial with the model parameters *A*, *B*, *C* are defined in chapter 4. The closed-loop stability of the control system strictly depends on the location of the roots of the characteristic equation. It should be noted that the delay-free ($\tau=0$) system is stable under the following conditions:

$$A>0,\ (B+CK_p+CK_f+CK_R>0),\ K_iC>0 \tag{3.146}$$

The synthesis of the controller entails coping with infinite dimensional characteristics, thus, some algorithms are used for the computation of the roots (Zítek et al., 2013; Zitek et al., 2016). The main purpose is to determine the parameter set (τ, K_p, K_i, K_R), which gives the maximum exponential decay rate for

the elaborated system. Toward this goal, the change of variable method is applied for $s \to (s-\sigma)$ which enables us analysing the σ-stability of $\Delta(s,\tau,K_r)$. Afterwards, the characteristic quasi polynomial can be written as follows:

$$\begin{aligned}\Delta &= (s-\sigma)^3 + A(s-\sigma)^2 + (B + CK_p + CK_f)(s-\sigma) \\ &\quad + CK_R e^{-(s-\sigma)\tau}(s-\sigma) + CK_i\end{aligned} \tag{3.147}$$

where σ again denotes the exponential decay rate of the feedback control systems.

3.5.2.1. Stability Crossing Boundaries: Decomposition of the (τ, k_r)

The presented method is a well-known technique called *D*-Decomposition method proposed by Neimark with many examples in the literature. Further, the *stability crossing* curves, wherein the characteristic equation of the closed-loop system has at least one root on the imaginary axis, are investigated to obtain the set of controller parameters. In addition to this, the implicit function theorem is employed to find the regions containing unstable roots compared to its neighbouring regions. The final step is devoted to characterize the regions wherein the controllers guarantee the stability of the system.

The stability analysis and design of the controller is addressed in the sequel. Toward this goal, a number of well-accepted methods namely, *D*-partition method, the boundary crossing theorem, and the implicit function theorem, are employed to compute stability regions. More specifically, the *D*-decomposition method or to the parameter space approach is applied (Neimark, 1949). In the sequel, the stability crossing curves represent the collection of all points for which the characteristic equation has at least one root on the imaginary axis (Hernández-Díez et al., 2017). Next step comprising the use of some properties of analytic functions enables detecting if a region has more or fewer unstable roots than

neighbouring regions (Hernández-Díez et al., 2017). This allows the designer to obtain controller gains guaranteeing the stability of the system.

The control design problem is mainly focused on obtaining a better performance in the sense that $\sigma > \delta\nu$,where ν is the non-damped frequency and δ is the damping factor which can be obtained from the model of the system. Then the delay-based controller stabilizes the system.

In this section, the stability regions are investigated with respect to delay (τ) and proportional gain of delay (K_r). A useful outline can be found in (Ramirez et al., 2016). According to the (Ramírez et al., 2017), there may be a stability switch if some roots cross the imaginary axis. Thus, the crossing points (τ, K_r) such that

$$\tilde{\Delta}(\sigma, j\omega, \tau, K_r) = 0 \tag{3.148}$$

The stability crossing points (τ, K_r) must be satisfied (3.148). Corresponding to the singular value $\omega = 0$, the characteristic quasi polynomial (3.148) can be rewritten as:

$$\tilde{\Delta} = \sigma^2 - (a + K_f b + K_p b)\sigma - K_r b e^{-s\tau} e^{\sigma\tau}\sigma + K_i b \tag{3.149}$$

and the crossing curve is obtained as follow

$$K_r = \frac{\sigma^2 - (a + K_f b + K_p b)\sigma + K_i b}{b e^{\sigma\tau}\sigma} \tag{3.150}$$

It is to be noted that (3.150) describes an exponential decaying curve on the (τ, K_r) plane, where an invariant root exists on this curve at $-\sigma$. Thus, the exact domain of stability is described by the hypersurfaces generated by (3.150), also known as stability crossing boundaries (Hernández-Díez et al., 2017; Ramírez et al., 2017; López et al., 2018).

3.5.2.2. Parameter Tuning

This section presents a guideline for tuning of the present delay-based control technique. The central idea is to obtain proportional gain and derivative term, according to the proportional delayed control technique. Then try to tune the proportional and integral gain by optimizing a predefined cost function, which depends on the control designer.

In order to complete For every given desired exponential lower bound on the decay $\sigma > 0$, satisfying $\sigma > \delta\nu$, where ν is the non-damped frequency and δ is the damping factor which can be obtained from the model of the system. On the other hand, tuning of the controller, which has four gains and one time-delay, only depends on two terms, namely σ_d. The desired exponential decay rate σ_d, which defines the dominant roots of the inner control loop and sets its bandwidth, is easily computed by using the following parameter tuning formulaes (Villafuerte et al., 2013).

$$K_f = \frac{\left[(\sigma - \delta\nu)^2 - \nu^2(1-\delta^2)\right]}{B} \tag{3.151}$$

$$\tau = \frac{1}{\left[\sigma - \delta\nu\right]} \tag{3.152}$$

$$K_r = \frac{\left\lfloor 2(\sigma - \delta v)^2 \right\rceil}{Be^{\sigma h}} \tag{3.153}$$

On the other hand, tuning of the outer position loop is performed by fixing a value of σ_d, tuning the inner velocity loop using equation (3.151)-(3.153), and subsequently applying a sequence of increasing values of the proportional gain K_p Then, the pair (σ_d, K_p) giving the least numerical value of J would correspond to the optimal tuning value.

From a design point of view, several performance metrics such as IAE, ISE etc., may assist the designer to optimize the controller parameters. In this study, the IAE and ISCI criteria are considered as the cost function (*J*).

Now, the outer loop is tuned by the IAE and ISCI of the control signals, which is a well-known minimization technique for controller parameter tuning.

$$J = \int |r(t) - y(t)| \mathrm{d}t + \int u^2 \mathrm{d}t = \int |e(t)| \mathrm{d}t + \int u^2 \mathrm{d}t \tag{3.154}$$

4. EXPERIMENTAL SET-UP AND PRELIMINARIES

This section introduces the systems for real-time experiments, which are conducted to validate the proposed control strategies. Firstly, it explains the electromechanical system, and then secondly an air heating process is described. The systems are used in experimental applications: i) an electromechanical system, ii) air-heating process.

4.1. Data Acquisition for Electromechanical System

A computer having 2.0 GHz microprocessor and 1 GB RAM is used to perform experiments. Table 4.1 presents the specification of DAQ board for electromechanical system.

Table 4.1 Advantech PCI-1716 DAQ board

Analog Input	Channels	16 SE/Diff
	Sampling Rates	250 kS/s
	Resolution	16 bits
	Unipolar Input (V)	0~10,0~5,0~0.25,0~1.25
	Bipolar Inputs	±10,5,2.5,1.25,0.625
Analog Output	Channels	2
	Resolution	16 bits
Digital I/O	Digital Input Channels	16
	Digital Output Channels	16
General	Bus	PCI
Timer/Counter	Resolution	16 bits
	Time Base	10 Mhz
	Channels	1

The measurements are transmitted from experimental set to the computer via Advantech PCI-1716 data acquisition card (DAQ). Matlab/Simulink is used for all calculations and controller design. Furthermore, the installed DAQ scheme is presented in Figure 4.1.

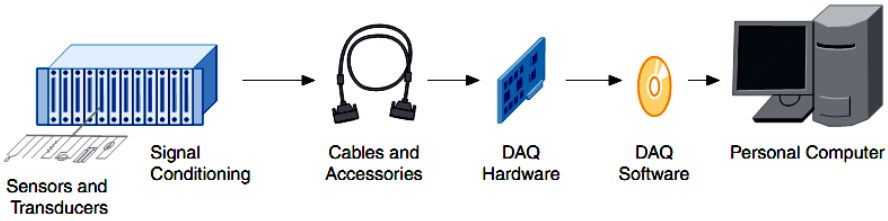


Figure 4.1 Utilization of data acquisition board

4.2. Electromechanical System

Electromechanical systems are frequently employed in various industrial applications such as robot control, manufacturing process, automotive applications. Further, electromechanical systems are crucial plants for testing a novel control strategy as well as teaching a control system.

In order to test the proposed control algorithms, an electromechanical system consists of a direct current (DC) motor and a tachagenarator connected via shaft. There are several sensors and transducers on the shaft, which can be designated as the load on the shaft. A figure of the system is depicted in Figure 4.2.

The sensors and transducers given in Figure 4.2 are presented as in Table 4.2.

Table 4.2 Sensors and transducers with electromechanical system

Label	Equipment	Label	Equipment
A	DC motor	E	Hall effect sensor
B	Slotted optos sensor	F	Servo potentiometer
C	Reflective opto sensor	G	Tachogenerator
D	Inductive sensor		

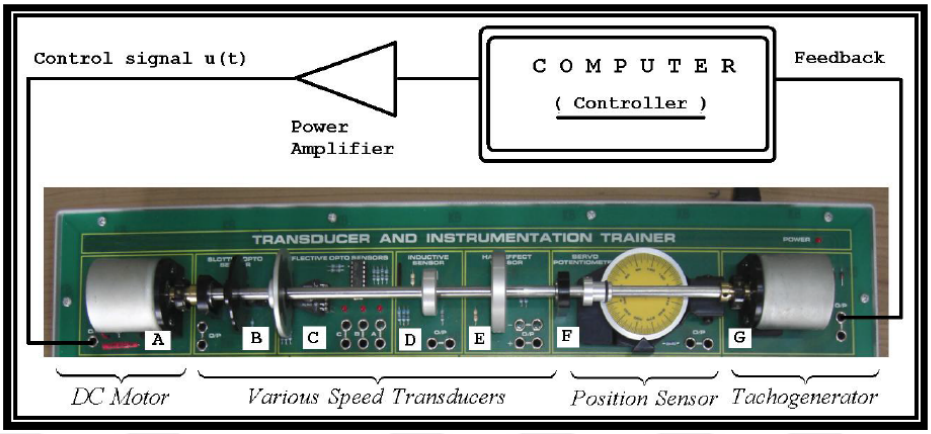


Figure 4.2 Electromechanical system

As seen in Figure 4.2, a DC motor system is mounted on a DIGIAC 1750 control training set. The motor drives a shaft, which comprises various, transduces and tachnogenerator. The slotted-opto transducer is used to measure shaft speed during the experiments. Further, the tachogenarator, which produces voltage according to the shaft speed, is employed as a speed transducer.

4.2.1. Modelling of the System

Modelling and control of electromechanical systems have been greatly attracted in control community since they are encountered in a wide range of application areas. Direct Current (DC) motors have been used in various industrial control applications such as disk motion control, liquid pumping, position control of robotic manipulators (Eker, 2004). Furthermore, DC motors have various advantages like easy position/speed regulation, simple structure, and low maintenance. Numerous studies are dedicated to position and velocity control of DC motors achieving set point regulation, tracking accuracy, robustness, and energy efficiency.

The schematic diagram of the system is shown in Figure 4.3 and the parameters are depicted in Table 4.3.

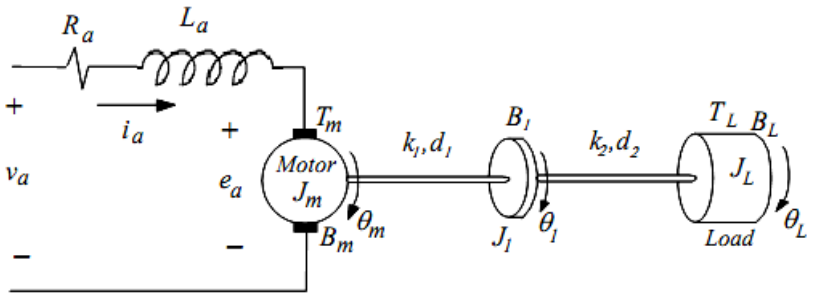


Figure 4.3 Schematic diagram of the electromechanical system.

Table 4.3 DC motor parameters

v_a	Armature voltage	R_m	Viscous friction,
L_a	Armature inductance,	K_M	Torque coefficient,
R_a	Armature resistance,	T_m	Generated motor torque,
i_a	Armature current,	T_d	External load disturbance,
T_s	Nonlinear friction,	T_f	Transmitted shaft torque,
J_m, J_L	Moments of inertia,	ω_m, ω_L	Rotational speeds

The dynamical equations of the electromechanical system are given as.

$$v_a(t) = L_a \frac{d}{dt} i_a(t) + R_a . i_a(t) + K_m \omega_m(t) \tag{4.1}$$

$$J_m \left(\frac{d}{dt} \omega_m(t) \right) = T_m(t) - T_s(t) = R_m \omega_m(t) - T_f(\omega_m) \tag{4.2}$$

$$T_s(t) = k_s(\theta_m(t) - \theta_L(t)) - B_s(\omega_m(t) - \omega_L(t)) \tag{4.3}$$

$$\frac{d}{dt}\theta_m(t) = \omega_m(t), \frac{d}{dt}\theta_L(t) = \omega_L(t) \tag{4.4}$$

where DC motor parameters are given in Table 4.2.

Model of the nonlinear friction $T_f(\omega)$ can be considered as an asymmetrical characteristic as (Jang and Jeon, 2000):

$$T_f(\omega) = \left(\alpha_0 + \alpha_1 e^{-\alpha_2|\omega|}\right)\mathrm{sgn}1(\omega) + \left(\alpha_3 + \alpha_4 e^{-\alpha_5|\omega|}\right)\mathrm{sgn}2(\omega) \tag{4.5}$$

where $\alpha_1 - \alpha_5$ are positive constants and $\alpha_0 \neq \alpha_3$, $\alpha_1 \neq \alpha_4$, $\alpha_2 \neq \alpha_5$ and the signum functions are defined as:

$$\begin{aligned} \mathrm{sgn}1(\omega) &= \begin{Bmatrix} 1\, if\ \ \omega \geq 0 \\ 0\, if\ \ \omega \leq 0 \end{Bmatrix} \\ \mathrm{sgn}2(\omega) &= \begin{Bmatrix} 0\, if\ \ \omega \geq 0 \\ -1\, if\ \ \omega \leq 0 \end{Bmatrix} \end{aligned} \tag{4.6}$$

Block diagram of the electromechanical system is presented in Figure 4.4.

The DC motor specifications are presented in Table 4.4. The parameters are obtained with a number of experiments. Input voltage of the motor and corresponding output voltage of tachogenerator is measured and tabulated in Table 4.5.

Table 4.4 Sensors and transducers with electromechanical system

Armature Resistance	6.2 Ω
No load current	120 mA
Stall current	1.93 A
Starting torque	7 Ncm/A
Torque constant	3.5 Ncm/A
Efficiency	70%-80%
Shaft speed at no load	2400 rpm (max)

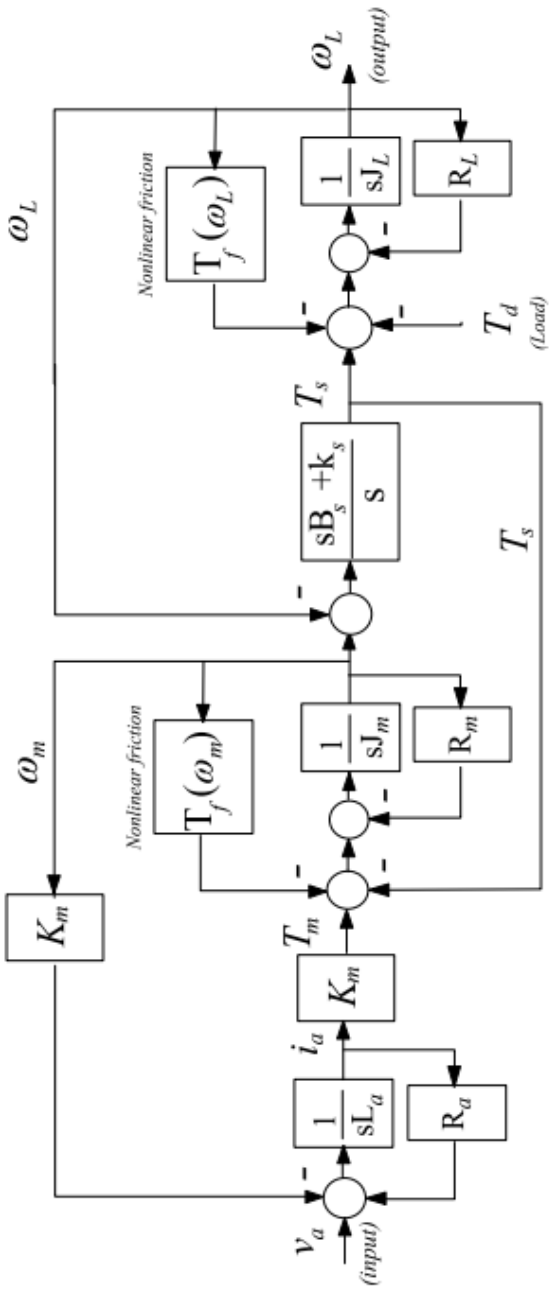


Figure 4.4 Block diagram of the electromechanical system

Table 4.5 DC motor system responses to different input signals

Shaft Speed (rpm)	Tachagenarator output voltage (V)
600	2.37
800	3.03
900	3.39
1200	4.48
1500	5.52
1800	6.71

4.2.2. System Identification

It is evident that to obtain the parameters in dynamical equations is a challenging problem. Control designer always needs a proper model in order to achieve satisfactory closed-loop control performance. However, the highly complicated nature of the most physical systems makes the development of exact models tedious task. Due to the fact that, a proper approximated model should be obtained by a number of system identification techniques. In the present study, the identification problem has been treated as linear time-invariant (LTI) ones in order to obtain an appropriate model. The actual system output is compared with predicted model output to validate the model, which should produce output responses similar to measured output responses (Eker, 2004; Kara and Eker, 2004).

System identification, which has a crucial importance for control engineers, is defined as an art of building the mathematical models of dynamic systems from observed input-output data. So far, many innovative system identification tools have been created. An interactive software tool, which is highlighted in (Ozbek and Eker, 2015), is used in the present work, in which the proposed graphical user interface (GUI) is very useful both for educational and research purpose

4.2.2.1. Process Reaction Curves

The process reaction curve is a well-accepted tool to determine the characteristic properties of a system under different conditions. Further, a number of dynamical properties of the system such as rise time, settling time, and time constant can be obtained directly.

In order to obtain the plant model, the armature of the DC motor is excited by a step input $u(t)$, of magnitude 5.20 Volts, and shaft speed is obtained in revolution per minute (RPM). The output voltage produced by the tachogenerator is measured to be 4.48 Volts that corresponds approximately to 1200-rpm shaft speed to approximate a second-order model as (Furat and Eker, 2014):

$$\frac{Y(s)}{R(s)} = \frac{C_n}{s^2 + A_n s + B_n} \tag{4.7}$$

Further, a number of system parameters are obtained corresponding to different operating conditions of the system. An application example for the identification of DC motor is presented in Figure 4.5.

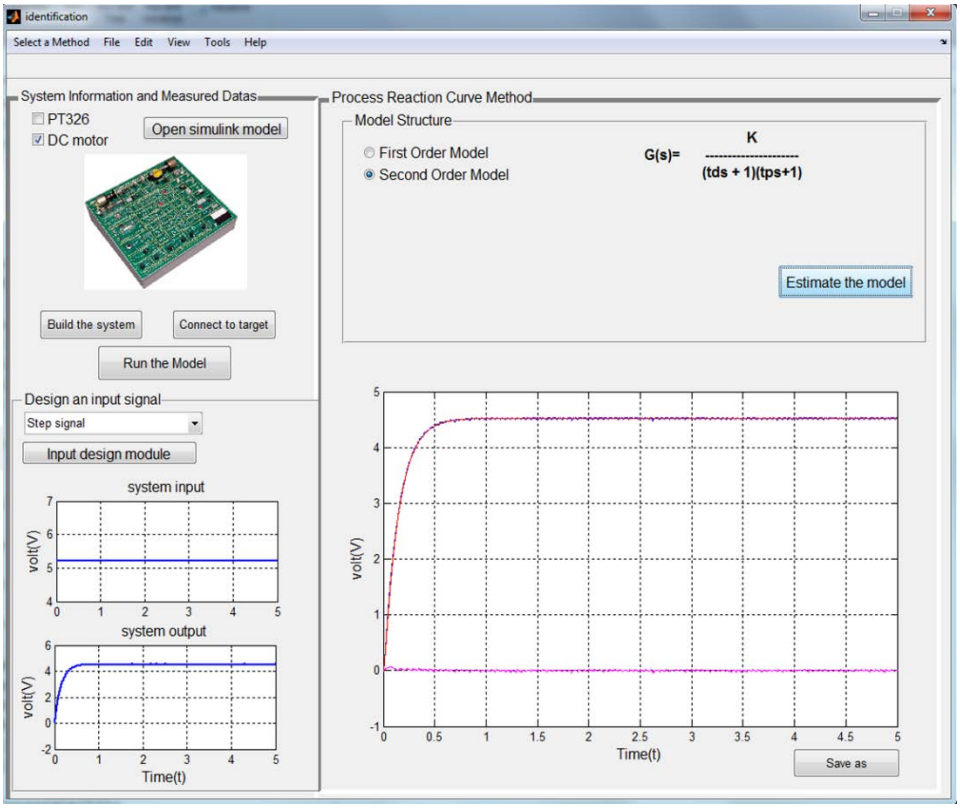


Figure 4.5 An example screen from the identification tool

The real-output and the model-output of the system is given in Figure 4.6.

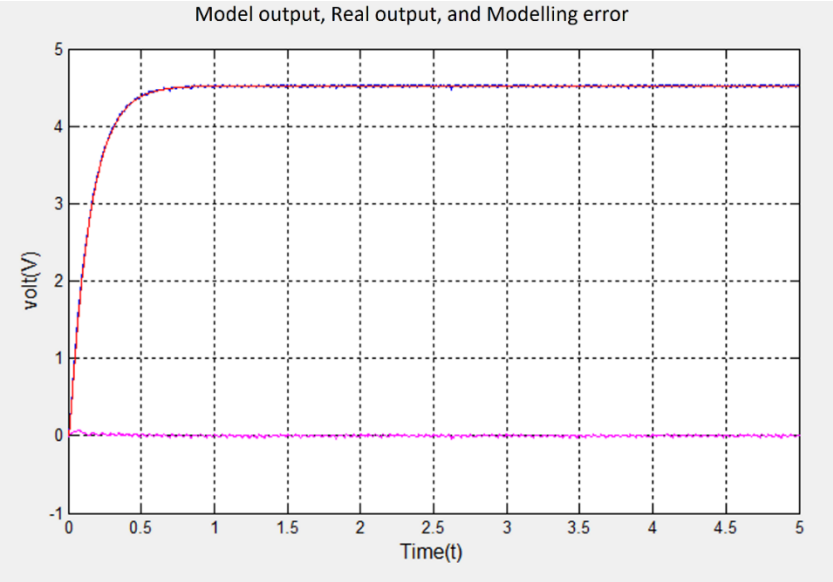


Figure 4.6 The real-output, model-output, and modelling error of DC motor

The model, which is given in (4.7), can be represented as $\ddot{y}_m(t) = -A_n\dot{y}_m(t) - B_n y_m(t) + C_n u(t) + D(t)$ and the nominal model parameters are obtained A_n=118.1763, B_n=783.5861, and C_n=663.4962, respectively. It is to be noted that the model parameters are obtained with a number of experiments.

The designed GUI provides some facilities to the users. The user can easily manipulate the experimental steps (input design, model structure, parameter estimation, and validation) of proposed methods. The model structure, model output, measured output, and the modelling error are demonstrated on the right panel. The modelling error, defined as the difference $y(t) - \hat{y}(t)$, is presented in Figure 4.6 such that the red line presents approximated model response, the blue line demonstrates the real system output, and the pink line shows the modelling error between the measured output and the model output. The comparison of the measured output and predicted output responses show that the model gives a

satisfactory result as far as the modelling error is concerned. The modelling error is about 1% including transient and steady state outputs.

4.3. Data Acquisition for the Air Heating Process

The specifications of data acquisition board employed for real-time experiments are presented in Table 4.6 (Alkaya, 2012).

Table 4.6 National Instrument NI PCI-6229 DAQ board

Analog Input	Operating System/Target	Real-Time, Linux, Mac OS, Windows
	Measurements Type	Digital, frequency, voltage
	Channels	32, 16
	Single-Ended Channels	32
	Differential Channels	16
	Resolution	16 bits
	Sample Rate	250 kHz
	Maximum Voltage Range	-10 V, 10 V
	Maximum Voltage Range Accuracy	3100 µV
	Maximum Voltage Range Sensitivity	97.6 µV
	Minimum Voltage Range	-200 mV, 200 mV
	Minimum Voltage Range Accuracy	112 µV
	Minimum Voltage Range Sensitivity	5.2 µV
Analog Output	Channels	4
	Resolution	16 bits
	Voltage Range	-10 V, 10 V
	Voltage Range Accuracy	3230 µV
	Update Rate	833 kHz
	Current Drive Single	5 mA

The system is linked to a PC with 1 TB HD, 16 GB RAM, Windows 7 operating system through NI-PCI-6229 DAQ device which has 32 analog input, 4 analog output, 48 digital I/O.

Analog Input (AI) channels of the DAQ device acquire the measured output temperature. The control signal and the external reference trajectory link to the Analog Output (AO) port of the DAQ, and then finally go to the electrical heater and the process, respectively.

Further, the technical details of the data acquisition board can be presented in Table 4.7 (Alkaya, 2012).

Table 4.7 National Instrument NI PCI-6229 DAQ board

Physical Specifications	Length	15.5 cm
	Width	9.7 cm
	I/O Connector	68-pin VHDCI female
Triggering/Synhronizations	Triggering	Digital
	Synchronization	Yes

The control algorithm is implemented using Matlab/Simulink® software on a computer running in Windows environment. The aforementioned tool needs MATLAB/Simulink®, Control Toolbox, Real Time Workshop® (RTW), Real Time Windows Target® (RTWT) and a compiler in order to get machine code for real-time application. The schematic diagram of real-time application is depicted in Figure 4.7.

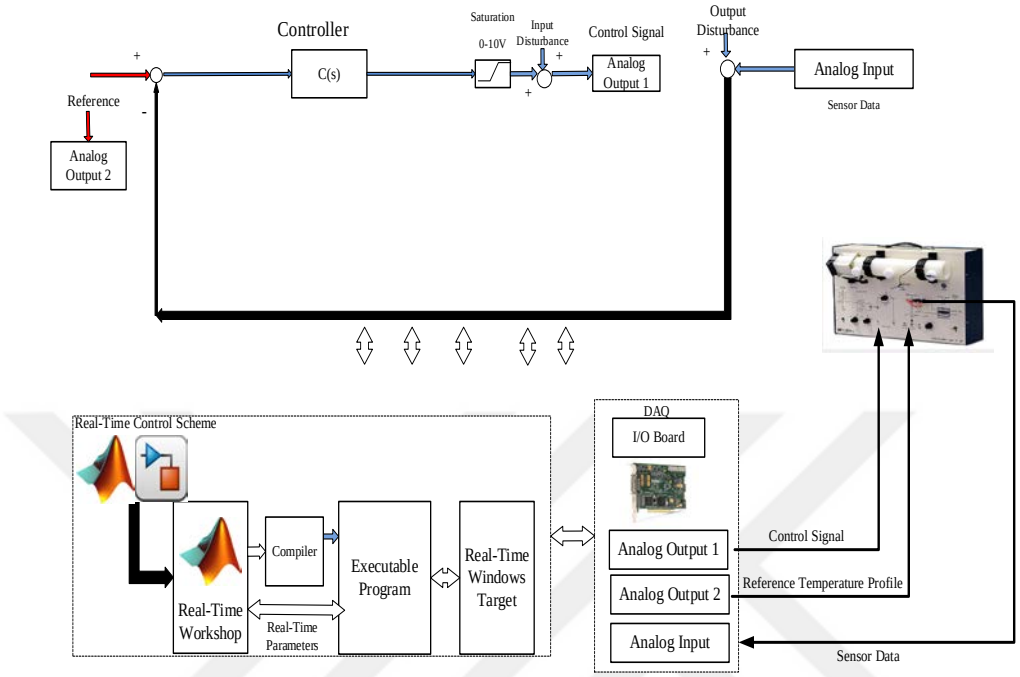


Figure 4.7 Real-time experimental application steps

These aforementioned tools are necessary to obtain the executable file from the control law model built in MATLAB/Simulink®. After designing the controller, C++ source program is obtained by Real-Time Workshop. Then, in order to get an executable program, the C++ compiler compiles and links the code by Real-Time Workshop. In this phase, Real-Time Windows Target interfaces with the hardware device through I/O board by communicating with the executable program running as a controller. Real-Time Windows Target controls bidirectional data flow between controller and real-system via I/O board. One of the main advantages of this application is that the control designer can use the graphical tools in Simulink® to achieve process-oriented outcome without having to be concerned with the communication mechanism to and from the real control system.

4.4. Air-Heating Process

The second experimental setup employed in this research is an air-heating temperature process that comprises a number of important characteristics for control systems.

The system is a laboratory-scale air heating process which is used for testing a novel controller (Khan and Rahman, 2010; Rehan et al., 2011; Rosa et al., 2016). The heating process may show different types of challenging behaviours such as saturation, hysteresis, and long delay. Hence, it is actually quite tough to obtain an appropriate model that represents the relation between the output temperature and the power input, since there always exists parameter variations in heat flow dynamics and the temperature of the ambient may change time-dependently. The classical control schemes employing the approximate plant model may not perform a satisfactory control result for a wide range of temperatures. To mention a few, when considering real-time experimental applications, the following situations should be considered:

- It is to be noted that the parameters of the linear model are always known approximately.
- In real-time experiments, the exact values of model uncertainties are difficult to obtain. Further, it is worth remarking that there is always uncertainty related to some parameters of the system.
- The process dynamics may vary due to nonlinearities and changes in the operating conditions such as variations in the external ambient air impelled into the duct. Even though those changes are small, they do exist.
- There always different kinds of constraints on measurement devices, sensors, and actuators. This may even give rise to uncertainty in the manipulated inputs since the actual input is often measured and adjusted in a cascade manner.

Finally, the implementation of the controller may differ from the one obtained by theoretical results. Because, the designer should include parameter uncertainty, unmodelled dynamics, and experimental constraints to compensate the implementation inaccuracies and to obtain better control performance.

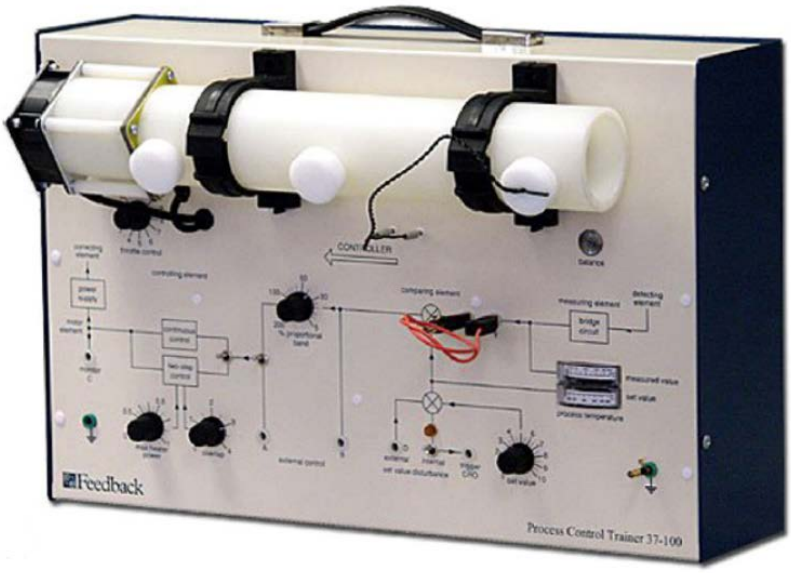


Figure 4.8 The experimental set-up to be used

The system comprises a heating element, an air tube, a thermistor, and an air damper as seen in Figure 4.8. The ambient air is drawn through an adjustable blower and passes through an electrical heater. Then, the air returns to the atmosphere through the tube. The main purpose is to control the temperature of the outgoing airflow. The manipulated variable and the output of the process are in the form of electrical voltage [V] applied to the heating coil that produces a current and accessible to the computer. The experimental set-up is presented in Figure 4.9.

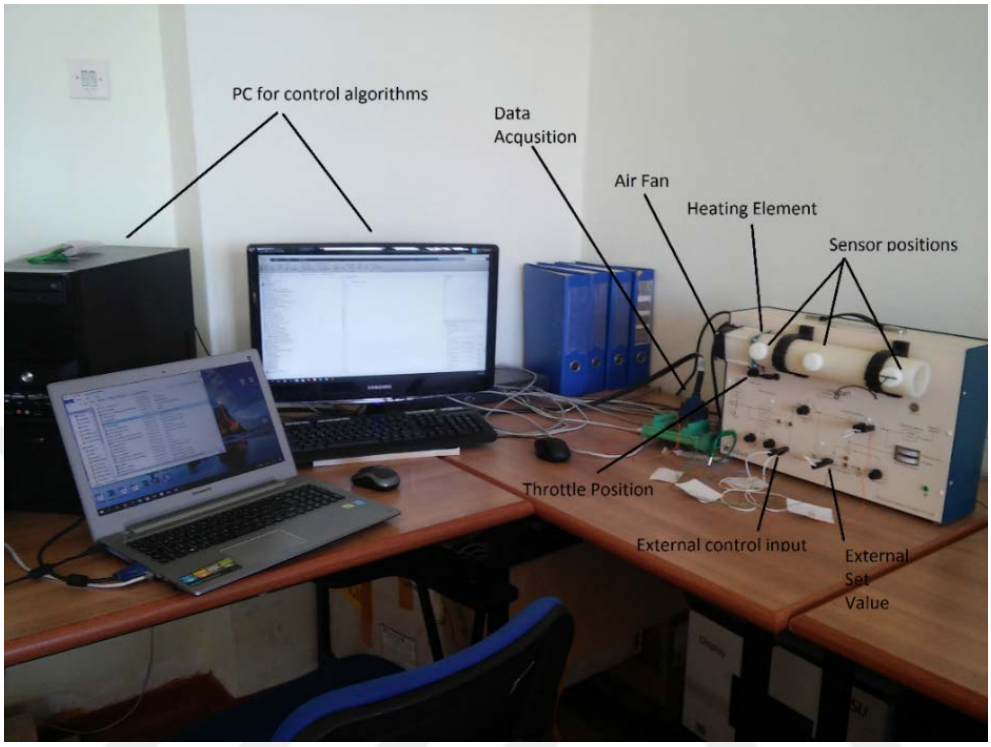


Figure 4.9 A scene from experimental set-up

The system is operated, in the range of 25 ^{o}C to 60 ^{o}C, depending on the ambient temperature.

4.4.1. Mathematical Modelling of Heating Process

In general, the heating system is modelled as a first order plus dead time model (FOPDT). However, a high order model such as second order plus dead time (SOPDT) provides more efficient model-based control strategy. Thus, a number of research studies present higher model of the system (Grega, 2001; Rehan et al., 2011) (Khan and Rahman, 2010; Bouzrara et al., 2012; Hussain et al., 2012; Rosa and Silvestre, 2014; Dziwinski et al., 2015; Taouali et al., 2015)

The model of the air-heating process comprises two main parts, first one is the model of the heater, and the second one is the model of the heat transfer from

the heater to air. The following physical parameters are introduced for the modelling of the process.

The physical parameters and symbolic notations of the system given in Figure 4.8 are given in Table 4.8 (Grega, 2001).

Table 4.8 Physical parameters of the system

L	Length of the heat exchange area	m
A	Cross sectional area of the pipe at the narrow (heating point)	[m^2]
l	Space variable of heat exchange	[m],$l\epsilon$[0,L]
$T(t,l)$	Temperature of the air flowing through the heater measured relatively to the room temperature,	[^{0}C]
$H(t,l)$	Temperature of the heater measured relatively to the room temperature, the function of time and space	[^{0}C]
v	Speed of the air flow time delay	[m/s]
$P(t)$	Power of the heater	[W]
r	Heat exchange circumference	[m]
η	Heat exchange coefficient	[J/s.m^2.^{0}C]
M	Mass of the heater	[kg]
c_g	Heat capacity	[J/kg.^{0}C]
c	Heat capacity of the air	[J/kg.^{0}C]
ρ	Air density at 40 ^{0}C	[kg/m^3]

It is to be noted that the heat transfer of the air within the pipe can be modelled in a variety of forms, including a model based on a complex heat equation. In the considered system, the radial heat transfer of the hollow cylinder may be neglected. For this reason, the problem can be reduced with lumped systems analysis to an ordinary differential equation with transport delay. Concerning the matter, a number of studies are used to constitute the model of the system. (Grega, 2001; Khan and Rahman, 2010; Rehan et al., 2011; Bouzrara et al., 2012; Hussain et

al., 2012; Rosa and Silvestre, 2014; Dziwinski et al., 2015; Taouali et al., 2015). The schematic of the system is presented in Figure 4.10.

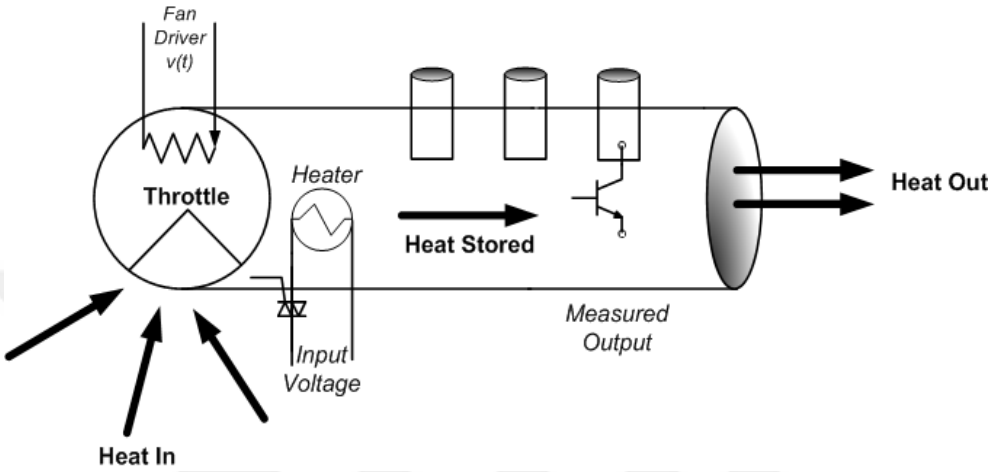


Figure 4.10 The schematic diagram of the process

Now, consider an infinitely small uniaxial element of the heater *dl*, its mass is presented as:

$$dM = \frac{dl}{L} M \tag{4.8}$$

Furhter, the energy of the elaborated element can be represented:

$$dQ(t,l) = dMc_g T(t,l) = \frac{dl}{L} Mc_g T(t,l) \tag{4.9}$$

The heat flow transferred to the element of the heater mass is given as:

$$\Upsilon_{we}(t,l) = dP(t) = \frac{dl}{L} P(t) \tag{4.10}$$

Further, the heat flow streaming out of the considered heat element

$$\Upsilon_{wy}(t,l) = \eta r dl(T(t,l) - H(t,l)) \tag{4.11}$$

Then, the heat flow equation can be presented as (Grega, 2001):

$$\frac{dQ(t,l)}{dt} = \Upsilon_{we}(t,l) - \Upsilon_{wy}(t,l) \tag{4.12}$$

and

$$\frac{\partial(\frac{dl}{L} Mc_g T(t,l))}{\partial t} = \frac{dl}{L} P(t) - \eta r dl(T(t,l) - H(t,l)) \tag{4.13}$$

The constant parameters M and c_g denote mass of the heater (kg), heat capacity of the heater (J/kg.^{o}C) respectively, and then one can get:

$$\frac{dl}{L} Mc_g \frac{\partial T(t,l)}{\partial t} = \frac{dl}{L} P(t) - \eta r dl(T(t,l) - H(t,l)) \tag{4.14}$$

The energy balance equation which expresses the behavior of the system

$$\frac{\partial T(t,l)}{\partial t} = \frac{1}{M.c_g} P(t) - \frac{\eta r L}{Mc_g}(T(t,l) - H(t,l)) \tag{4.15}$$

where the initial condition is: $T(0,l) = 0$.

Further, the heat exchange modelling is considered in the sequel. For this purpose, an imaginary air volume passing through a surface *A* with the speed *v* (Grega, 2001). The volume handled will have covered an infinitely small distance as *dl*, after the time *dt*. The considered mass of the air volume and the internal energy *dQ* can be presented as:

$$dM = \rho A dl, \tag{4.16}$$

$$dQ(t,l) = dMcH(t,l) = A\rho dlcH(t,l) \tag{4.17}$$

where $A\rho v$ is the stream of mass flowing into the considered volume, $H(t,l-dl)$, is the temperature of air at the previous infinitesimal distance *dl*. Further, the flow of heat to the outside can be given as:

$$\Upsilon_{wy}(t,l) = A\rho vcH(t,l) \tag{4.18}$$

where $H(t,l)$ is the temperature of the air inside the considered volume:

$$\Upsilon_{we}(t,l) = A\rho vcH(t,l-dl) + \eta rdl(T(t,l) - H(t,l)) \tag{4.19}$$

Assuming that there is no other energy source and loss in the elaborated region, the dynamical equation, which governs the behaviour of the heat flow, can be written as:

$$\begin{aligned} \frac{\partial(A\rho dlcH(t,l)}{\partial t} &= A\rho vcH(t,l-dl) \\ &+ \eta rdl(T(t,l) - H(t,l)) - A\rho vcH(t,l) \end{aligned} \tag{4.20}$$

Finally, the dynamical equations can be given as:

$$A\rho dlc\frac{\partial H(t,l)}{\partial t} = A\rho vc(H(t,l)-dl)-H(t,l)) + \eta rdl(T(t,l)-H(t,l)) \tag{4.21}$$

$$\frac{\partial H(t,l)}{\partial t} = -v\frac{H(t,l)-dl)-H(t,l)}{dl} + \frac{\eta r}{\rho Ac}(T(t,l)-H(t,l)) \tag{4.22}$$

For $dl \to 0$ we have:

$$\frac{\partial (H(t,l)}{\partial t} = -v\frac{\partial (H(t,l)}{\partial t} + \frac{\eta r}{A\rho c}(T(t,l)-H(t,l)) \tag{4.23}$$

Then, (4.23) constitutes the model of the heat exchange by using the initial and boundary conditions $H(0,l)=0$, $H(t,0)=0$.

The resulting dynamic system model is based on the implementation of the Laplace transform for the equations (4.15) and (4.23) (Grega, 2001). Further, the transformation is applied by using the time variable (*s*) and the space variable (*p*).

$$sT(s,p) = \frac{1}{Mc_g p}P(s) - \frac{\eta rL}{Mc_g}T(s,p) + \frac{\eta rL}{Mc_g}H(s,p) \tag{4.24}$$

$$sH(s,p) = -vpH(s,p) + \frac{\eta r}{\rho cA}T(s,p) + \frac{\eta r}{\rho cA}H(s,p) \tag{4.25}$$

It is to be noted that $T(s,p)$ can be obtained by (4.24). Then, the inverse transform can be applied with respect to the space variable (Grega, 2001):

$$H(s,l)=\frac{\gamma}{Mc_g s(s+\vartheta+\gamma)}(1-e^{-\frac{s(s+\vartheta+\gamma)}{v(\vartheta+s)}.l})P(s) \tag{4.26}$$

where

$$\vartheta=(\eta rL)/(mc_g) \text{ and } \gamma=(\eta r)/(\rho cA) \tag{4.27}$$

The transfer function of the systems can be represented as:

$$G_{WC}(s,L)=\frac{H(s,L)}{P(s)}=\frac{\gamma}{Mc_g s(s+\vartheta+\gamma)}(1-e^{-\frac{s(s+\vartheta+\gamma)}{v(\vartheta+s)}L}) \tag{4.28}$$

The following transfer function is obtained by including the heat transportation delay between the heating element and measurement point:

$$G(s)=\frac{H(s)}{P(s)}=\frac{\gamma}{Mc_g s(s+\vartheta+\gamma)}(1-e^{-\frac{s(s+\vartheta+\gamma)}{v(\vartheta+s)}L})e^{-s.\tau} \tag{4.29}$$

where, $e^{-\tau s}$, $H(s)$, and $P(s)$ denote the heat transportation delay, the air temperature in the sensor location, and the power of the heater, respectively (Grega, 2006). The system model has been expressed in the following to make it suitable in the controller design. Then, we obtain the following lumped parameter model.

$$G(s)=\frac{H(s)}{P(s)}=\frac{\gamma}{Mc_g(s+\vartheta+\gamma)(s+\frac{v.\vartheta}{L(\vartheta+\gamma)})}e^{-s.\tau} \tag{4.30}$$

4.4.1. System Identification for the Heating Process

Several studies have been addressed the parameter identification of second order model. For instance, Bajarangbali et al. present relay based identification techniques in (Bajarangbali et al., 2014). Further, Cox et al. present a comparative study for identifying FOPDT and SOPDT systems with various software based identification methods (Cox et al., 2016). An indirect identification method for continuous time delay system is given in (Du et al., 2011). A simple identification technique based on frequency domain methods is presented in (Santos and Barros, 2010).

4.4.1.1. Process Reaction Curves

The second order plus dead time model obtained in (4.31) can be represented as:

$$\frac{Y(s)}{U(s)} = P_m(s) = \frac{K_p}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau s} \tag{4.31}$$

where K_p, T_1, and T_2 are obtained as 0.7796, 0.4146, 0.1814. Then, the nominal model parameters a, b, and c are given as 7.3085, 13.2979, and 10.3670 respectively. Further, the frequency response of the system is given in Figure 4.11.

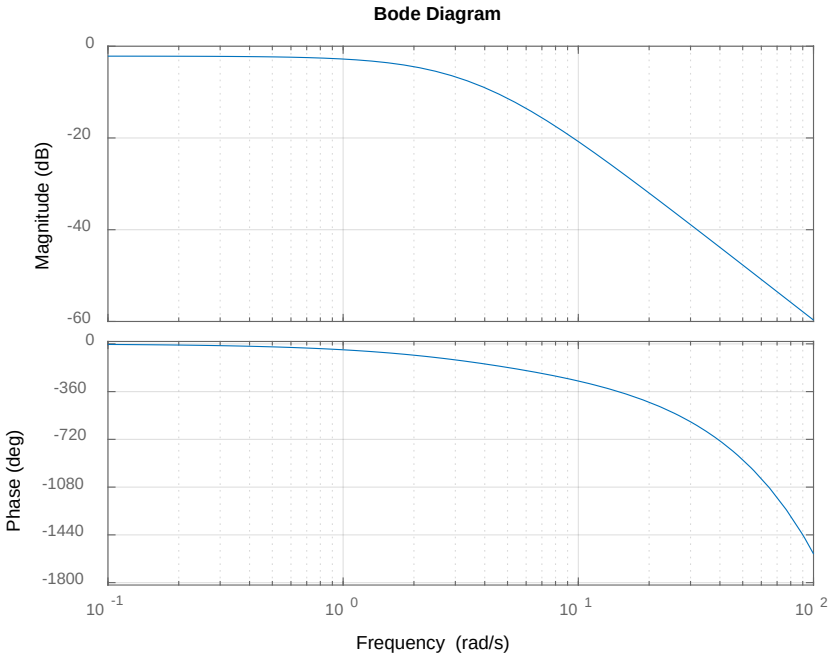


Figure 4.11 Bode plot of the identified open loop system

Further, the real-output and model output are presented in Figure 4.12.

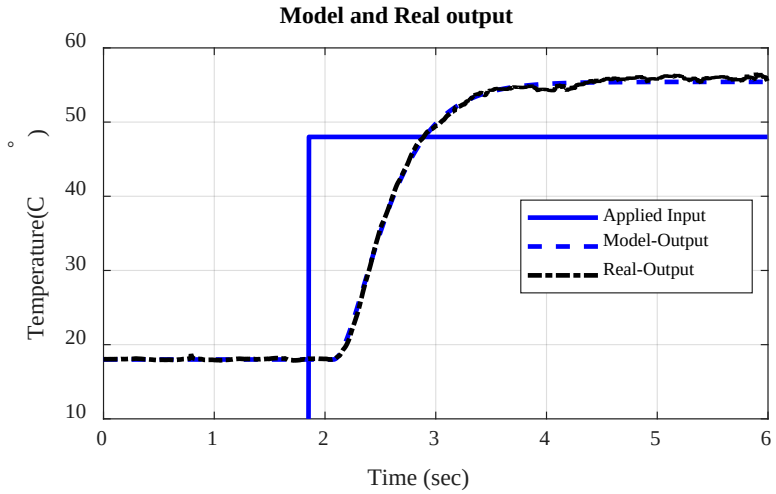


Figure 4.12 Applied input, model output, and real output

Further, the modelling error is given in Figure 4.13. The approximated first order plus dead time model can be represented as follows

$$G(s) = \frac{K_p}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau s} \cong \frac{K_p}{T_p s + 1} e^{-\tau_p s} \tag{4.32}$$

where τ_p=0.3131, T_p=0.5053, and K_p=0.7796 denote the delay, time constant, and gain of the system respectively (Skogestad, 2003).

The corresponding system parameters are obtained by applying process reaction curve methods. Toward this goal, a number of step inputs are applied in real-time and the system output is recorded.

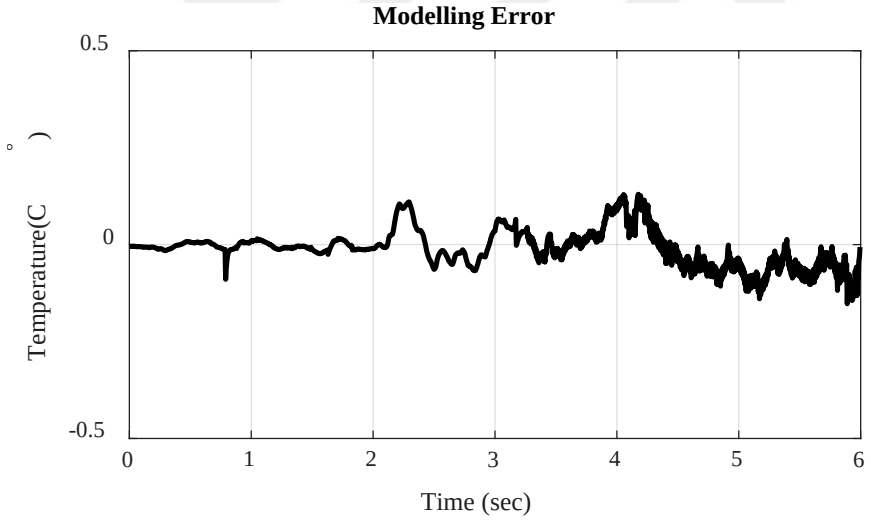


Figure 4.13 Modelling error

4.4.1.2. Digital Identification

In order to obtain a system model, real-time online identification is conducted by using a number of algorithms such as a recursive least squares algorithm (RLS). Both continuous and discrete model are obtained by applying a

sinusoidal reference comprising various frequencies and pseudo-random binary sequence (PRBS). Further, real-time windows target tool is used to obtain machine code for the implementation of the controller.

The identified model parameters are obtained by using recursive least squares (RLS) based identification techniques similar to that in (Eker, 2004; Kara and Eker, 2004; Bedoui et al., 2013). However, the selected transfer function of the process is higher order in the present study. The third order model is chosen to reflect the actual plant sufficiently close.

RLS based system identification, which is very efficient technique, display a number of significant properties such as easy to implement and fast parameter convergence.

The system identification block diagram, which are depicted in Figure 4.14, are presented as follows. It is assumed that the error $e(k)$ is uncorrelated noise with variance σ_e^2 and $E\{e(t)\} \coloneqq 0$. The model parameters, $a_i$and b_j are unknown and should be estimated. Since the process linearized dynamics is time-varying, a black-box ARX model is used to model the process, with repeated on-line identification. The model of the plant is chosen as

$$G_e(z^{-1}) = z^{-d}\,\frac{B_e(z^{-1})}{A_e(z^{-1})} \in R(z^{-1}) \tag{4.33}$$

where

$$\left\{\begin{array}{l} A_e(z^{-1}) = 1 + \hat{a}_1 z^{-1} + \hat{a}_2 z^{-2} + \ldots + \hat{a}_n z^{-n_n} \in R(z^{-1}) \\ B_e(z^{-1}) = \hat{b}_0 + \hat{b}_1 z^{-1} + \hat{b}_2 z^{-2} + \ldots + \hat{b}_n z^{-n_m} \in R(z^{-1}) \end{array}\right\} \tag{4.34}$$

The orders of the identified model are n_m and n_n with $n_m \le n_m$. The identified matrix can be given as:

$$\hat{\theta} = [\hat{a}_1, \hat{a}_2, ..., \hat{a}_{n_a} \hat{b}_0, ... \hat{b}_{n_b}]^T \tag{4.35}$$

The estimated model output is represented:

$$\hat{y}(k) = \phi^T(k)\hat{\theta}(k-1) \tag{4.36}$$

The parameter vector is given as:

$$\hat{\theta} = \left[\phi^T(k)\phi(k)\right]^{-1}\left[\phi^T(k)y(k)\right] \tag{4.37}$$

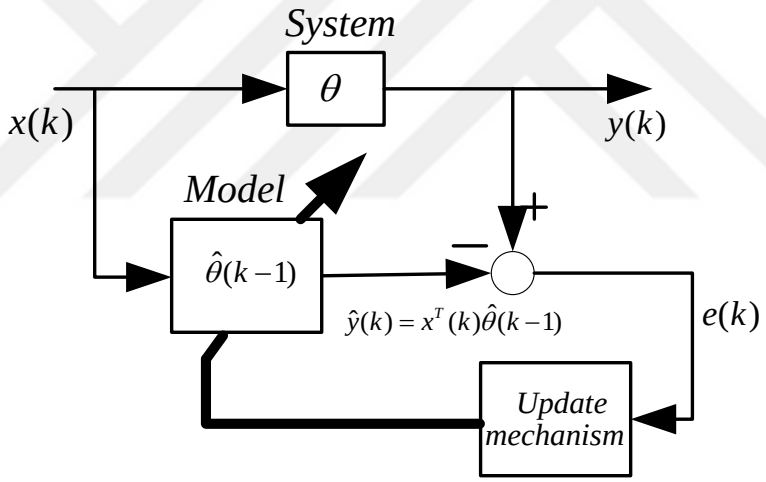


Figure 4.14 Recursive identification

In RLS method, the input/output information is renewed in each sampling interval. Further, the data, which is obtained from the previous sampling period $\hat{\theta}(k-1)$, is used to obtain the system output $\hat{y}(k)$. Then, the estimated output is compared with the real system output $y(k)$, and the difference between these

variables generates the model prediction error $\varepsilon(k)$. The model prediction error $\varepsilon(k)$, which is the crucial element of RLS, is represented as:

$$\varepsilon(k) = y(k) - \phi^T(k)\hat{\theta}(k-1) \tag{4.38}$$

Further, the covariant matrix is denoted by $P(k)$ which is given as:

$$P(k) = \left[\phi^T(k)\phi(k)\right]^{-1} \tag{4.39}$$

The parameter vector is updated with the help of the matrix inversion lemma (Ljung, 1997; Sodestrom & Stoica, 1989). Hereby, the model parameters are estimated as:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + P(k)x(k)\varepsilon(k) \tag{4.40}$$

Further, the estimator covariance matrix, which is denoted as $P(k)$, is updated as follows (Eker, 2004a, 2004b):

$$P(k) = \frac{1}{\lambda}P(k-1)[I_z - \frac{\phi(k)\phi^T(k)P(k-1)}{\lambda + \phi^T(k)P(k-1)\phi(k)}] \tag{4.41}$$

where λ is the forgetting factor for the recursive least square estimation. The model prediction error and the vector of unknown parameters can be presented:

$$\left\{\begin{array}{c} \varepsilon(k) = y(k) - x^T(k)\hat{\theta}(k-1) \\ \hat{\theta}(k) = \hat{\theta}(k-1) + P(k)x(k)\varepsilon(k) \end{array}\right\} \tag{4.42}$$

Further, the parameter effects on the model by observing root mean square error and related validation tests are performed for each selected model. Forgetting factor λ is another important parameter, which directly effects the identification performance. There is critical a trade-off between the parameter convergence and noise amplification. At this point, it is to be noted that faster parameter convergence is achieved if the forgetting factor is reduced, but this leads to noise amplification. The real-time identification results are shown in Figure 4.15, wherein the model-output, the real-output, and the modelling error are given.

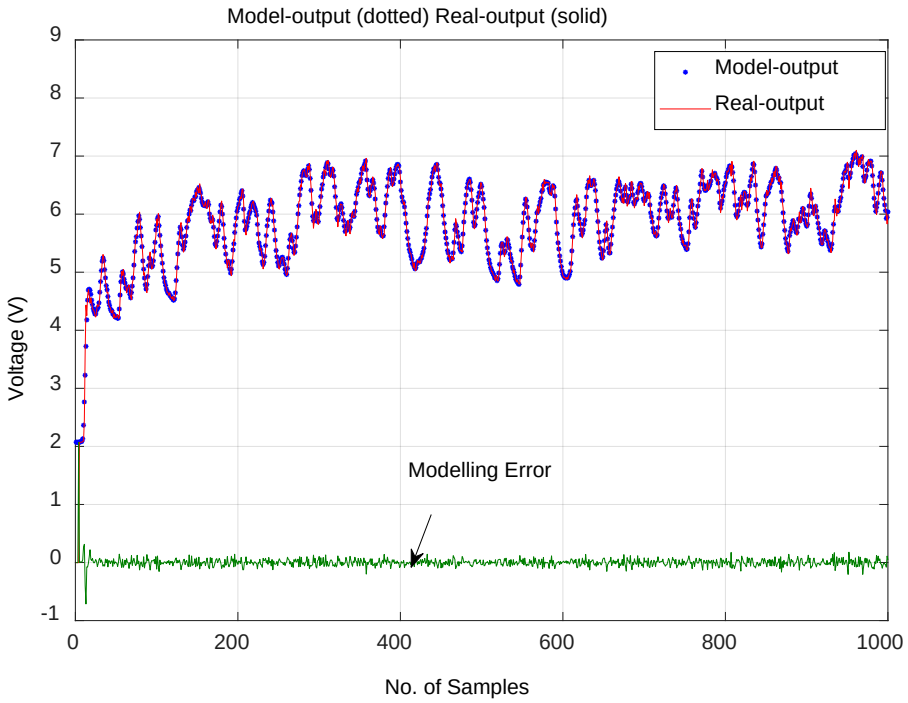


Figure 4.15 Real-output and model-output of the system

The result of system identification with a second-order model is given in Figure 4.16. The estimated parameters for each sampling are presented in this

figure. In Figure 4.16, the blue line, green line, and red line are corresponding to a_1, a_2, and b_1 model parameters, respectively.

Furthermore, Figure 4.17 present the effect of forgetting factor on the model parameters. The first figure gives the parameter estimations with the highest forgetting factor that is $\lambda = 0.93$. It can be noted that higher values of forgetting factor may cause smooth parameter estimation and small parameter variations.

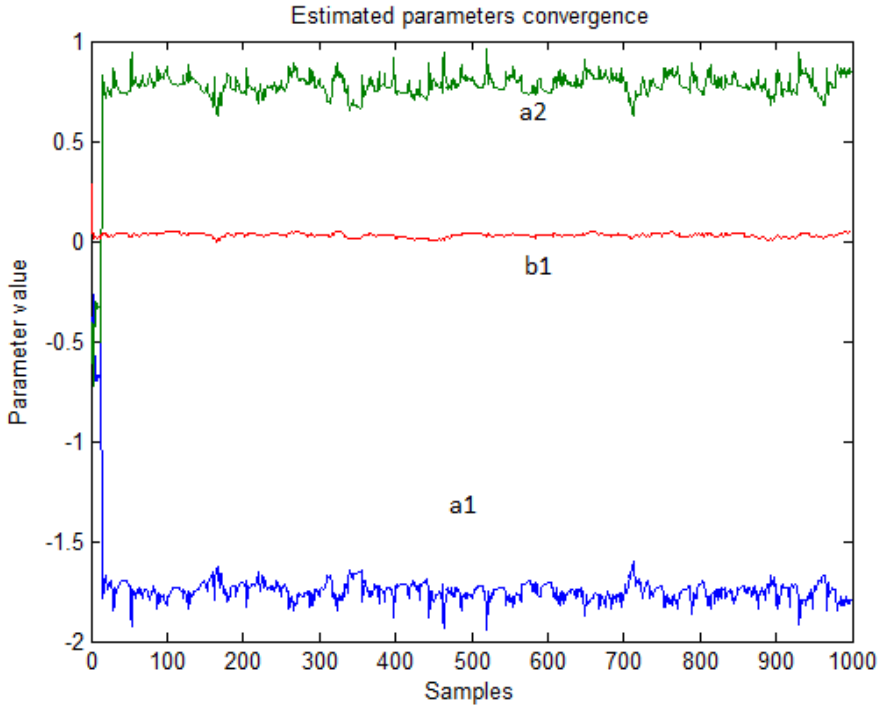


Figure 4.16 Estimated model parameters

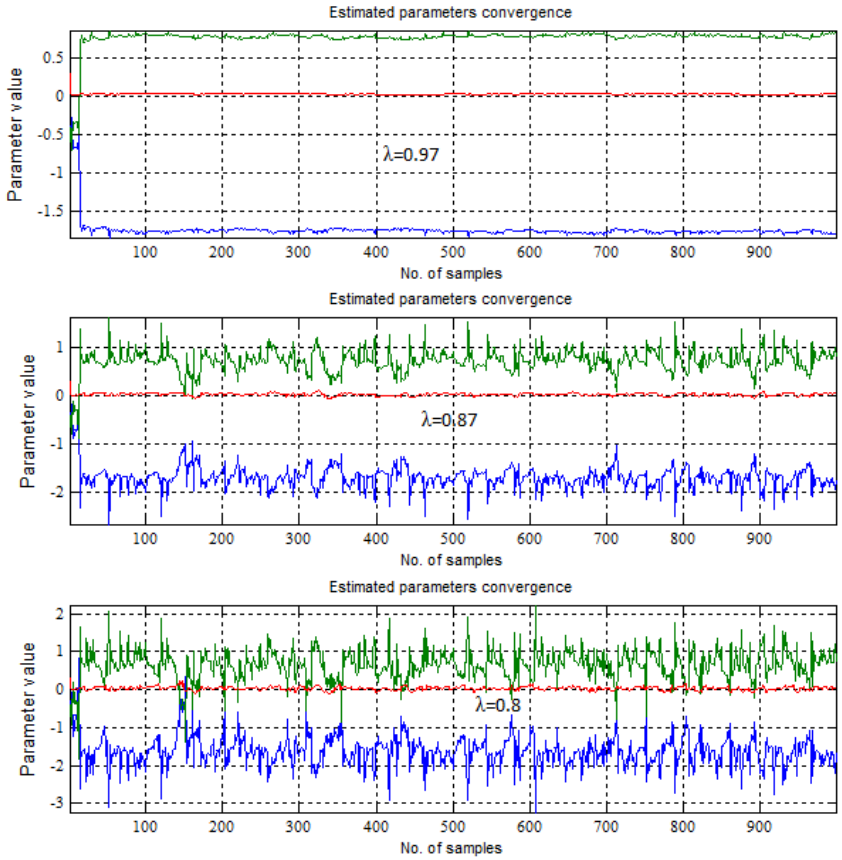


Figure 4.17 Effect of forgetting factor

An example scene of the system identification toolbox is highlighted in Figure 4.18. In this figure, a third-order model with three poles and two zeros is used to approximate the real system output. The identification performance is presented in Figure 4.18.

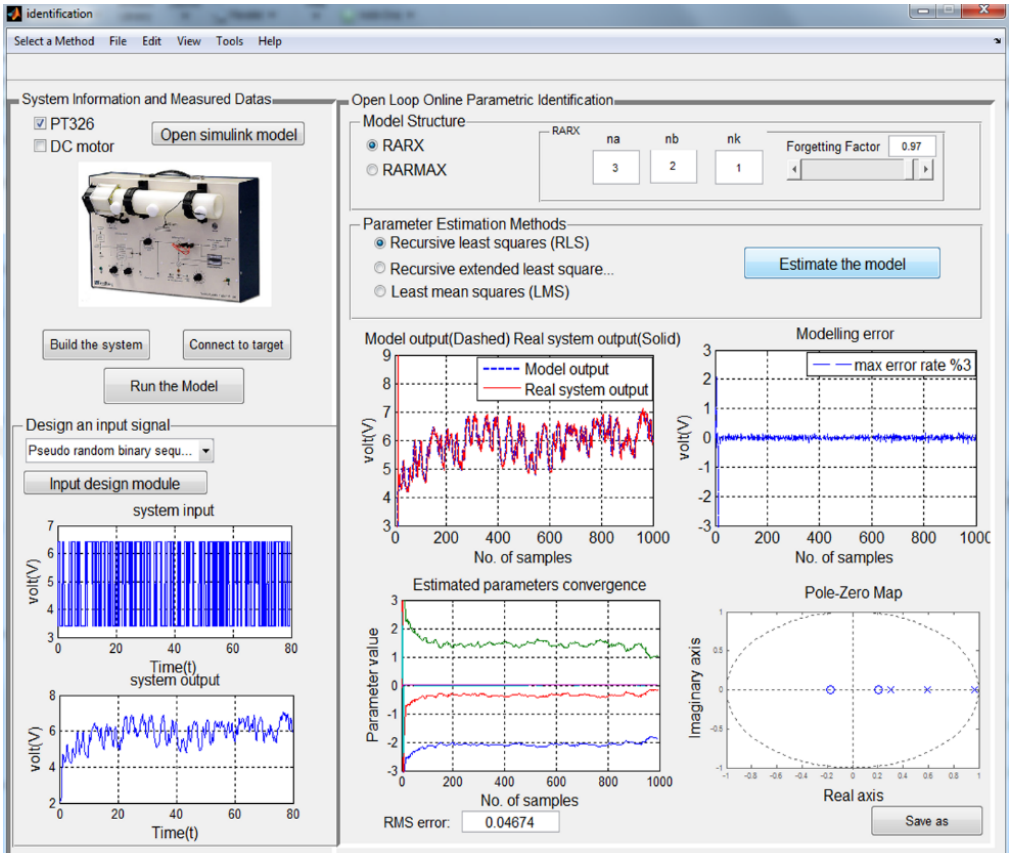


Figure 4.18 A scene from the real-time experimental identification tool

It should be noted that a different order model can be selected; however, in that case, it may be more difficult to characterize the whole dynamics of the thermal process.

A different modelling performance is demonstrated in Figure 4.19, wherein the user choose a second-order model with a zero for the model structure of the system.

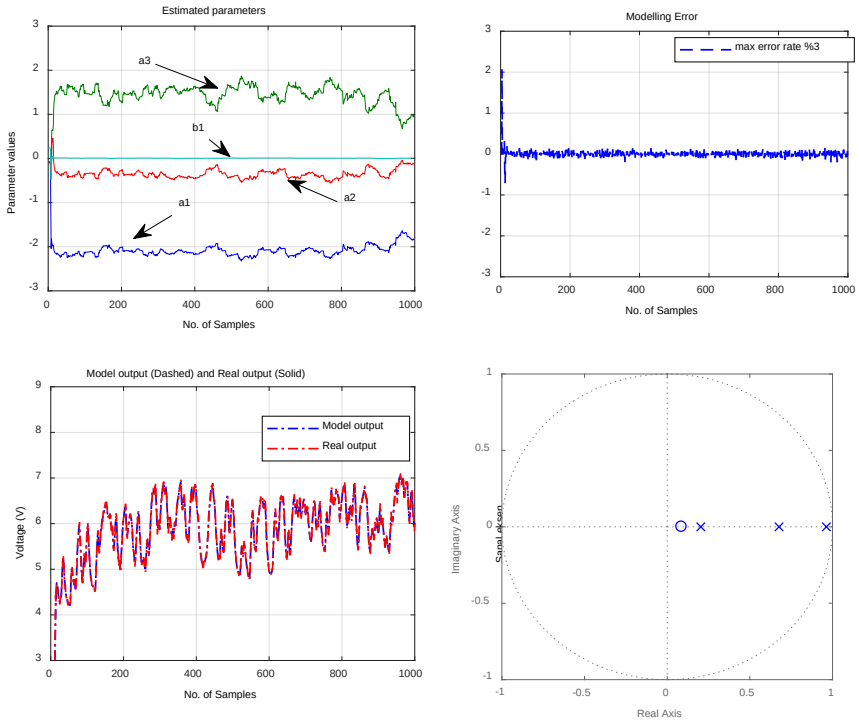


Figure 4.19 System identification for a second-order model

It must be stressed that the tuning of a PID type controller needs an accurate model that is obtained with an effective identification of the system. Various experiments have been carried out under different operating conditions. Even though in some cases one could obtain reasonable model based on mathematical modelling supported by prior known or directly measurable parameters still in most practical cases system identification experiments provide a remarkable improvement of analytical model or they are the only way to achieve system model. However, note that the comparison of the identified parameters to the original parameters of the heat flow dynamics to be quite difficult, as the original parameters are only known with some degree of confidence.

Typically, the system identification of air heating process is based on input-output data obtained from real-time experiments to be used in the

identification process. There are a number of critical choices in order to get an appropriate model. For instance, the excitation signal should be sufficient in frequencies to excite all system modes. The signal is designed by considering the slowest and highest modes of the system. Further, the period and length of the sequence are chosen properly. Concerning the matter, the determination of the frequency depends on the frequencies to be identified and the length of the sequence should be bigger than the settling time of the system. It should be noted that the excitation signal should not violate the operating range of the system or drive the system into an undesirable operating regime. In recursive estimation, the excitation signal *u(t)* should be constant between sampling intervals. Practically, it necessitates a synchronization between the transitions in the excitation signal and sampling device. The aforementioned synchronization problem is solved by generating the excitation signal in the computer. PRBS as an excitation signal can be applied for digital identification and multi-sine excitation input can be applied for frequency domain identification. In this aspect, the parametric models are estimated from the frequency-domain observations. Towards this goal, a sinusoidal excitation signal with different frequencies is applied to the blower of the heater. Then, by considering the frequency response data of the thermal system is used to identify the parametric system model. It is to be noted that different models can be obtained with experimental identification, however, the model employed in the experimental applications is as:

$$\frac{Y(s)}{U(s)} = \frac{(0.00758s+1)e^{-\tau_d s}}{0.00069s^3 + 0.0201s^2 + 0.602s + 1} \tag{4.43}$$

where the value of τ_d is depends on the position of the thermistor on the process. Through the experiments, the model in (4.43) is employed. Further, the temperature

[$^{\circ}$C] is measured at the point away from the heater by a distance of approximately 28 cm.

The model characterizes the system's input-output behaviour by observing the measured data; hence, they cannot ensure any insights on the internal dynamics of the system. Furthermore, the model parameters may vary in the external ambient air impelled into the duct by changing the throttle position which can be changed within [1,10]. Finally yet importantly, the overheating of the duct has a crucial impact on the system model.

4.5. Conclusion

This chapter is devoted to experimental set-up and some preliminaries. The plants, equipment, and software are described in detail. All systems are located in Control Systems Laboratory at the Department of Electrical and Electronics Engineering, Çukurova University, Adana, Turkey.

5. EXPERIMENTAL APPLICATIONS AND RESULTS

5.1. Experimental Constraints of the Air Heating System

The model parameters may vary in the external ambient air impelled into the duct by changing the throttle position which can be changed within 1-10. For instance, the delay change according to the throttle position is depicted in Figure 5.1. Through the experiments, the temperature [$^{\circ}$C] is measured at the point away from the heater by a distance approximately of 7, 14, 28 cm. Furthermore, it is to be noted that the overheating of the duct has a crucial impact on the system model. These situations have a direct impact not only on the actuation but also on the model of the process. Briefly, a process including all the aforementioned challenges is complex and has some vulnerabilities. Even though those changes are small, they do exist (Ahn et al., 2009; Rosa et al., 2016). However, the delay variation can cause an important effect on the system performance. Note that the comparison of the identified parameters to the original parameters of the heat flow dynamics to be quite difficult, as the original parameters are only known with some degree of confidence. In fact, this is quite typical case reported also for other industrial examples.

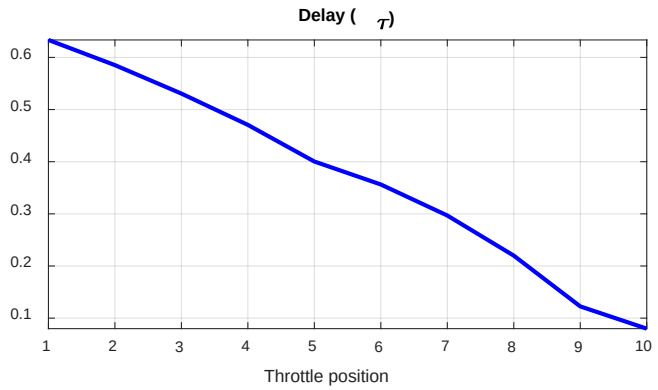


Figure 5.1 Delay variation

An input voltage between 0-10 V with a personal computer manipulates the operating power of the heater. The output of the system, which is accessible to the computer, is in a voltage form. However, the authors give a temperature trajectory from the computer. Thus, the designer should characterize the measured voltage signal and the obtained temperature T [°C]. To produce an appropriate temperature [°C] reference trajectory, it is necessary to characterize temperature-voltage (V) relation. Toward this goal, the output voltage of the system is converted into required range and then converted into temperature by utilizing a calibration equation, which is implemented on the computer. A number of experiments are conducted to characterize the input voltage and temperature relation. In these experiments, various input voltages are applied and the corresponding measured voltages at the sensor output and temperature values are recorded. Then, a curve fitting method is applied to obtain the mathematical relation between these variables. In the present study, a third order polynomial is chosen since the system may show nonlinear characteristics at lower and at a higher temperature. Hence, the polynomial temperature-voltage dependent temperature is obtained from experiments:

$$T = 0.0812V^3 - 0.3103V^2 + 2.2823V + 36.2219 \tag{5.1}$$

5.2. Experimental Applications and Results of SP based Fractional Order Control

A set of efficient fractional-order control techniques within a Smith predictor structure is designed for an integer order time-delay process. The fractional order controllers are designed based on the techniques given in chapter 3. In general, the controller parameters are computed using a procedure, which may lead to complicated situations. However, the elaborated control techniques have few tuning parameters, which can be easily obtained using the presented formulas

(Safaei and Tavakoli, 2017). This is one of the main advantages of the elaborated fractional order techniques.

The closed-loop control performance is evaluated by applying set point change to different operation points and external disturbance test. Experimental applications validate the tracking performance for a predefined temperature profile and disturbance rejection performances of the closed loop control system. The elaborated control techniques ensures the robustness against the model uncertainties in system parameters and internal/external disturbances.

It is observed that the SP based fractional order PI control techniques perform satisfactory control behaviour, even the set point changes are applied through the experiments. It is to be stated that comparing all control techniques at the same conditions is very difficult, however in all experiments; the conditions are chosen to be as close as possible. Furthermore, the system produces different characteristics depending on the operating point. Despite the fact that all controllers have stable behaviour in the output temperature.

Tuning procedure for technique I (Bettayeb et al., 2017): In order to control the heating process, the fractional integral order λ is chosen according to the overshoot formula as 0.1443, note that also, the limit values of the time constant T_c, which ensures the stability, can be chosen according to the (3.18) and (3.38). The value is chosen as $T_c = 3.3865$. The other control parameters are used from the model of the system as given in (3.36). This control method seems the easiest technique among the other controllers.

Tuning procedure for technique II (Vu and Lee, 2014): Accordingly, the proposed control scheme shows better tracking and disturbance rejection performance with fractional order term as $\varsigma = 0.76689$, which produces the smallest value of Integral of the Squared Error (ISE). Then, the proportional and integral gains of the controller are tuned by using the values of ω, ω_{cg} and ς to satisfy the desired system performance. In order to obtain a satisfactory control

performance (small ISE), the frequency variables are considered as ω (0.2259 rad/sec) and ω_{cg} (0.17 rad/sec) and ξ is chosen as 1.3526. Further, the tuning of the controller parameters is performed by the minimization of an ISE criterion. The phase margin is selected between $85°-105°$ for the elaborated system. The proportional gain and integrator gain are calculated by using (3.49) and (3.50). The controller parameters are presented in Table 5.1.

Table 5.1 Selected controller parameters for technique 2 (Vu and Lee, 2014)

	Parameters		
	K_p	K_i	ς
Set-I	0.78	0.923	0.76689
Set-II	0.53	1.049	0.6887
Set-III	0.65	1.18	0.7889

The corresponding frequency response (bode diagram) of the closed loop system is presented in Figure 5.2.

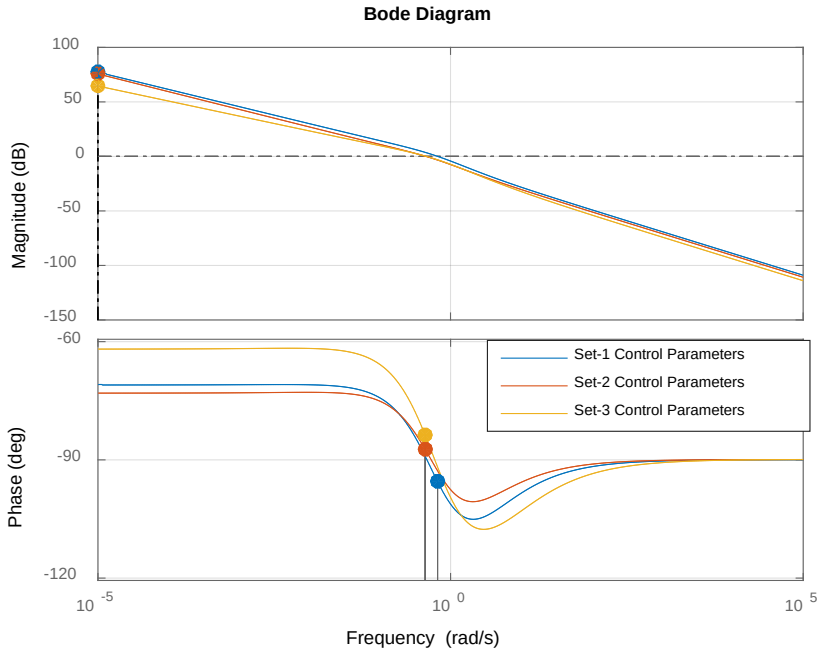


Figure 5.2 Bode plot of three different control sets

Tuning procedure for technique III (Muresan et al., 2015): It is to be noted that both FOPDT and SOPDT model can be adopted in this technique. However, the experiments are conducted on the system model described in (4.31). According to these relations, the controller parameters associated with the internal model control technique can be chosen as follows. In order to obtain a better control response, the phase margin is chosen as 100^0 and the fractional order is obtain as $\zeta = 0.8889$. Further, the time constant is obtained as $\alpha = 4.8312$, by considering the gain crossover frequency of the system.

Figure 5.3 demonstrates the transient performance of the closed-loop systems; Figure 5.4 shows the corresponding control signals in transient regime. Concerning the experiment applications, the initial temperatures are a little bit different in each experiment this is the reason of the differences on starting points.

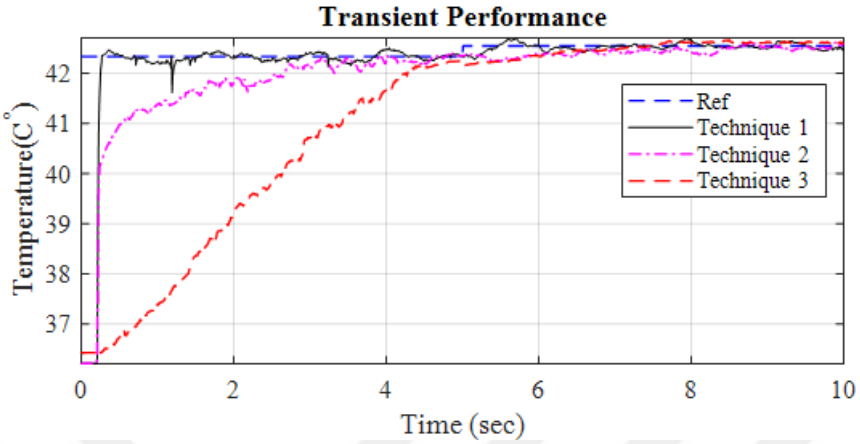


Figure 5.3 Transient control performance of FOC based SP Structures, Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015)

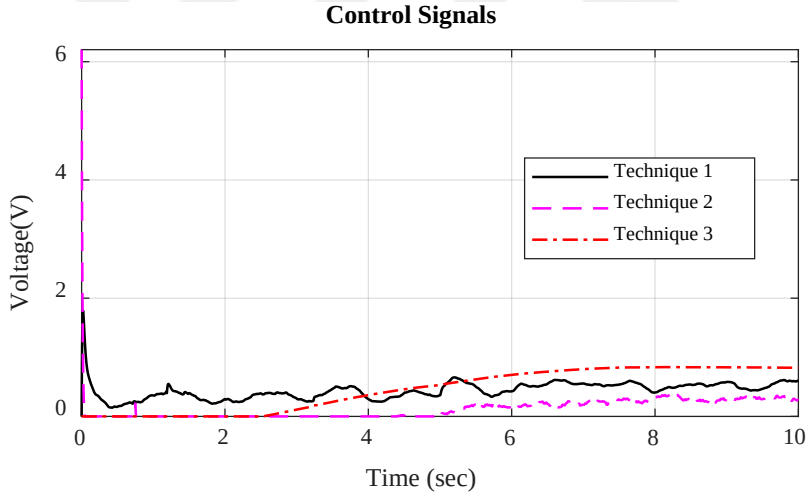


Figure 5.4 Control signals in transient regime, Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015)

It is to be noted that the settling time is different for the three controllers. The rising and settling time are slightly better with the technique 1 (Bettayeb et al., 2017) than technique 2 and technique 3. However, large values of λ may cause

larger overshoot, since the voltage required is higher than the maximum permissible value.

Concerning the controller parameter effects, it is to be stated that additional fractional-order integrator helps improving the steady-state response, however, the settling time of the closed-loop system will be larger that makes the system response slower (Monje et al., 2010).

The performance results in terms of the rising time, the settling time, the overshoot, and the EV are presented in Table 5.2.

Table 5.2 Measured performances of the elaborated controllers

Criterion	Technique 1	Technique 2	Technique 3
Rising Time	0.23	0.98	3.71
Settling Time	0.35	0.89	4.12
Overshoot (0-20 sec)	No overshoot	No overshoot	No overshoot
EV	0.4861	0.6250	2.1660

The tracking capability to the set point changes proves that the controller is able to handle the dynamic variations and its ability to handle operating point changes. According to the results, one can see that the technique 1 (Bettayeb et al., 2017) performs better response with short settling time and lowest ISE measure when compared to other SP based fractional order controllers. It is to be noted that, the controller performs well, however, a slight increase in overshoot is observed with technique 1, as seen in Figure 5.5. The reason may be the high control input value. As far as the technique 3 (Muresan et al., 2015) is concerned, there exists a steady-state error. The control signals for tracking performance is demonstrated in Figure 5.6.

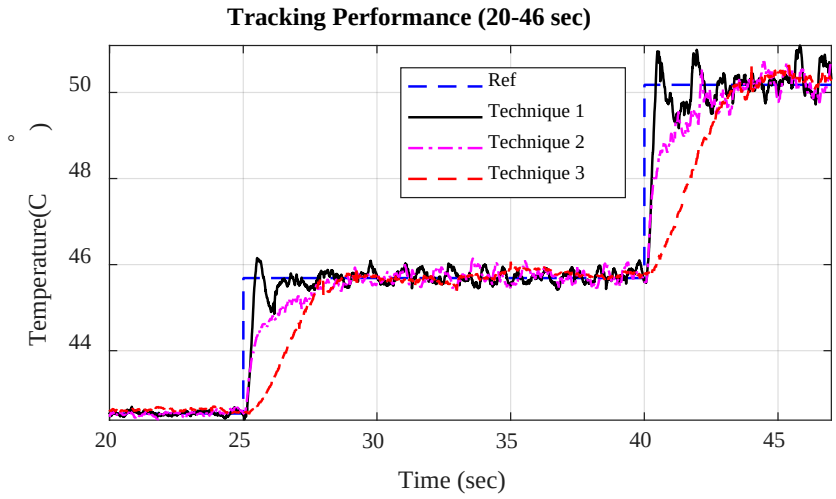


Figure 5.5 Tracking performance (20-46 sec), Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015)

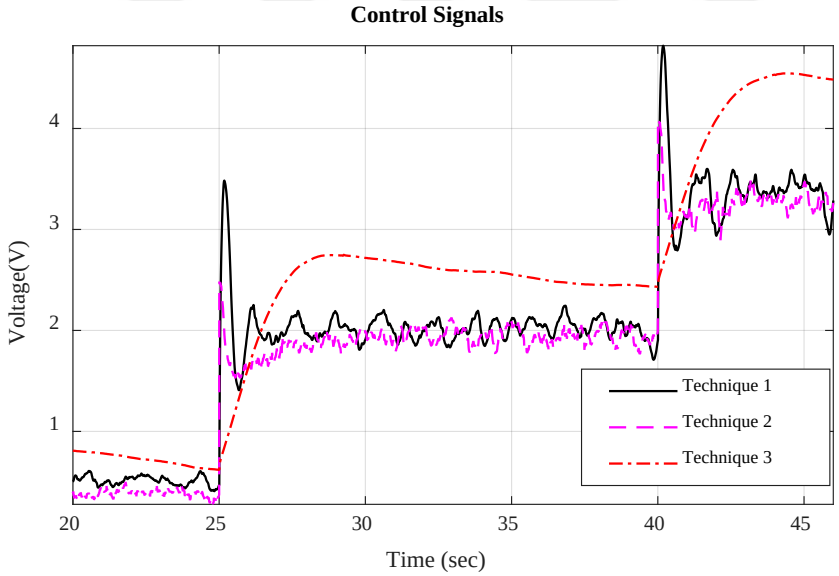


Figure 5.6 Control signals (20-46 sec) Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015)

The controllers have stable behaviour in all operating range, in spite of the presence of additional strong disturbances. However, when the set point is changed

to 50 ^{0}C the system response has more fluctuations. The thermal effects of the system cause this result. The controllers are robust enough to control the output temperature.

To validate the robustness of the controllers to an external disturbance, a step disturbance is applied at t=50 sec. The control techniques again demonstrate adequate robustness performance in the presence of modelling uncertainties and disturbance. The disturbance rejection performance are shown in Figure 5.7 and the control signals are shown in Figure 5.8.

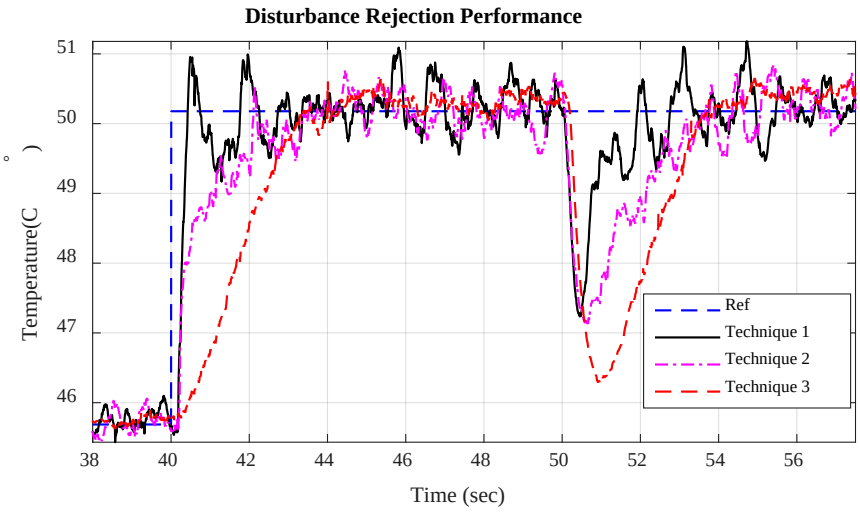


Figure 5.7 Disturbance rejection performance, Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015).

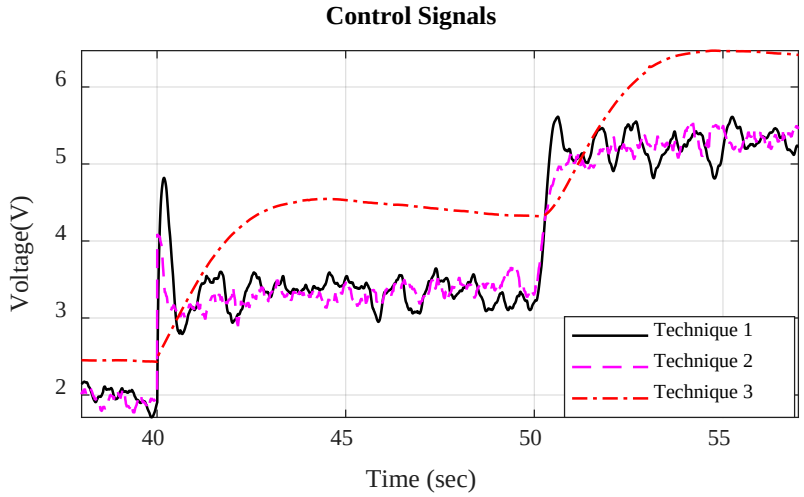


Figure 5.8 Control signals, Technique 1 (Bettayeb et al., 2017), Technique 2 (Vu and Lee, 2014), Technique 3 (Muresan et al., 2015).

The best disturbance rejection performance is observed by technique 1 during the external disturbance test. It is evident from Figure 5.7 that the technique 1 (Bettayeb et al., 2017) for the tuning SP based fractional order PI controller shows minimum values of IAE, ISE, and MAE for tracking control problem. The only limitation observed with the Bettayeb et al. (Bettayeb et al., 2017) technique is that it produces an offset in the response if the fractional order λ is less than 1.

Figure 5.8 presents the corresponding control signals generated by the three controllers. Although the technique 1 presents the best output in terms of error index, the technique 2 produce less control effort. Further, in order to provide satisfactorily tracking, the control input is increased, and an oscillatory behaviour can be observed in that case.

A note can be added for technique 2 and technique 3. It is observed that a better closed loop response can be achieved when fractional order PI controller is tuned by the technique 2 (Vu and Lee, 2014) compared with the technique 3 (Muresan et al., 2015). But the application of the technique 2 (Vu and Lee, 2014) for some lag dominant processes may result in an overshoot in the response. The

technique 3 (Muresan et al., 2015) is suggested for such processes. However, the large rising time and settling time make the technique 3 (Muresan et al., 2015) least preferred for tuning the SP based fractional order controller. Moreover, the technique 3 presents higher values of performance indices and thus not a choice for tuning the elaborated SP based fractional order control.

The performance of the three-control techniques can be explained as follows. The technique 1 (Bettayeb et al., 2017) is slightly better than other control techniques in terms of settling time. Further, the steady-state error is eliminated and the response is faster with acceptable overshoot.

Among the control strategies, the technique 1 (Bettayeb et al., 2017) and the technique 2 (Vu and Lee, 2014) show better performance during the real-time experiments. However, the technique 3 known as internal model control based FOPI (Muresan et al., 2015) gives a large steady state error. This is due to the low value of fractional order integral. In terms of the EV, the poorest results are observed with the technique 3 which is knonw as SP based fractional order IMC control (Muresan et al., 2015).

Further, a set of statistical performance measures named as IAE, ISE, ITAE, Integral Time Squared Error (ITSE), MAE, EV are used to show the performance metrics of each strategy. The measured performance indices are given in Table 5.3.

Table 5.3 Measured performance indices of the controllers

Criterion	Technique 1	Technique 2	Technique 3
IAE	3.9339	9.1559	14.4103
ISE	1.6232	4.0397	10.3093
ITAE	181.8732	432.3482	675.9209
ITSE	84.3894	205.4305	523.7575
MAE	0.2353	0.3560	0.6691

The control input performance is tabulated in Table 5.4, wherein the ISCI and total variance of the corresponding control signals are given.

Table 5.4 Performance of control signals

Criterion	Technique 1	Technique 2	Technique 3
ISCI	657.6250	624.4334	714.8418
Total Variance	2.8799	2.7277	3.6331

The radar diagram is presented in Figure 5.9 in order to compare the performance results of the technique 1 (Bettayeb et al., 2017), technique 2 (Vu and Lee, 2014), and technique 3 (Muresan et al., 2015). Note also that some of the the performance metrics are normalized in order to obtain a good comparison and a proper visualization in the radar chart.

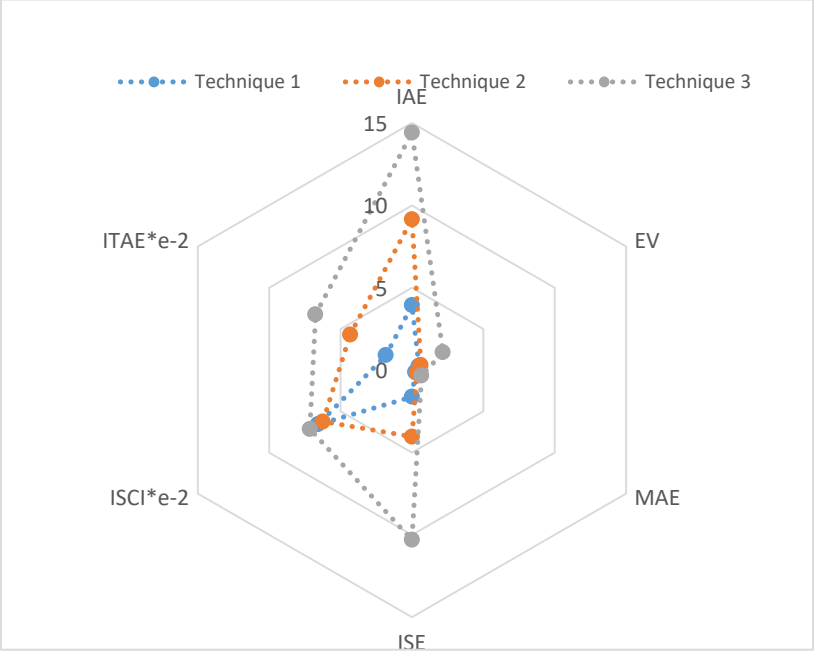


Figure 5.9 Performance comparison of fractional order controllers

5.2.1. Performance Discussion of Fractional Order Control Based Smith Predictors

A number of modified SP based fractional order control structures are investigated in this section. The present study attempts to apply the controllers proposed in (Vu and Lee, 2014; Muresan et al., 2015; Bettayeb et al., 2017) for an integer-order time delay system to a practical lab experiment. Several experimental tests are carried out to investigate the performances of the three controllers in the presence of disturbances and uncertainties. Design aspects and design criteria are different in the elaborated control techniques.

It is to be noted that the fractional order controller may achieve more robust control performance in the presence of uncertainties and disturbances (Feliu-Batlle et al., 2009; Castillo-Garcia et al., 2013). In this aspect, various recently proposed techniques are validated on a real industrial system. All the controllers were evaluated experimentally to an air heating process, which is approximated as a FOPDT model. The evaluation includes robustness against set point change and external disturbances.

The present control techniques are tested with a number of quantitative measures. Furthermore, the effect of the control parameters on the closed-loop control performance is investigated. In this aspect, presented experimental studies are elucidated as contributions to the literature.

From the results, all techniques provide stable response without any overshoot; however, technique 1 shows an oscillatory response with high temperatures. According to each algorithm, control signal presents different characteristics. More specifically, the lowest energy consumption is observed from technique 2. However, the more robust behaviour is obtained by technique 2 in the presence of disturbances. Overall, according to the results, technique 1 achieves more accurate control performance. However, it should be pointed out that the magnitude of the control signal of is relatively larger than other control techniques.

Further, the elaborated control scheme demonstrate satisfactory control performance even if there exists model uncertainties, disturbances, and measurement noise.

5.3. Experimental Applications and Results of Robust Control Techniques

This section addresses SP based robust control technique that belongs to the class of the high-order sliding mode control technique. The effectiveness of the proposed algorithm in terms of convergence and robustness is confirmed by the satisfactory experimental results. In addition, the proposed algorithm has been compared experimentally, with SP based first-order SMC control technique.

The initial transient responses of controllers are illustrated in Figure 5.10.

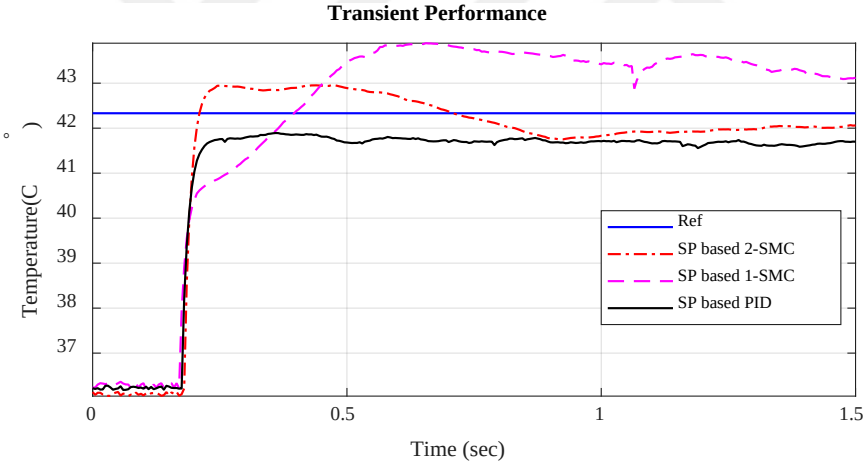


Figure 5.10 The transient performance of the controllers

The control signals in initial transient regime for second-order sliding mode control (2-SMC), first-order sliding mode control (1-SMC), and PID control are demonstrated in Figure 5.11, Figure 5.12, and Figure 5.13, respectively.

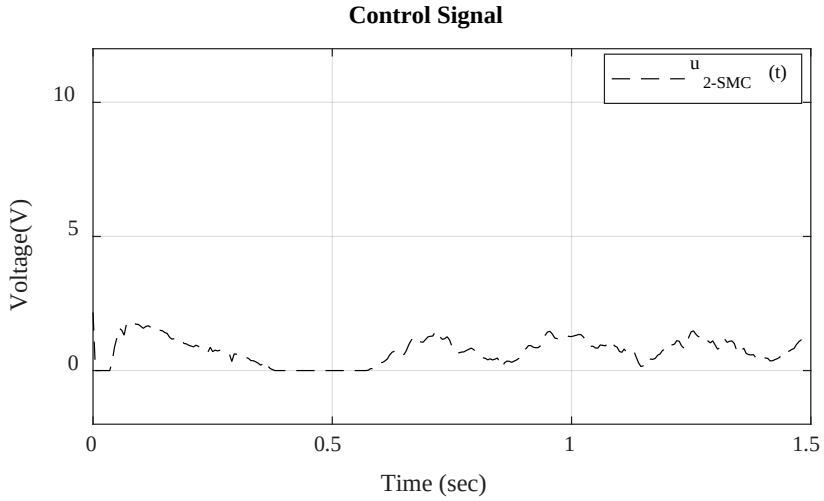


Figure 5.11 The control signal of 2-SMC in transient regime

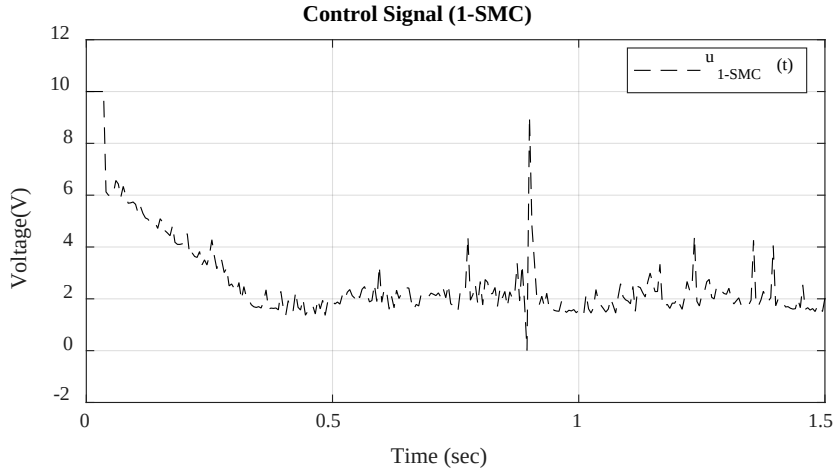


Figure 5.12 The control signal for 1-SMC in transient regime

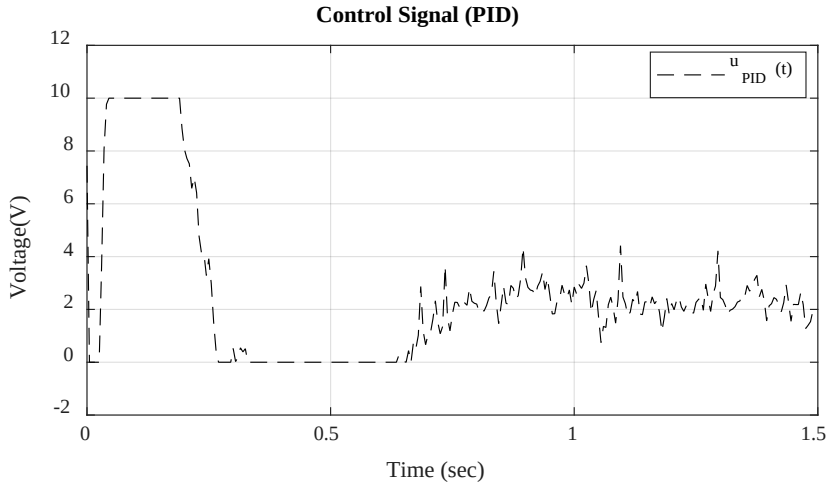


Figure 5.13 The control signal for PID control in transient regime

The transient response (between t=0-10 seconds) of the controllers is presented in Figure 5.14, wherein the response of the controller is observed to be acceptable levels.

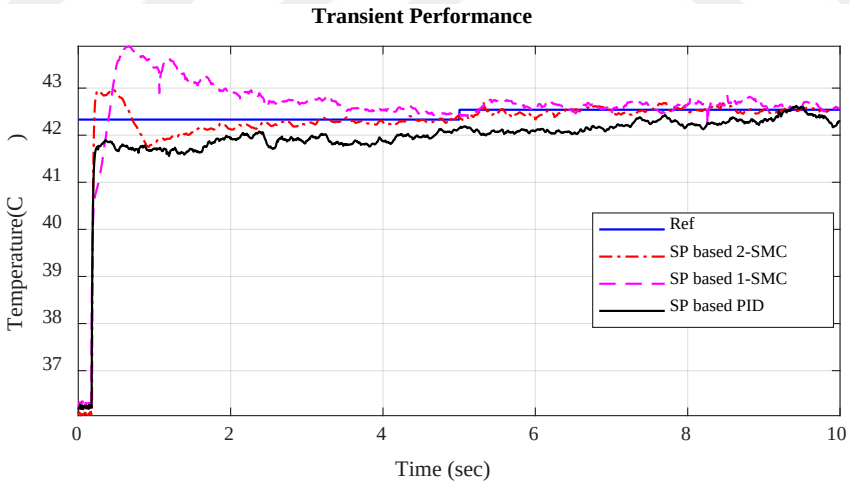


Figure 5.14 The transient performance with SP based robust control techniques

Some performance indicators of the transient performance quality based on the time domain analysis are presented in Table 5.5.

Table 5.5 Measured performances of the robust controllers

Criterion	First-order SMC	Second-order SMC	PID
Rising Time	0.37	0.32	0.42
Settling Time	4 sec	2.02 sec	5.85 sec
Overshoot (0-20 sec)	<2.3%	<1%	-
Error Variance	0.0334	0.0299	0.0496

The control signals in transient regime (between t=0-10 seconds) for 2-SMC, 1-SMC, and PID control are demonstrated in Figure 5.15, Figure 5.16, and Figure 5.17, respectively.

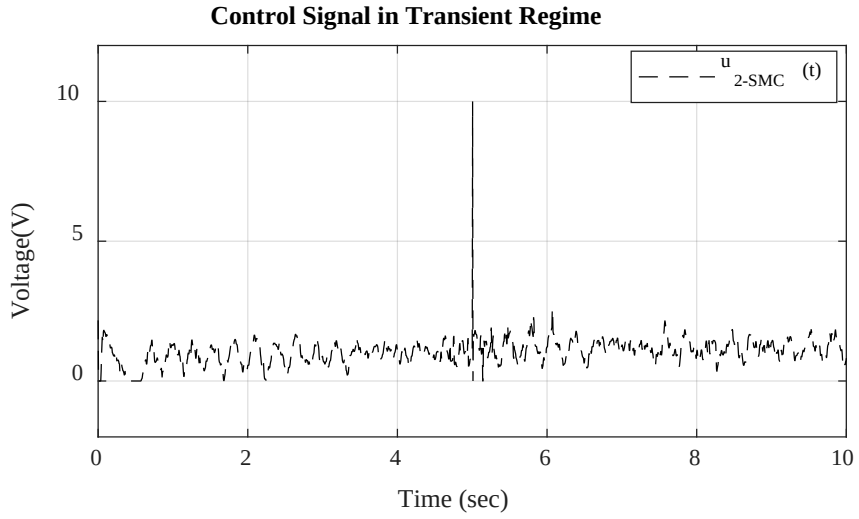


Figure 5.15 The control signal of 2-SMC (t=0-10 sec)

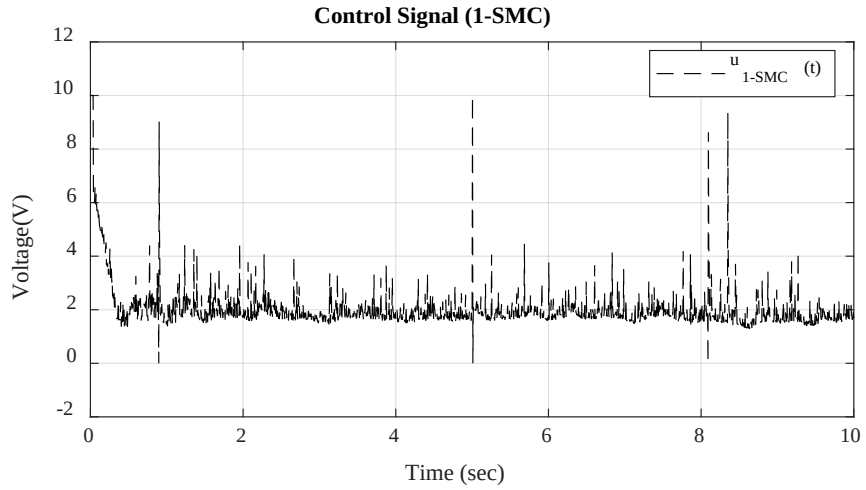


Figure 5.16 The control signal of 1-SMC (t=0-10 sec)

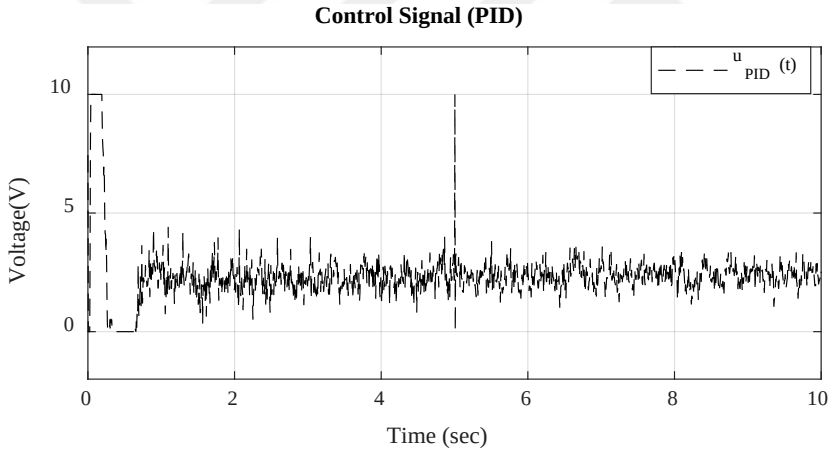


Figure 5.17 The control signal of PID (t=0-10 sec)

In the following, Figure 5.18 presents the switching signal of 2-SMC in the transient regime and Figure 5.19 shows the switching signal of 1-SMC.

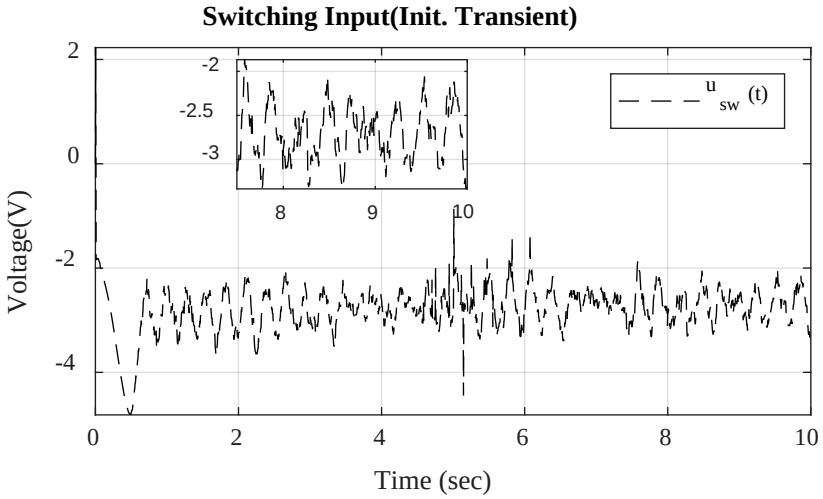


Figure 5.18 The switching control signal of 2-SMC in the transient regime

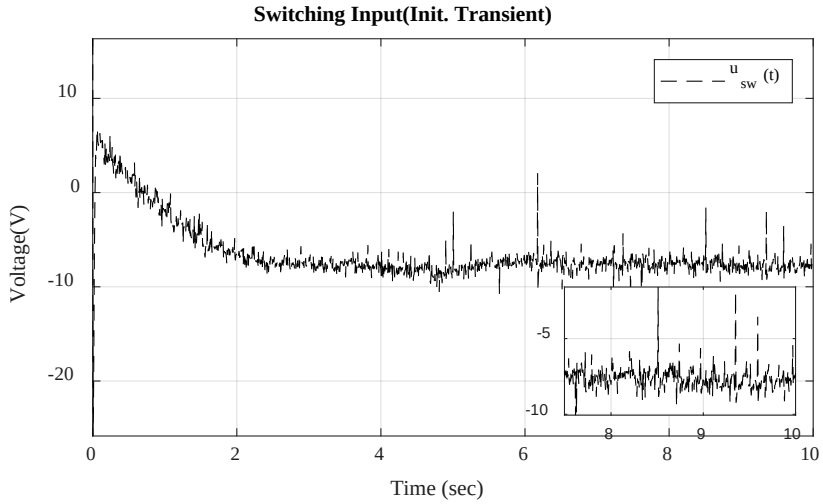


Figure 5.19 The switching control signal of 1-SMC in transient regime

The tracking performance around t=25 sec is given in Figure 5.20 and the tracking performance around t=40 sec is presented in Figure 5.21. It is seen that tracking precision is fairly good for 2-SMC and 1-SMC.

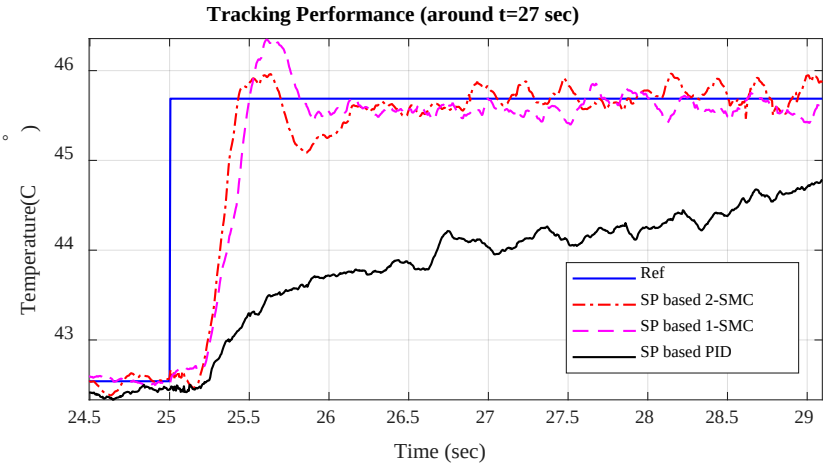


Figure 5.20 The tracking performance around t=25 sec

The tracking error, realized with second-order SMC is more constant in the presence of external disturbances. From the results, it can be concluded that SP based SOSMC are more robust to external disturbances than a SP based first-order SMC and SP based PID control. It is to be noted that the error value is found around zero except from the changes on temperature profile.

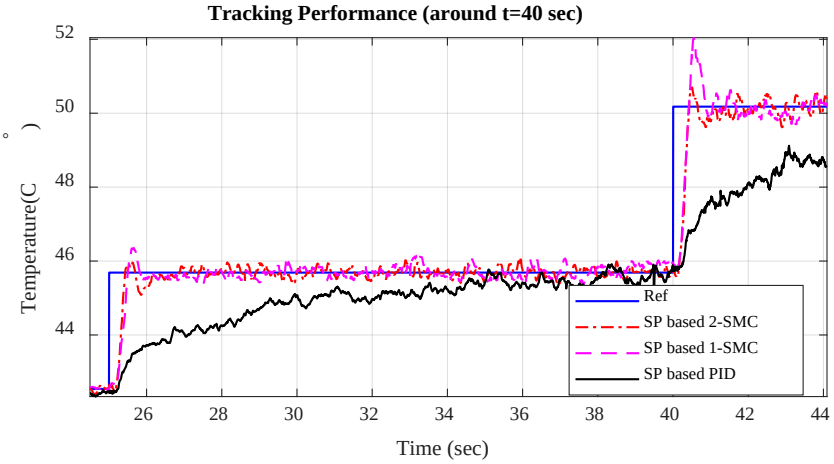


Figure 5.21 The tracking performance around t=40 sec

The control signals around t=40 seconds for 2-SMC, 1-SMC, and PID control are demonstrated in Figure 5.22, Figure 5.23, and Figure 5.24, respectively.

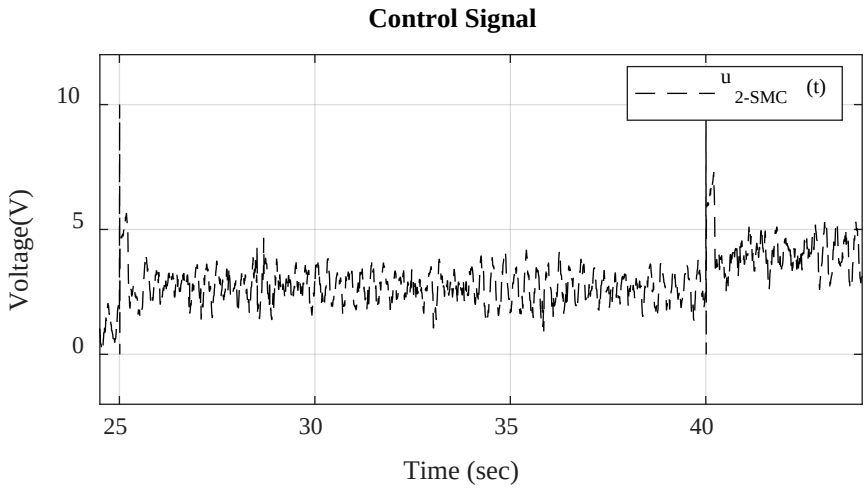


Figure 5.22 The control signal of 2-SMC (around t=40 sec)

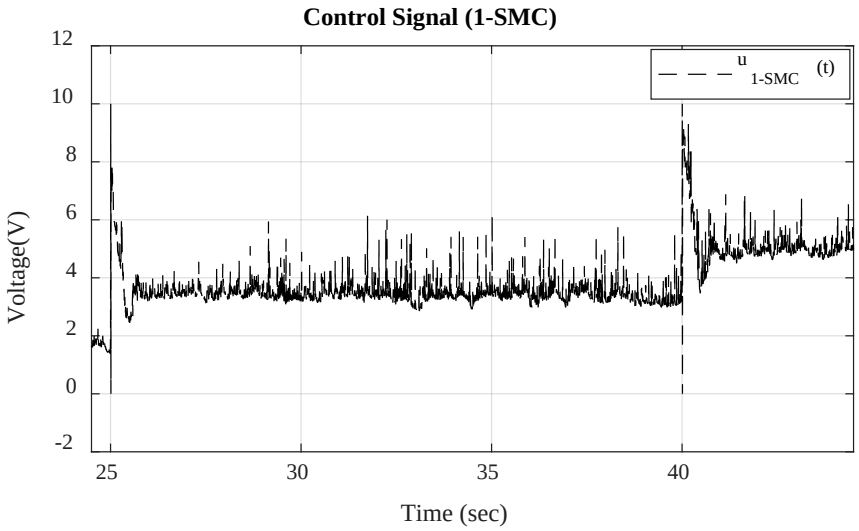


Figure 5.23 The control signal of 1-SMC (around t=40 sec)

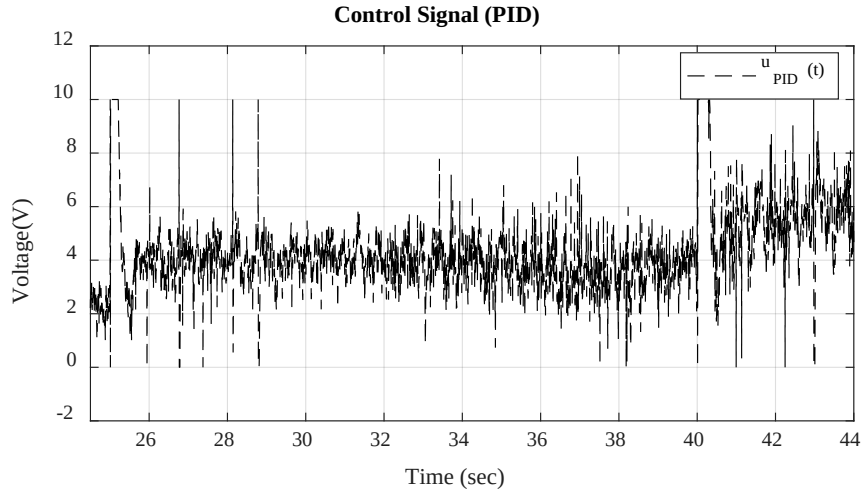


Figure 5.24 The control signal of PID (around t=40 sec)

Moreover, Figure 5.25 presents the switching signal of 2-SMC in the transient regime and Figure 5.26 gives the switching signal of 1-SMC.

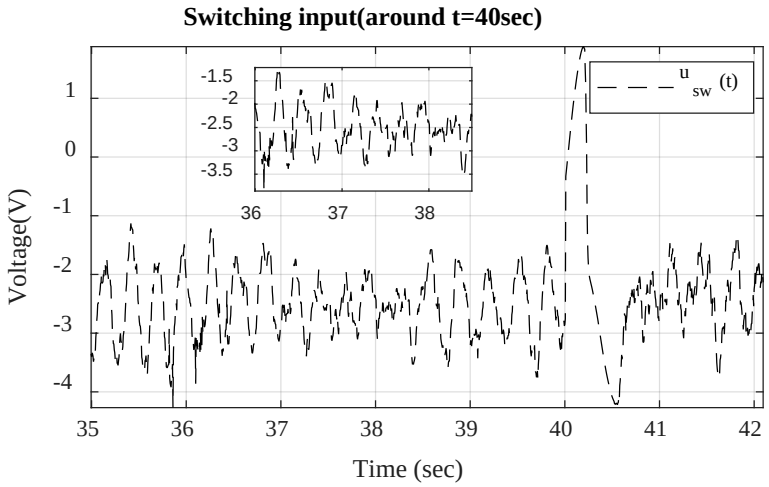


Figure 5.25 The switching signal of 2-SMC around t=40 sec

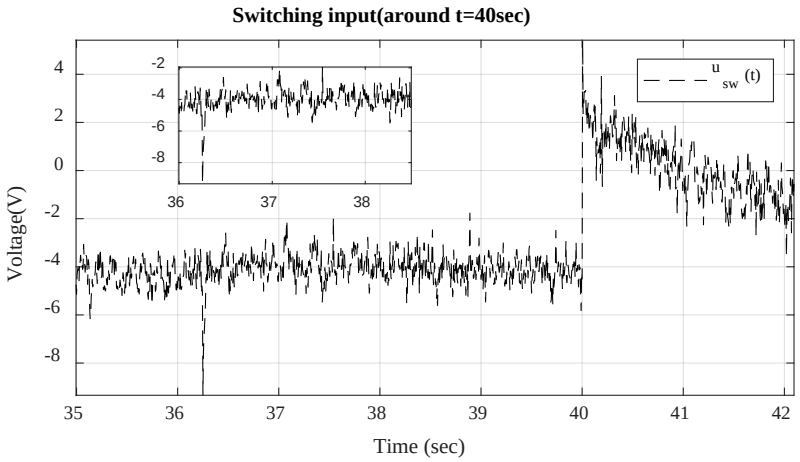


Figure 5.26 The switching signal of 1-SMC around t=40 sec

The proposed controllers have been implemented and demonstrate satisfactory performances for both external disturbances as well as model uncertainties. The robustness of the controller is tested in the presence of an external disturbance, which is applied as a step signal to the measured output at t=50 sec. The disturbance rejection capability is demonstrated in Figure 5.27, where the maximum tracking error is less than $3C^{o}$ in the presence of external disturbance.

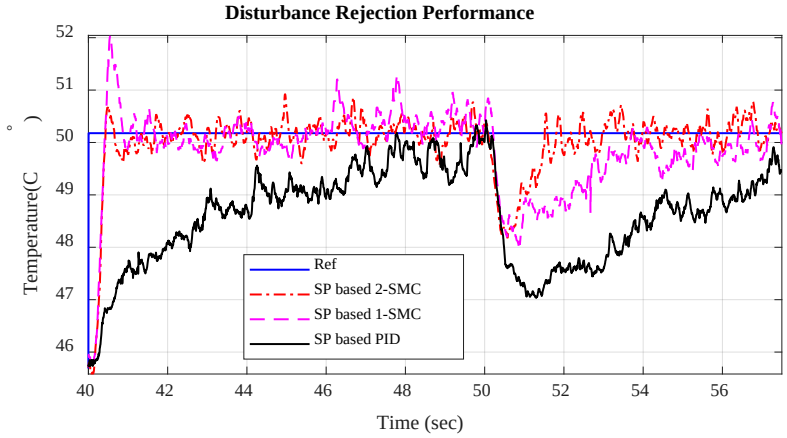


Figure 5.27 The disturbance rejection performance

The applied control signals for 2-SMC, 1-SMC, and PID are presented in Figure 5.28, Figure 5.29, and Figure 5.30, respectively. The chattering phenomenon is found at acceptable level for second-order SMC than the first-order SMC technique. It can be observed in Figures 5.28-5.30 that the control signal amplitude increases as the reference temperature increases and the disturbance occurs.

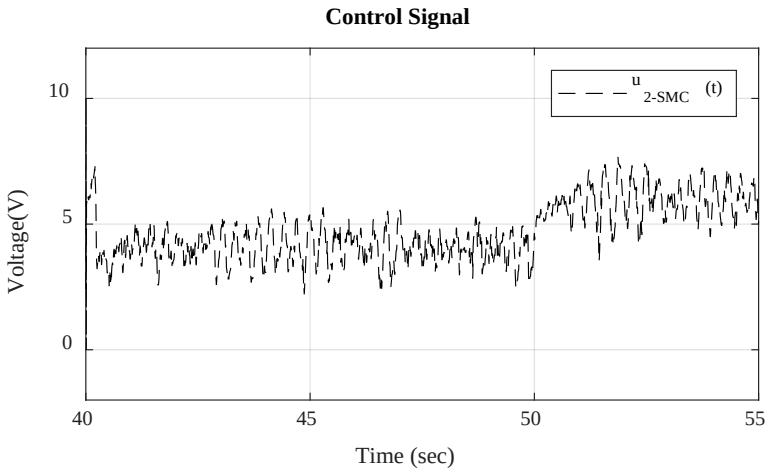


Figure 5.28 The control signal of 2-SMC in disturbance rejection t=50 sec

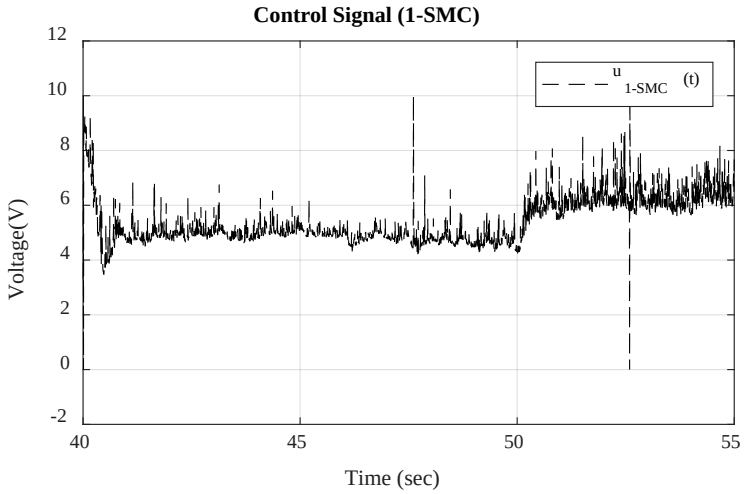


Figure 5.29 The control signal of 1-SMC in disturbance rejection

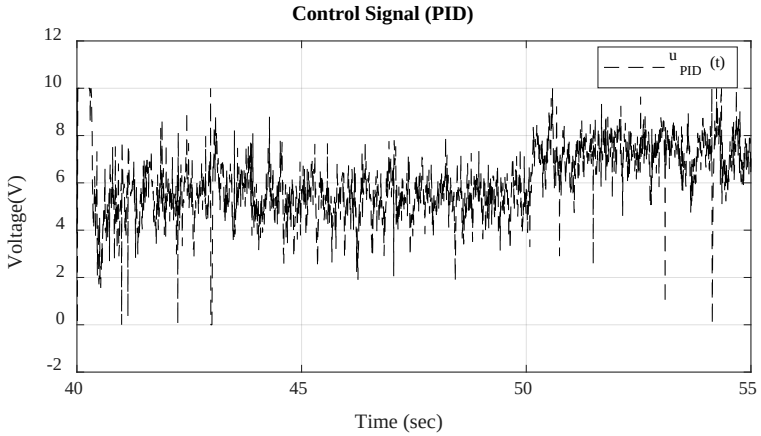


Figure 5.30 The control signal of PID in disturbance rejection

Variations of the switching control, $u_{sw}(t)$ during the experiment are presented in Figure 5.31 for the second-order SMC and Figure 5.32 for the first-order SMC system. The results verify that more variations in the control input are obtained from the first-order SMC system and these cause more control activity.

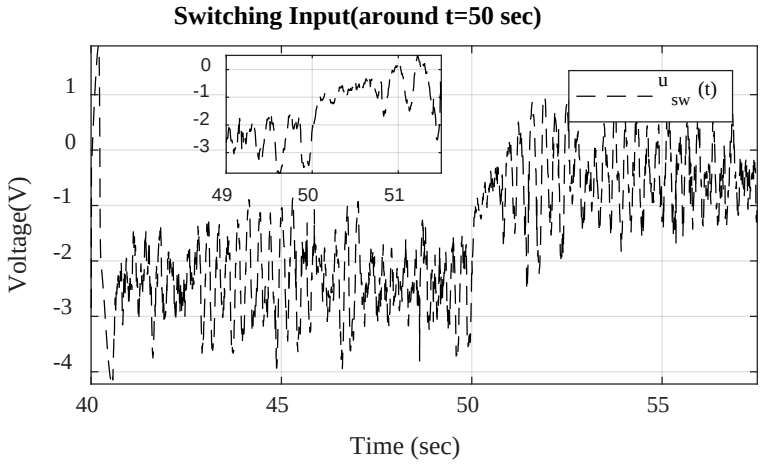


Figure 5.31 The switching signal for 2-SMC around the disturbance

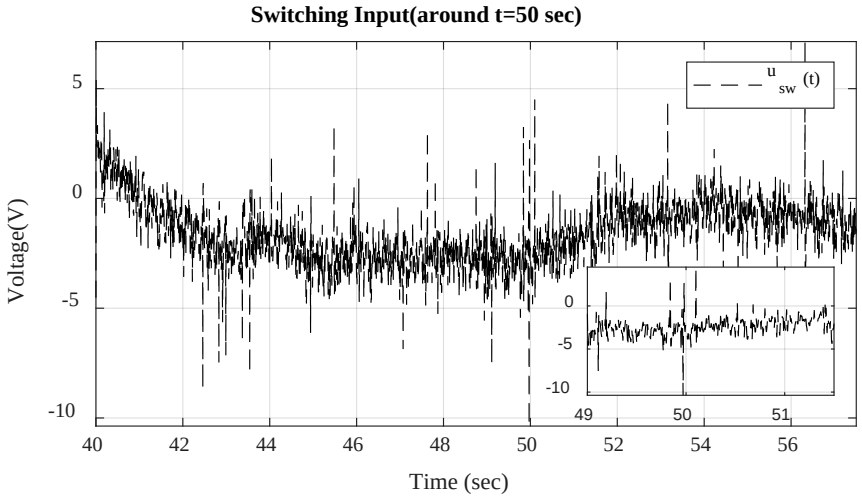


Figure 5.32 The switching signal for the 1-SMC around t=50sec

Figure 5.33 indicates that the reference tracking error performance is obtained with a good level of precision; however, the results obtained with second-order SMC are better than the first-order SMC.

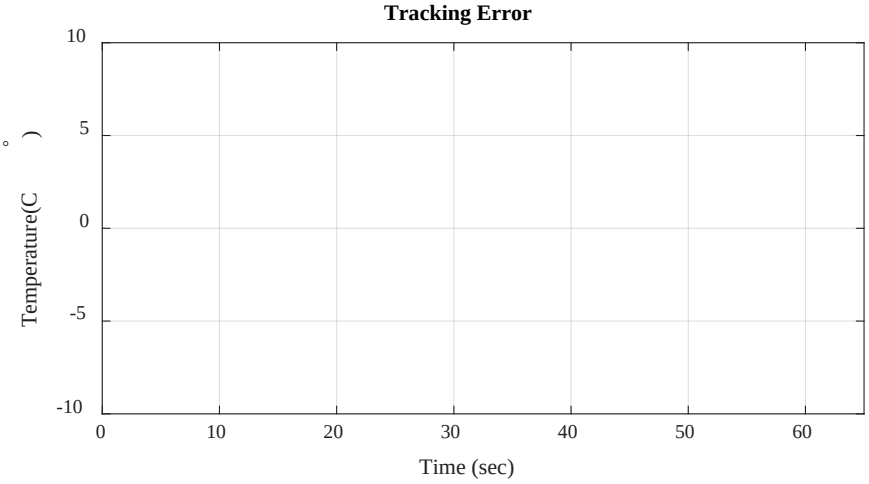


Figure 5.33 The tracking error with SP based second-order SMC

The phase plane of the 2-SMC is demonstrated in Figure 5.34, wherein the figures present the sliding function versus its first time derivative. From the theoretical point of view, it is expected that the sliding function converge to zero as much as the control input matches the uncertainties, disturbances, and measurement noise. However, unmatched uncertainties may cause oscillations around zero.

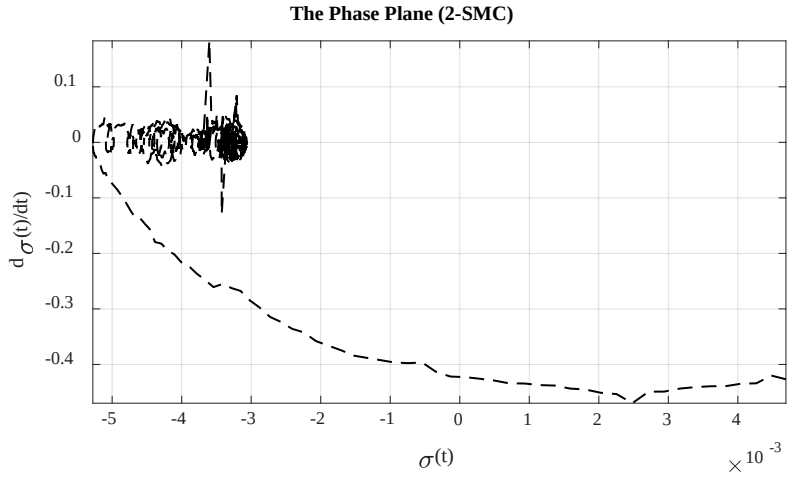


Figure 5.34 The phase plane of second-order SMC in transient regime

The main objective of the 1-SMC is to force the system trajectory to zero in a finite time, $e(t) = \dot{e}(t) = 0$ is the desired value to the system trajectory at that point. The phase plane obtained that is obtained with the error function versus its derivative is illustrated in Figure 5.35.

It is to be noted that the used scale for the figure of second order SMC is different from first order SMC, that's why the sliding function $\sigma(t)$ circulate around $-3e-3$.

Yet another inevitable source of uncertainty is measurement noise. Further, during the experiments there have been random peak magnitudes on the sensor output acts as measurement noise, which depend upon the experimental

environment. In such a case, controller must be able to eliminate the effect of noise in the closed loop to an adequate level. Again, the controller illustrates satisfactory performance by handling the uncertainty in the model parameters.

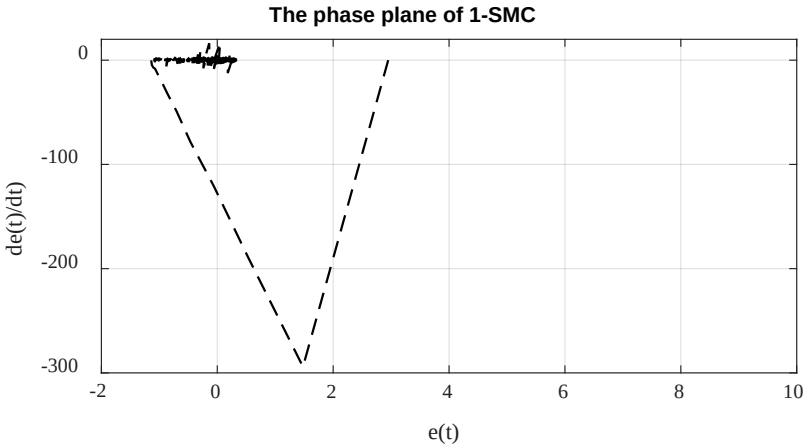


Figure 5.35 The phase plane of the SP based first-order SMC

5.3.1. Performance Evaluations

Although the system subjects to aforementioned disturbances and uncertainties, the present controller demonstrate satisfactory performance in terms of tracking precision. The present control techniques have demonstrated to be robust and precise, as expected theoretically, also in practice. A number of performance metrics tabulates this result.

The performance specifications of the second-order SMC are much better than that of the first-order SMC system such that the smaller rise time, settling time and the smaller output deviations in magnitude are reported from the elaborated SP second-order SMC system. The overshoot, which is obtained from the first-order SMC, is relatively larger than the SP based second-order SMC technique.

The present control techniques has demonstrated to be robust and precise, as expected theoretically, also in practice. A number of performance metrics tabulates this result.

It is to be stated that the convergence of the SP based first-order SMC is slower than the second-order SMC. The 2-SMC input converges faster and the variations are smaller in steady-state conditions. Further, the control input of the first-order SMC has larger variations in magnitude at the transient and steady-state conditions. The control parameters are given in Table 5.6 for the first-order SMC and Table 5.7, for the second-order SMC, respectively.

Table 5.6 Control parameters for SP based first-order SMC

Parameters	k_p	k_i	k_d	ε	k_s
Value	8.1285	4.0782	0.7350	2	15

Table 5.7 Control parameters for SP based second-order SMC

Parameters	k_p	k_i	k_d	δ	ε	k_s
Value	0.7585	0.6475	0.0850	20.3213	0.1	3

Note that the choice of the parameters used in experimental applications gives satisfactorily performance although the system has different effects such as hysteresis, uncertainties, and disturbances. The controller parameters of SMC are tuned heuristically. It is to be noted that best performance results are reported in this research. At this point, when the sliding surface parameter k_p, k_i, k_d of first-order SMC are chosen same with second-order SMC, the tracking precision as well as disturbance rejection performance of the firs-order SMC technique is worse than the presented results. In other words, although the controller generates more applicable control signal, the controller may lead performance degradation.

Some quantitative performance indicators of the temperature profile tracking quality based on the time domain analysis are presented in Table 5.8. Further, control signal performances are presented in Table 5.9.

Table 5.8 Measured performances indices of robust controllers

Criterion	First-order SMC	Second-order SMC
IAE	6.4633	3.9663
ITAE	313.0357	171.7432
ITSE	140.0986	87.5194
MAE	0.0808	0.0779

The SOSMC scheme is observed as the best performing approach in terms of IAE, ISE, ISCI measures.

Moreover, Table 5.8 reveals that the SP based second-order SMC technique provides a better performance than the SP based first-order SMC in terms of IAE, ITAE, ITSE, and MAE. However, it should be pointed out that the values at the higher temperatures are larger since the system is more vulnerable at large temperatures.

The applicability of the control signal is measured by total variance, and ISCI index. It is to be noted that the control input variation is measured a little bit more with SP based first-order sliding mode control technique. The control signal variation, TV was measured 12.6724 with SP based SMC whereas the control signal variation with SP based second-order SMC produces 10.8249. Further, according to the ISCI, SP based second-order SMC gives better results than first-order SMC.

Table 5.9 Measured control signals for SMCs

Criterion	First-order SMC	Second-order SMC
ISCI	1.3473	1.0299
Total Variance	12.6724	10.8249

As the main contribution of the present research, we elaborate the experimental realization of the second-order SMC for an industrial air heating

process with time delay. The control strategy is modified for enhancing transient regime and tracking capability of the closed loop system. Meanwhile, the control algorithm produces smooth control signals that prevents the untimely attrition and extend the service of life of actuators.

It is to be noted that the output signal deviation gives an idea about how the produced control signal matches the uncertainties and reject the disturbances. The second-order SMC technique performs better reference tracking with small temperature deviations. It is to be stated that the uncertainties are better matched, the disturbances are fully rejected, and the noise is surpassed by produced control input.

According to the results, the proposed SP based second-order SMC technique enable the system follow the reference trajectory comfortable in the presence of external disturbances. Further, the severity of the control performance degradation is the minimum for SP based second-order SMC, followed by first-order SMC.

It is worth mentioning that first-order SMC demonstrates considerable chattering in the implementation, while small chattering appears in case of second-order SMC. Thus, it is concluded that second-order SMC is more useful for the lifetime of the actuator because it prevents the possible harmful effects of chattering phenomenon.

The robustness is a highly desirable performance demand in many control applications since real systems always necessitate a robust control to operate in different modes accurately.

The control technique demonstrates the advantages of Smith predictor to cope with time delays and the sliding mode control for dealing with uncertainties as well as disturbances.

Table 5.10 Control parameters effect

	k_p	k_i	k_d	ε	k_s
Effect on	Transient Response, Sliding motion	Settling Time, Steady state, Sliding motion	Transient Response, Rising Time, Sliding motion	Chattering	Chattering, Robustness

Furthermore, the elaborated control scheme demonstrate satisfactory control performance even if there exists model uncertainties, disturbances, and measurement noise. According to the results, it is to be noted that the present control scheme demonstrates a balanced trade-offs between transient performance and actuator preservation while guarantying the robustness of the closed loop control system.

According to the control signals, both control signals present chattering effect. However, the sliding motion is more accurate with SOSMC technique.

As stated previously, various SP based design options have been offered to handle the delay phenomenon. In this study, a small-scale version of an industrial air heater systems is employed. The motivation of the research is to design a second-order SMC scheme considering the real-life operational conditions of an air heater process. Performance evaluation is illustrated through a set of performance measures.

The experimental tests with tabulated time domain measures showed that performance enhancement of the closed-loop system enables more robust behaviour, better disturbance rejection capability, and good noise suppression ability while less energy consumption in comparison with the first order SMC based SP scheme. It is also showed that the present controller provides better time domain specifications compared with the classical SMC in both tracking and disturbance rejection.

Table 5.11 Control parameters effects for SP based second-order SMC

	k_p	k_i	k_d	δ	ε	k_s
Effect on	Transient Response, Sliding motion on the surface	Settling Time, Steady state, Sliding motion	Transient Response Rising Time, Sliding motion	Reaching Phase, Robustness	Chattering	Chattering, Robustness

The controller shows improved robustness performance by means of second-order SMC technique while reducing the chattering phenomenon.

As the main contribution of this chapter, we elaborate the experimental realization of the SOSMC for an industrial air heating process with time delay. The control strategy is modified for enhancing transient regime and tracking capability of the closed loop system. Meanwhile, the control algorithm produces smooth control signals that prevents the untimely attrition and extend the service of life of actuators.

The present control strategy demonstrate the advantages of Smith predictor to cope with time delays and the sliding mode control for dealing with uncertainties as well as disturbances.

The applicability of the control signal is measured by total variance, and ISCI index. It is to be noted that the control input variation is measured a little bit more with SP based first order sliding mode control technique. The control signal variation, TV was measured 6.923 with SP based SMC whereas the control signal variation with SP based SOSMC produces 6.274. Further, according to the ISCI, the best performance is obtained with SOSMC.

According to the results, it is to be noted that the present control scheme demonstrates a balanced trade-offs between transient performance and actuator preservation while guarantying the robustness of the closed loop control system.

The robustness is a highly desirable performance demand in many control scenarios since real problem always necessitate a robust control system. According to the results, the proposed controller follow the reference trajectory comfortably in the presence of varying load disturbances. Further, the severity of the control performance degradation is the minimum for SOSMC, followed by conventional classical SMC scheme.

Yet another inevitable source of uncertainty is measurement noise. Further, during the experiments there have been random peak magnitudes on the sensor output acts as measurement noise, which depend upon the experimental environment. In such a case, controller must be able to eliminate the effect of noise in the closed loop to an adequate level. Again, the controller illustrates satisfactory performance by handling the uncertainty in the model parameters.

A number of experimental tests are conducted. The sensitivity of control strategies to uncertainties and noise is also explored. Both control signals present chattering effect. However, the sliding motion is more accurate with SOSMC technique. The SOSMC scheme is observed as the best performing approach in terms of IAE, ISE, ISCI measures.

5.5. Experimental Applications of Gain-Scheduled Controllers

Simulations and experimental results of gain-scheduled controllers are provided to demonstrate the performance of the proposed controller in the present section. Although the elaborated system has been studied in simulations, the real-time optimal control of the heating process is a tedious task. The challenges arising from the variations of heat flow, uncertainties of heating dynamics, the implicit process uncertainties, measurement and power constraints may impair the effectiveness of control strategies.

The defuzzifier parameters, denoted by y_{is}, are chosen between [0,4] for K_{p2} and K_i, [0-2] for, K_p and K_d, which are determined in the experiments. The corresponding fuzzy surfaces for K_p, K_i and K_d,and K_{p2} are given in Figure 5.36 and

Figure 5.37. The MFs are introduced in Figure 5.38 and Figure 5.39. Further, the output singletons are depicted in Figure 5.40.

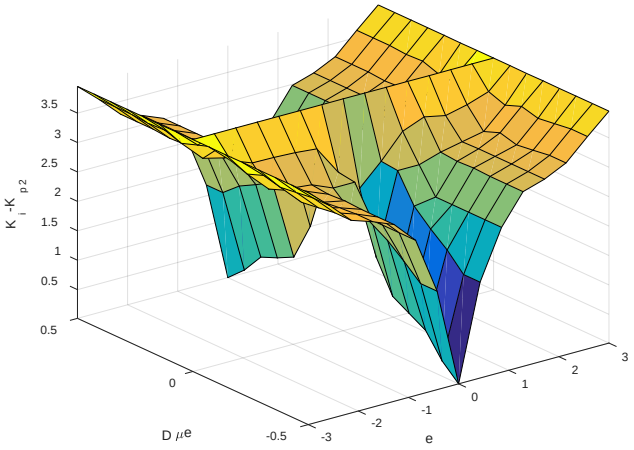


Figure 5.36 Membership functions for K_i, and K_{p2}

The rule table of the proposed fuzzy control scheme is given in Table 5.12 and Table 5.13.

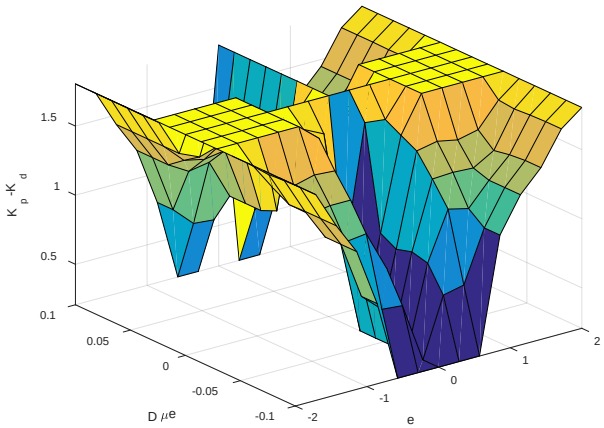


Figure 5.37 Membership functions for K_p and K_d

Table 5.12 Fuzzy Rules for K_i, K_{p2}

K_i, K_{p2}		$e(k)$						
		NH	**NM**	**NL**	**Z**	**PL**	**PM**	**PH**
$D^1e(k)$	**NH**	PH	PH	PH	PH	PH	PH	PH
	NM	PL	PH	PH	PH	PH	PH	PL
	NL	PL	PL	PH	PM	PH	PL	PL
	Z	PL	PL	PL	PL	PL	PL	PL
	PL	PL	PL	PH	PM	PH	PL	PL
	PM	PL	PH	PH	PH	PH	PH	PL
	PH	PH	PH	PH	PH	PH	PH	PH

Table 5.13 Fuzzy Rules for K_d, K_p

K_p, K_d		$e(k)$						
		NH	**NM**	**NL**	**Z**	**PL**	**PM**	**PH**
$D^1e(k)$	**NH**	PH	PM	PL	Z	PL	PM	PH
	NM	PH	PM	PM	PL	PM	PM	PH
	NL	PH	PH	PM	PM	PM	PH	PH
	Z	PH	PH	PH	PM	PH	PH	PH
	PL	PH	PH	PM	PM	PM	PH	PH
	PM	PH	PM	PM	PL	PM	PM	PH
	PH	PH	PM	PL	Z	PL	PM	PH

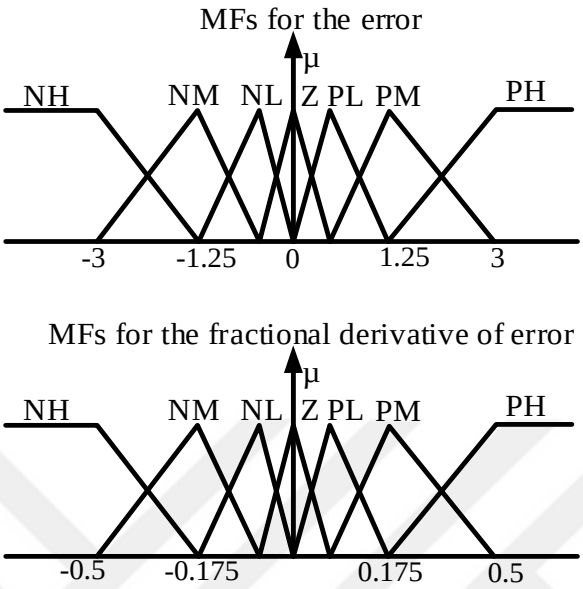


Figure 5.38 Structure of the tuned input MFs

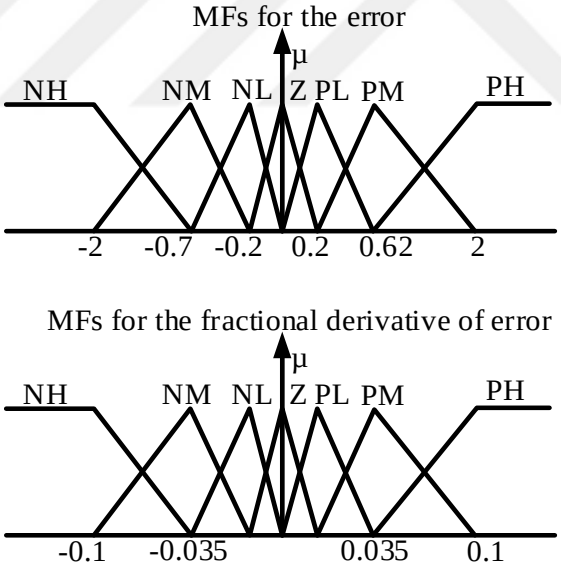


Figure 5.39 Structure of the tuned input MFs

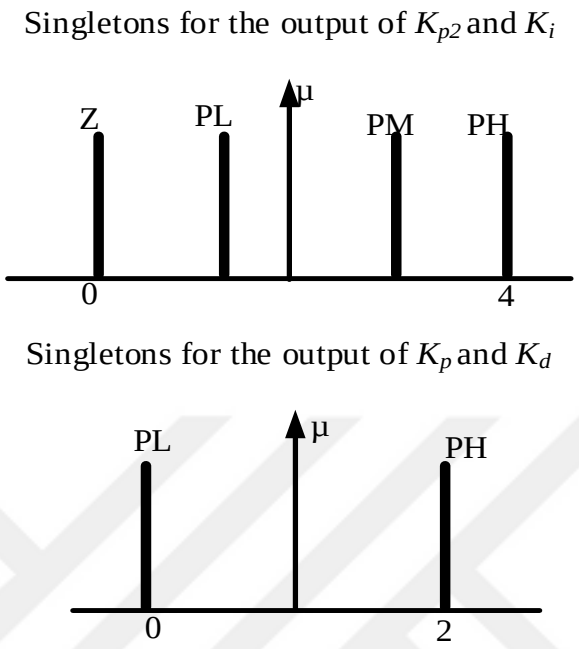


Figure 5.40 Singletons for the outputs of MFs

Concerning the tuning of the control parameters, after many experiments, the value of control parameters bound should be set as $\lambda \in [0.652 - 1.1]$, $\mu \in [0.7012 - 0.99]$, $\alpha \in [0.1 - 0.6]$, $K_{p\,max} \in [2 - 3.5]$, $K_{p\,min} \in [0.2 - 1]$, $K_{i\,max} \in [2.5 - 3.75]$, $K_{i\ min} \in [0.3 - 2]$, $K_{p2\,max} \in [1 - 2]$, $K_{p2\,min} \in [0.05 - 0.75]$, $K_{d\,max} \in [0.2 - 0.6]$, $K_{d\,min} \in [0.001 - 0.1]$ to ensure the convergence.

The selection process is achieved by using normalized geometric distribution, which needs less execution time than other selection techniques. After the selection, the crossover operation is performed by arithmetic crossover. Then, a uniform mutation operator is applied. In the present work, the population size, crossover rate, the maximum iteration number are chosen as 100, 0.85, and 100 respectively. These values were determined after several trials of the GA using the specified parameters. It should be noted that increasing the population size and number of iterations might provide further enhancements; however, due to a

number of constraints, the processor may fail to finish the calculations within the sampling time in experimental applications. Further, the selection operator and the crossover operator involved in the GA ameliorate the convergence speed while mutation operator whose responsibility is to foster diverse solution in the search space, become ineffective due to high selection pressure caused by selection operator and the algorithm is trapped into local optima (Kumar and Kumar, 2017). The performance of GA strictly depends on a number of user-defined parameters e.g. population size, mutation rate, crossover probability, and the computer (Sharma et al., 2014). In this line of thought, GA is used to find the optimal set of fuzzy parameters as well as the fractional mathematical operators for the proposed controller. GA progressively minimizes the cost function over the iterations while finding the optimal set of controller parameters (Tenreiro machado, 2010; Oh et al., 2011; Astudillo et al., 2013; Sharma et al., 2016; Kumar and Kumar, 2017). The search process is iterated until a desired optimal solution is achieved. Then finally, the process terminates if the value of the objective function does not change appreciably over consecutive iterations. The tuned parameters are presented in Table 5.14. Moreover, time domain performances of other controller structures are compared and the effectiveness of the different controllers are evaluated (Das et al., 2012).

Table 5.14 Tuned controller gains for fractional fuzzy PI-PD

$\boldsymbol{\lambda}$	$\boldsymbol{\mu}$	$\boldsymbol{\alpha}$	$K_{p\,max}$ -$K_{p\,min}$	$K_{i\,max}$ - $K_{i\,min}$	$K_{p2\,max}$ - $K_{p2\,min}$	$K_{d\,max}$- $K_{d\,min}$
0.9118	0.8826	0.2226	2.55– .651	3.125-1.05	1.788-.216	0.53– 0.05

Selecting appropriate GA parameters, which completely depends on the problem, still is a research avenue which needs further efforts and new suggestions (Kaya and Nalbantoğlu, 2016). However, a guideline for selecting GA parameters is presented in (Grefenstette, 1986). The design process requires executing the GA

several times, experimenting with different values and selecting the ones that lead to the smaller *J*, for the selection of the appropriate control parameters. For instance, the GA is repeated 30 times and then the best result, which leads to the smaller *J*, is taken for the optimum set of values for the controller parameters.

The control algorithm is implemented using Matlab/Simulink® software on a computer running in Windows environment. The aforementioned tool needs MATLAB/Simulink®, Control Toolbox, Real Time Workshop® (RTW), Real Time Windows Target® (RTWT) and a compiler in order to get machine code for real-time application. The schematic diagram of real-time application is depicted in Figure 5.41.

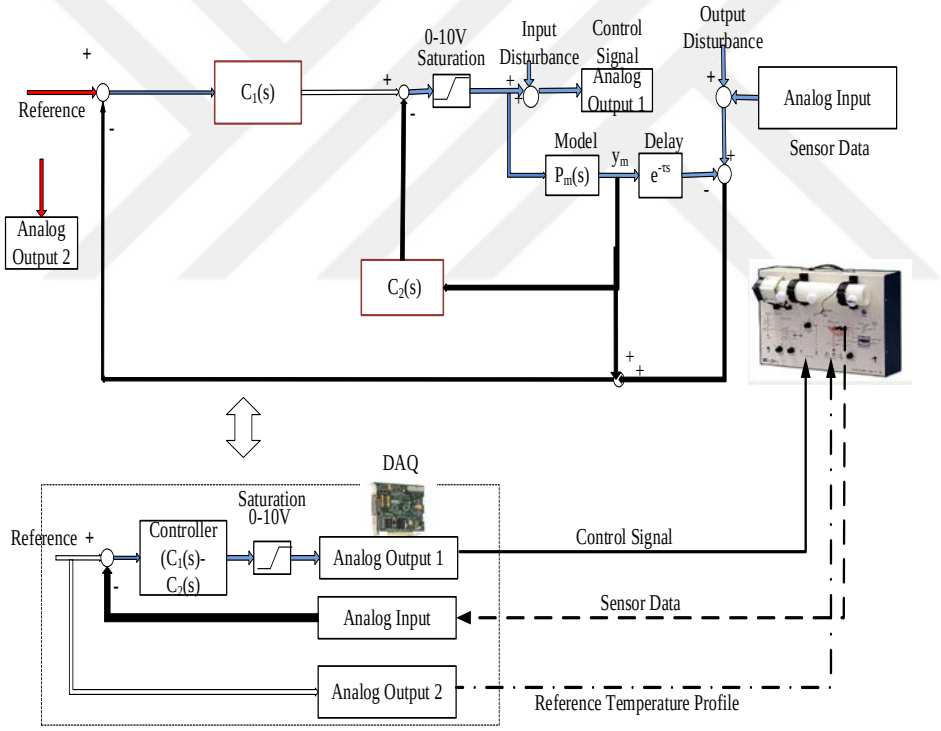


Figure 5.41 Real-time experimental flowchart

These aforementioned tools are necessary to obtain the executable file from the control law model built in MATLAB/Simulink®. After designing the controller, C++ source program is obtained by Real-Time Workshop. Then, in order to get an executable program, the C++ compiler compiles and links the code by Real-Time Workshop. Real-Time Windows Target interfaces with the hardware device through I/O board by communicating with the executable program running as a controller to control bidirectional data flow between controller and real-system via I/O board. One of the main advantages of the application is that the control designer can use the graphical tools in Simulink® to achieve process-oriented outcome without having to be concerned with the communication mechanism to and from the real control system.

The implementation problem can be investigated in two folds; software and hardware implementation. The present study mainly focuses on the software implementation issues. A number of tools have been developed for the real-time software implementation of fractional order controllers such as CRONE (Oustaloup et al., 2000), FOMCON (Tepljakov et al., 2011; Tepljakov, 2017), noninteger (Valério and Costa, 2004). The aforementioned tools are used for simulation and practical implementation of fractional order operators. In these methods, a fractional order operator or the fractional-order transfer function are replaced by an integer-order transfer functions that have the same behaviour as the fractional-order. A number of methods are employed to obtain integer approximations of fractional operators (Mishra et al., 2015). However, Oustaloup's band-limited frequency domain rational approximation technique is used in this study (Li et al., 2016). The Oustaloup filter provides a very good fitting to the fractional-order elements within a selected frequency band (ω_l , ω_h) and order *N*. In the present study, each fractional order differentiator and integrator λ, μ, α inside the optimization procedure is constantly rationalized with the Oustaloup's rational approximation within the chosen frequency and *N* (Arya, 2017).

However, the proposed controller demonstrate satisfactory performance for parameter changes in particular variable transport-delay, randomly varying load disturbances, as well as model uncertainties.

5.5.1. Simulations

The transient performance of simulations is demonstrated in Figure 5.42, where a constant delay is applied to the system.

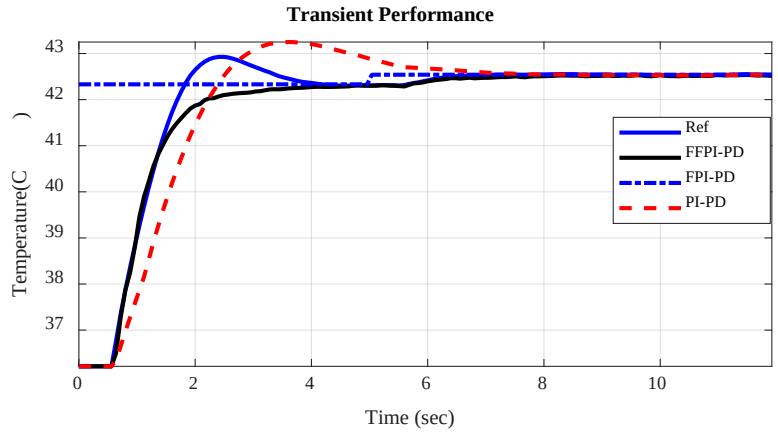


Figure 5.42 Initial transient performance of simulated system

The corresponding control signal in transient regime is demonstrated in Figure 5.43.

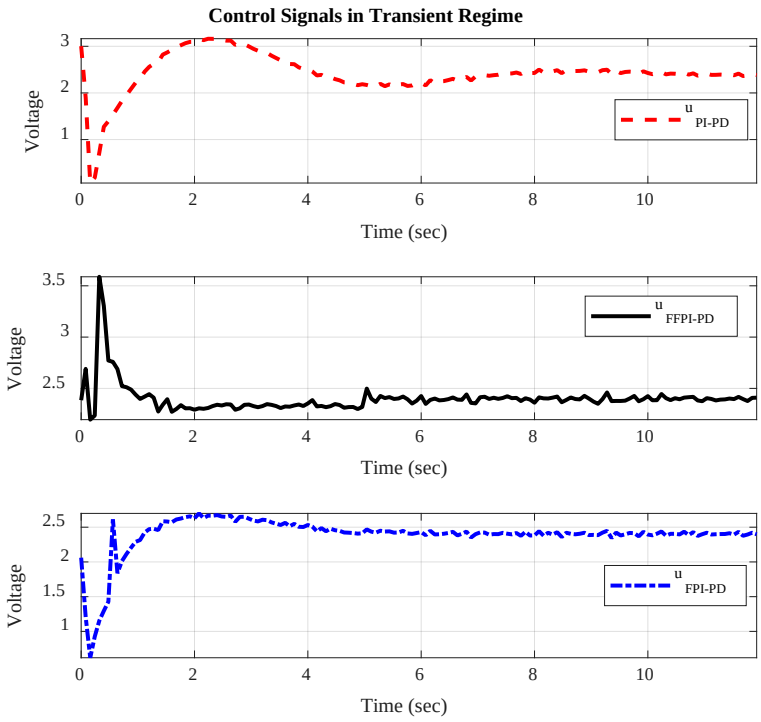


Figure 5.43 Control signals of gain-scheduled controllers in transient regime

The tracking capability of each control technique is showed in Figure 5.44, wherein the tracking precision of the FFPI-PD control performs best results. Moreover, the control signals during the tracking performance are demonstrated in Figure 5.45.

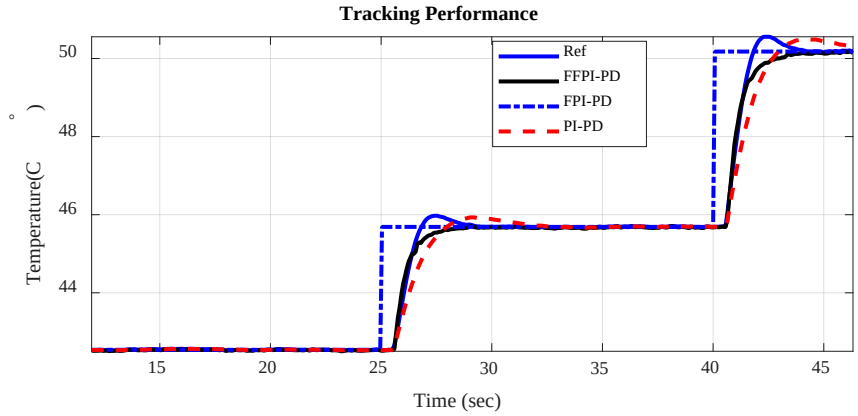


Figure 5.44 Tracking performance of simulated system

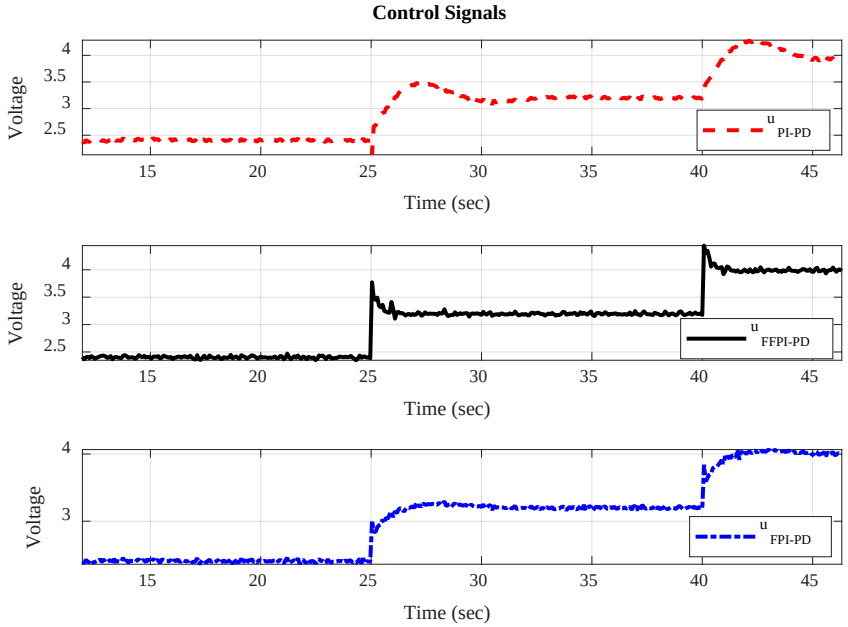


Figure 5.45 Control signals during the tracking of predefined temperature profile

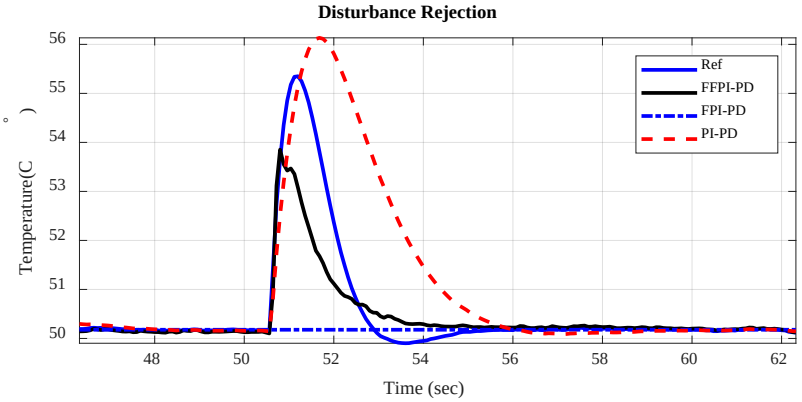


Figure 5.46 Disturbance rejection performance in simulations

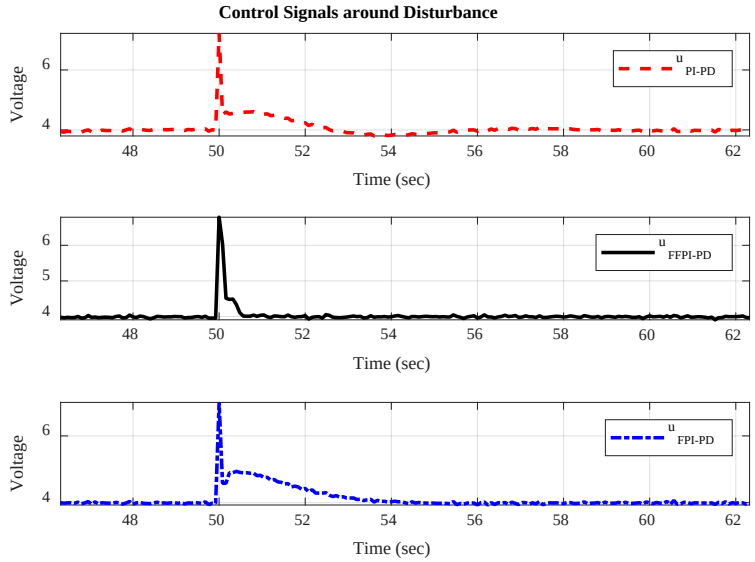


Figure 5.47 Control signals of gain-scheduled controllers around disturbance

The simulation results of tracking capability under noise, uncertainties, and disturbances obtained with the elaborated control schemes are given in Figure 5.48, where it is seen that the trajectory tracking is obtained with a very good level of precision. It is to be noted that in the presence of low disturbance, all control

schemes show nearly the same control performance. However, PI-PD control performance immediately degrades in the presence of high levels of disturbance.

One of the results is presented in Figure 5.48, wherein a variable time delay is applied to the system in order to test the system performance in the presence of delay variations. Furthermore, the delay, which is assumed time varying in this scenario, is added to the system by variable time delay. The parameters of the model part in SP structure are changed by 20%± from their original identified values in order to test the system performance against model uncertainties as well as parameter changes. Further, an external step disturbance approximately +8 ^{o}C is applied at about 50th second. Yet another performance demand expected from a controller is the noise rejection capabilities. Further, noise suppression capability is also tested under a band-limited white noise with 0.0025 noise power (Mishra et al., 2015).

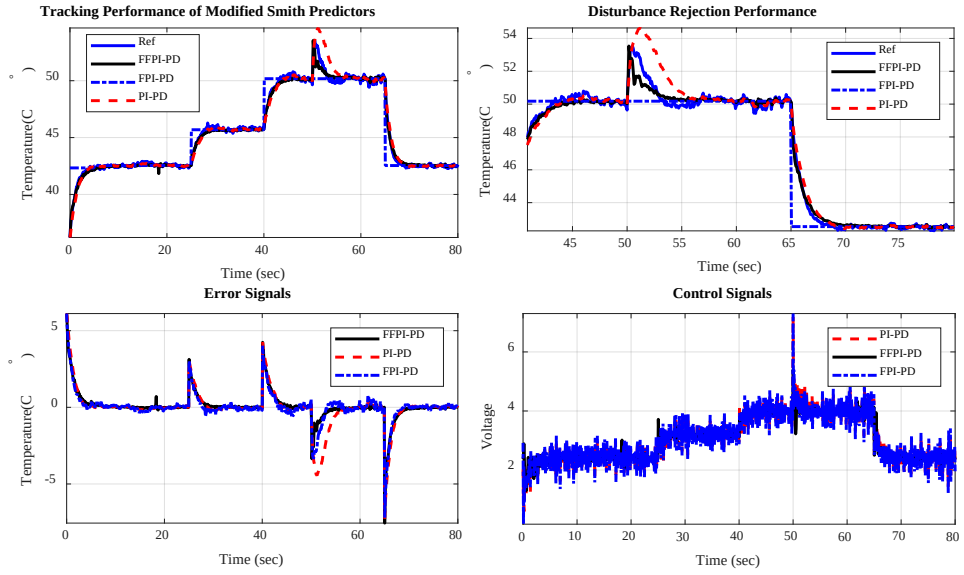


Figure 5.48 Performance of simulated system in the presence of model uncertainties (20 %+), variable time-delay (maximum delay value is 1 second), noise (with 0.03 noise power), and disturbances (+5 ^{o}C)

According to the simulation results, the present control outperforms the conventional PI-PD and the integer order fuzzy logic control schemes. From the produced error curves, it is difficult to distinguish that the proposed control scheme performs better than other two strategies, however, it can be observed from the performance indices of experimental results given in Table 5.15.

5.5.2. Experimental Applications and Results

Experimental application is performed to demonstrate effectiveness of the proposed controller. Further, the robustness is a crucial performance demand in many control applications since real problem always necessitate a controller that alleviates various uncertainties. According to the real-time experimental application results, the proposed controller follow the reference trajectory comfortably in the presence of load disturbances and parameter changes. The parameters of the SP model is again increased by 10%. The real-time control performance is relatively lower than that those of the simulation; this may be due to the overheating phenomenon in the air duct, and ambient temperature of the laboratory. Further, it is difficult to obtain completely smooth temperature profile because of the internal/external disturbances.

An experimental application performance is demonstrated in Figure 5.49. It is to be noted that even though the variations are small, the model parameter changes during the experiment. More clearly, the increased airflow reduces the process gain as well as the process time-delay.

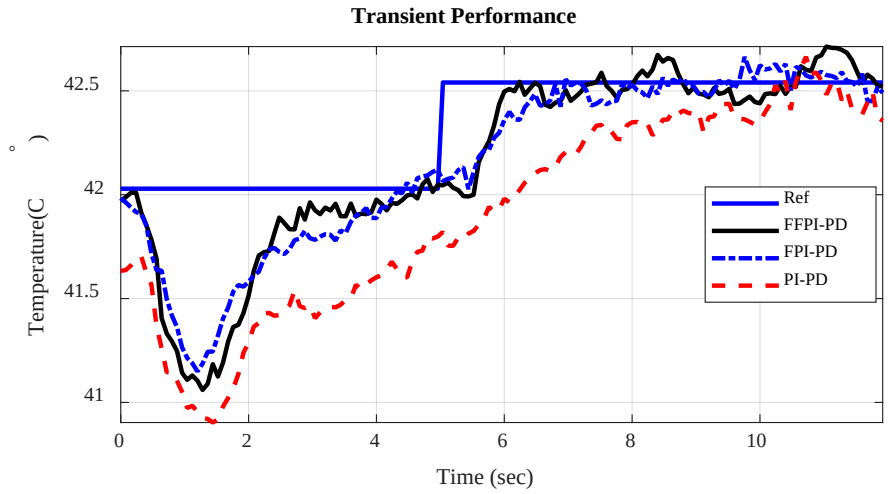


Figure 5.49 Real-time experimental performance with model uncertainties

The results show that the convergence during the transient phase is faster with the fractional fuzzy than that with the integer order fuzzy technique. Further, the severity of the control performance degradation is the minimum for fractional fuzzy PI-PD, followed by integer fuzzy and the conventional PI-PD control scheme. The corresponding control signals in the transient performance are highlighted in Figure 5.50.

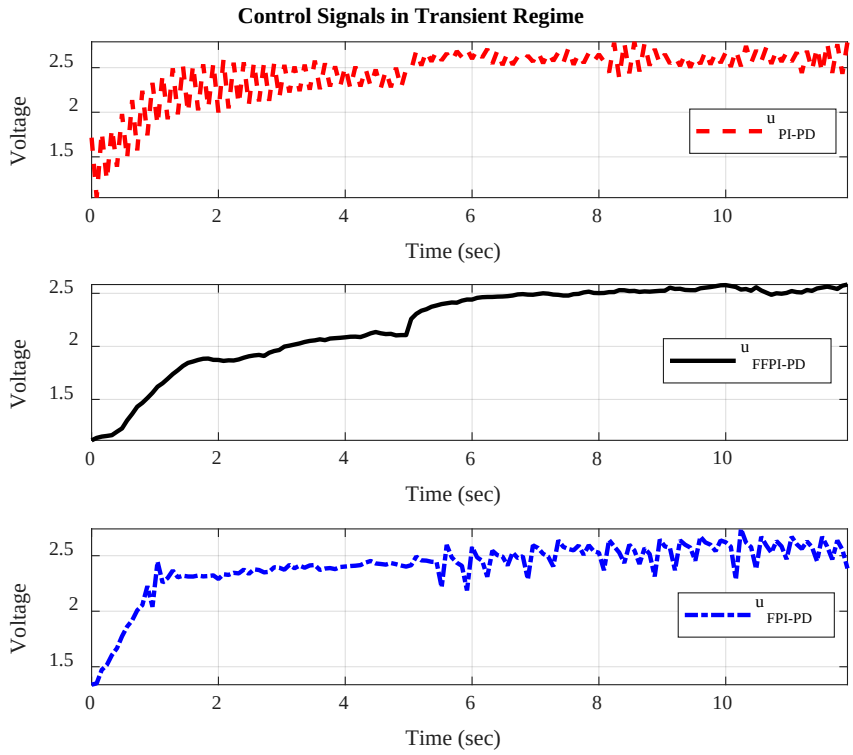


Figure 5.50 Control signals in transient regime

The tracking performance of the SP based gain-scheduled controllers are demonstrated in Figure 5.51, wherein FFPI-PD controller achieves the best performance.

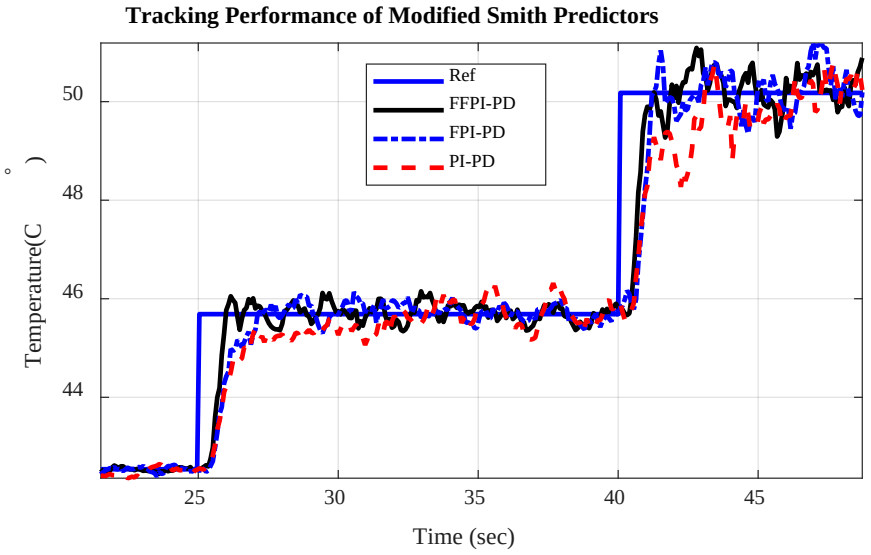


Figure 5.51 Tracking performance of gain-scheduled controllers

In the tracking performance, the experimental results show that the proposed FFPI-PD controller can achieve fast response time and good tracking performance under variable disturbances. Further, the severity of performance degradation is the minimum for FFPI-PD, followed by integer FPI-PD and conventional PI-PD control scheme.

From the control input figures, Figure 5.52, it can be concluded that the rapid changes and oscillations for the fractional fuzzy control are less than that with conventional PI-PD and the integer fuzzy PI-PD control scheme. This is critical especially for practical implementation since the rapid changes in control signal may reduce the lifetime of the actuators by damaging its components.

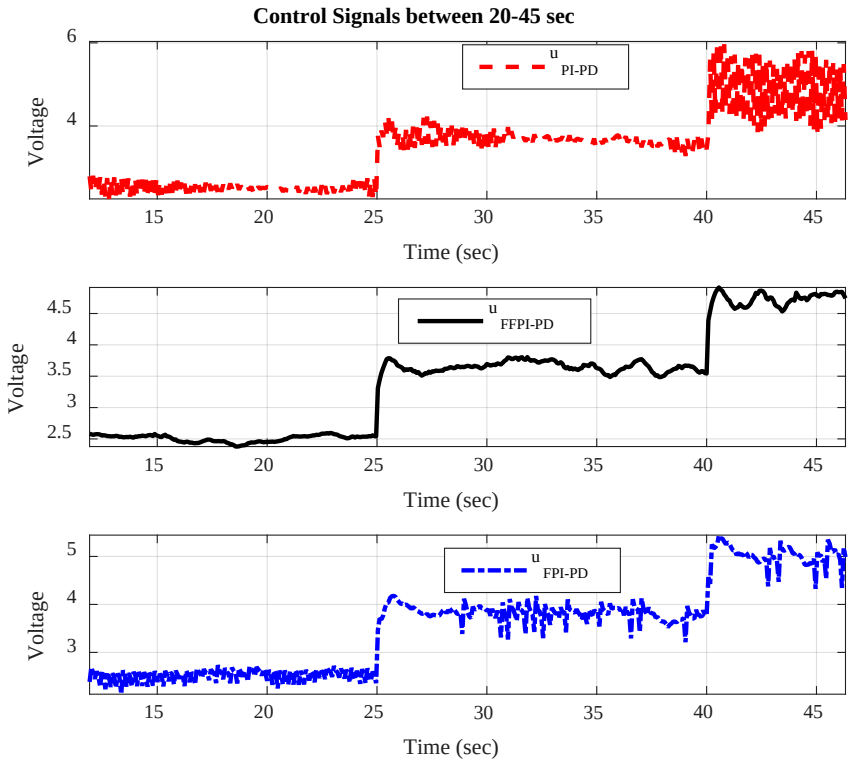


Figure 5.52 Control signals during the tracking performance

Figure 5.53 shows the robustness capability of the controller in the real-time test. An external disturbance is introduced into the system by applying disturbance signal from the computer. In the present study, after the reference temperature profile is settled, a disturbance approximately -5 ^{o}C is injected at the 50th second from the computer. Figure 5.53 demonstrates the disturbance rejection performance of the control scheme. The disturbance rejection performance reveals that FFPI-PD controlled system re-settles to its set point with less oscillatory transients than that of the FPI-PD control. The control signals of each control technique are given in Figure 5.54.

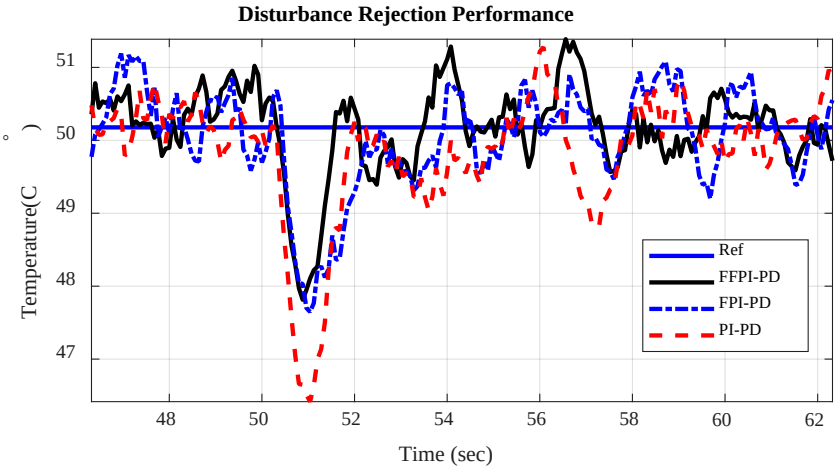


Figure 5.53 Disturbance rejection performance of the controllers

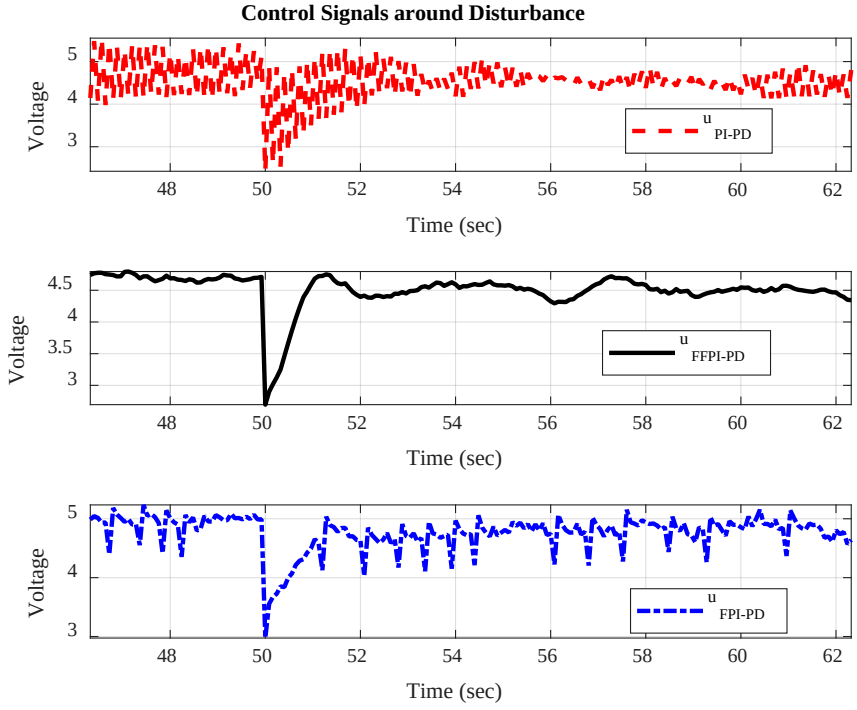


Figure 5.54 Control signals for the real-system subject to external disturbance

The tracking error is given in Figure 5.55. According to the results, the proposed control scheme, which combines the advantages of conventional controllers in steady state and the efficiency of fractional order controllers in the transient state, verify the effective performance.

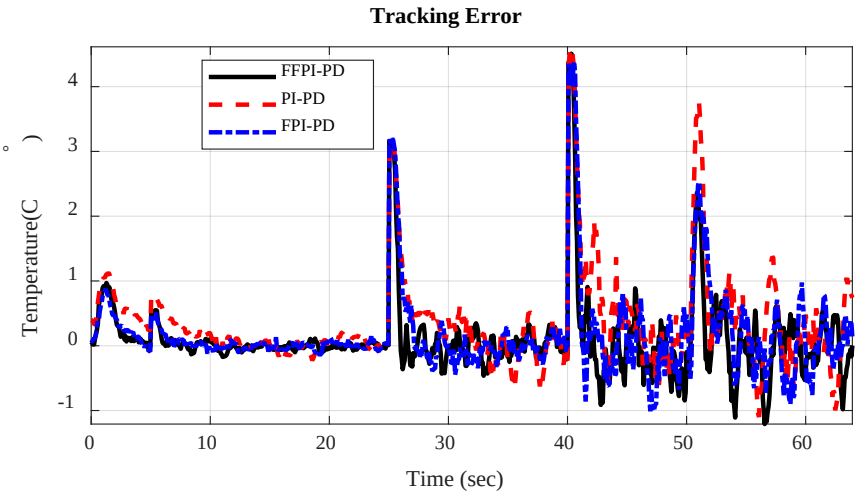


Figure 5.55 Tracking error of SP based gain-scheduled controllers

Finally, it is concluded that a number of experiments have been conducted to present the better tracking capabilities by a more cost-effective control input.

5.5.3. Performance Evaluations

The performance metrics of elaborated controllers are presented in Table 5.15 and the produced control signal is given in Table 5.16 such that the numerical results of the present control system provide better performance measure. From the tabulated results in Table 5.15, it can be concluded, the noise elimination and the energy consumption of the classical PI-PD control scheme are the worst. The performance is better with fuzzy gain-scheduled PI-PD and the best with the fractional fuzzy PI-PD control strategy. The results show that the elaborated FFPI-PD controller outperforms than other methods in terms of maximum absolute error,

integral of absolute error, total variance of control signal etc. and offer more energy efficient and robust behaviour especially in uncertain environment and unknown load disturbance conditions.

Table 5.15 Measured performances of the elaborated controllers

	Optimized Performance Measures					
	IAE	MAE	ISE	ITSE	EV	Cost Function (J)
PI-PD	3.1087	2.3646	1.287	5.485	0.4990	1.5443
FPI-PD	3.0684	2.1904	1.229	5.187	0.4592	0.0249
FFPI-PD	3.0198	1.9346	1.2089	4.038	0.0490	0.0097

Although the control signals contain high-frequency variations, which are found to be dominant at high temperatures, the fractional fuzzy control scheme has a simpler control input that makes it more convenient for experimental applications. Because of failing to produce a smooth control input, the poorest results are obtained with the classical PI-PD controller in terms of the EV.

Table 5.16 Measured ISCI and control signal variances of the control schemes

Criterion	PI-PD	FPI-PD	FFPI-PD
ISCI	3.7038	3.7202	1.540
Control input variance	2.4517	1.6251	1.4019

A radar diagram for performance comparison is presented in Figure 5.56. It can be concluded that the fractional fuzzy controller performs the most accurate control, however, the magnitude of the control signal of classical PI-PD control scheme is relatively larger than the integer and fractional fuzzy PI-PD controllers.

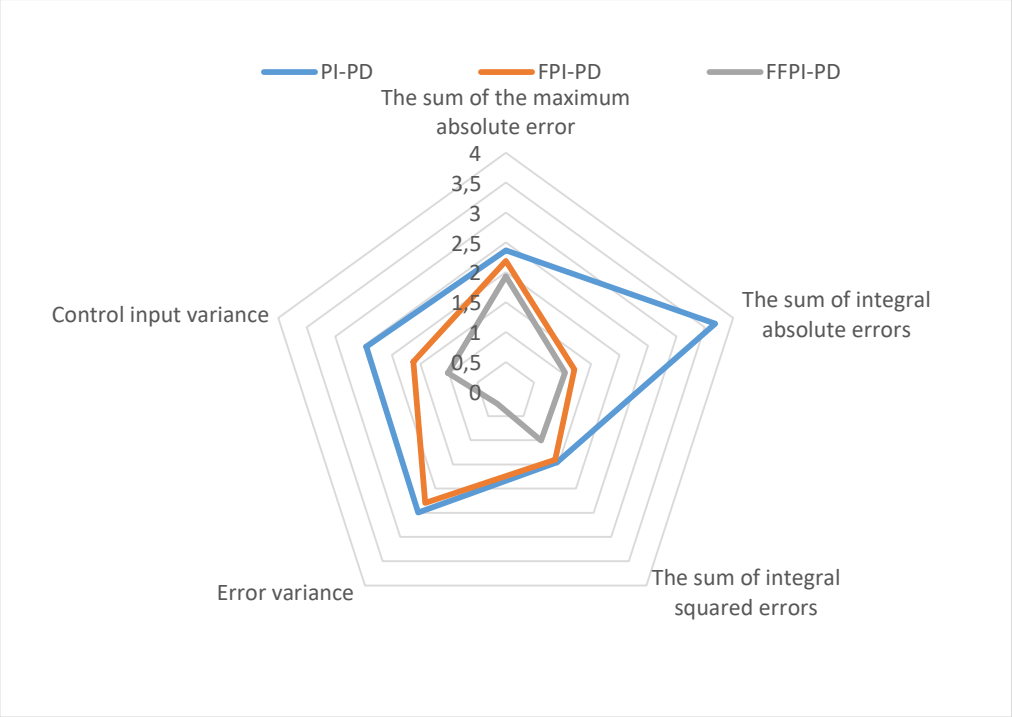


Figure 5.56 The comparison of the control strategies (normalized values)

It is worth mentioning that to design an efficient real-time control scheme for a system, which is strictly dependent on the internal/external factors, is not straightforward. From this perspective, the advantages of the present control scheme in terms of tracking, disturbance rejection, measurement noise, uncertainties, and actuator saturation can be summarized as follows.

Tracking performance: The main goal is to track a temperature reference profile in the presence of model uncertainties, measurement noise, and disturbances. This strongly motivates the study to design a flexible and effective control strategy such as FFPI-PD, which can deal with all complexities that deteriorate the performances of the closed-loop system. The elaborated control scheme improves the dynamic response of the closed-loop system by reducing the oscillation on the outlet temperature and control signal. In spite of a sudden change

in the reference trajectory, the sharp intensity has been found smaller than other controllers have. Further, as seen from the experimental results the sustained oscillations are reduced. From a qualitative point of view, less oscillation in the response also takes the system farther off the stability limit on the ‘‘safe side’’. The values of IAE and ISE has been found smaller in the FFPI-PD controller as compared to PI-PD and integer FPI-PD controllers.

Disturbance rejection: Further, it is to be noted that the heating process of a thermal system is badly affected by model uncertainties and disturbances. However, remind that the classical SP structure fails to control a linear model with parameter changes, noise, and uncertainties. Considering the above drawbacks, the proposed scheme, with the help of fractional order operators, perform better transient and steady state control under several disturbances in the system under various scenarios. More specifically, the control scheme provides much less fluctuation against the occurred disturbances relative to other controllers.

Parameter changes and uncertainties: Yet another drawback of SP is the sensitivity of the closed loop system. Thus, if an SP based control structure copes with the parameter changes and model uncertainties it can have a further advantage by demonstrating flexible and robust control behaviour. In addition, elaborated control approach provides a sufficient control performance in the presence of uncertainties. Yet another advantage of the present control is that it is not necessary to design an observer to switch between multiple local models as stressed in (Rosa and Silvestre, 2014).

Measurement noise: A further important factor in practical applications is measurement noise that should be considered carefully to investigate the performance of the designed control strategy. Toward this goal, measurement noise with different values is added to the actual process output both in simulation and experimental application, and satisfactory control performance is achieved.

Actuator saturation: It is widely known that the control signal should be in an applicable range considering the upper and lower limits of the actuator. This

constraint is considered during the real-time application, in order to avoid actuator saturation and integral wind-up problem. From the point of view of the control signal, it is to be noted that the proposed scheme necessitates a lower value of voltage in comparison with traditional control schemes. Thus, the energy consumption of the control input has been reduced.

The aforementioned properties constitute the main results of the present study. Consequently, the motivation of the paper stems from designing a fractional order fuzzy controller considering the real-life operational conditions of an air heating process.

5.5.4. Contributions

A new optimal fractional fuzzy gain-scheduled Smith Predictor (SP) is proposed to improve the performance of control systems. The stability of the closed-loop system is proved to be Bounded Input Bounded Output (BIBO) stable. The control strategy employees a fuzzy algorithm to adjust convenient controller parameters based on the system's operating conditions. Further, the proposed controller comprises self-tuning capabilities at runtime that makes it adaptive in nature. Theoretical results are simulated and experimentally applied to a temperature air heating system. The simulation results and experimental tests with tabulated time domain measures showed that performance enhancement of the closed-loop system enables more robust behaviour in the presence of uncertainties, parameter variations, and internal/external disturbances while reducing energy consumption by producing a smooth control signal in comparison with the traditional integer order SP structures. It is also shown that the present controller provides better time domain specifications compared with the classical PI-PD SP and integer fuzzy controllers for both tracking and disturbance rejection.

Recently, the integration of computational intelligent techniques in the design of fractional order control schemes is very attractive in control community. This motivates us to investigate a real-time genetic algorithm based optimal FFPI-

PD controller. In this perspective, an FFPI-PD controller which is integrated into the SP structure that is optimized through the application of a GA, in order to achieve a better control performance. Furthermore, several experimental control results are demonstrated for a thermal process with time delay. In addition to this, a performance comparison with respect to trajectory tracking, disturbance rejection as well as uncertainties is highlighted. The contributions made by the paper can be summarized as follows:

- The present study highlights a novel modified control structure with the utilization of fractional operators for integral and derivative part of FPI-PD to control an industrial air heating process with time-delay. This control scheme is proposed to perform the best features of gain-scheduling and the fractional order operators, thereby yielding a superior control performance.
- In this study, it is mathematically shown and experimentally validated that one can obtain a satisfactory control performance with less steady state error and less control energy by designing FFPI-PD controller instead of using their integer counterparts.
- To the best of the author's knowledge, no work has been presented in the literature to design of the SP based FFPI-PD control scheme in control of an industrial thermal process with the experimental application.
- The main advantage of the novel FFPI-PD controller is to efficiently counter the effects of parameter variations and external disturbances. Thus, it might also be utilized in industrial applications such as furnaces, welding, chemical process, and nuclear reactors which need accurate temperature profile tracking in the presence of parameter variations, model uncertainties as well as internal/external disturbances.

- Parallel to this, we consider different types of real experimental applications such as inserting external disturbances, varying the throttle position.
- A more quantitative approach employing optimization method is presented in the paper. Further, the results have been expressed in some quantitative terms.

The aforementioned properties constitute the main results of the present study. Consequently, the motivation of the paper stems from designing a fractional order fuzzy controller considering the real-life operational conditions of an air heating process. Bearing these ideas in mind, the present Modified fractional fuzzy based SP control scheme can be applied to any time-delayed system that contains uncertainties and parameter changes. One of the main advantages of the proposed controller is that a more robust control performance is achieved with a smoother control input.

5.6. Experimental Applications and Results of Delay–Based Control

The present section shows simulation and experimental results of delay-based control techniques.

5.6.1. Proportional Integral Delayed Control Application to the DC Motor: Simulation and Experimental Results

Direct Current (DC) motors have been employed in various industrial applications such as disk motion control, liquid pumping, and position control of robotic manipulators. Furthermore, DC motor has various advantages like easy position/speed regulation, simple structure, and low maintenance. In this regard, numerous studies are dedicated to position and velocity control of DC motors achieving set point regulation, tracking accuracy, robustness, and energy efficiency.

In DC motor control applications, angular position and velocity are the main control variables. Thus, the control designer needs the velocity measurement, which may contain a considerable amount of high-frequency noise (Aström and Wittenmark, 2011; Segovia et al., 2014). At this point, control designer generally adapt a low pass filter into the feedback system so as to reduce noise effect (Ozbek and Eker, 2017). However, this brings more computational burden, and may cause energy consumption. It is worth noting that a control technique, which does not need any filter structure may decrease the complexity of the design and realization while an acceptable control performance can be provided.

Hence, inserting a time delay in a motion control algorithm may offer several opportunities. For instance, a time-delayed controller avoiding unnecessary velocity measurements. In other cases, it is to be noted that if velocity measurements are not available, a derivative filter is used to estimate the velocity from position data. In such a case, the derivative filter, which shows high-pass filter characteristic, will produce velocity estimates with a high level of measurement noise.

Now, employing the results presented above, the controllers' gains of the proportional integral delayed control technique are chosen as Table 5.17.

Table 5.17 Tuned controller parameter

PIR	K_p	K_i	K_r	τ
	5.7780	96.7578	0.6887	0.0519 sec
PID	K_p	K_i	K_d	
	5.853	20.6	0.023	

Further, the controller gains K_p, K_i and K_d are determined by classical controller design approaches based on a nominal system model obtained around a desired operating point.

The transient performance of the closed-loop control is presented in Figure 5.57. It is observed that the settling time of the PI-R controller is better that the PI-R controller. However, it is to be noted that the analytical tuning parameters are strictly depended on the predetermined decay ratio, thus the transient performance can be improved by increasing the value of $\sigma = 0.501A$. However, it may cause a bigger control input with high frequency signal (Ramirez et al., 2016). The corresponding control signals are presented in Figure 5.58.

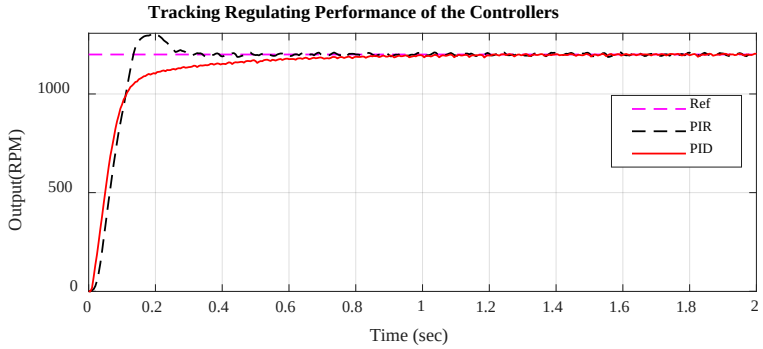


Figure 5.57 Transient performance of PIR and PID control

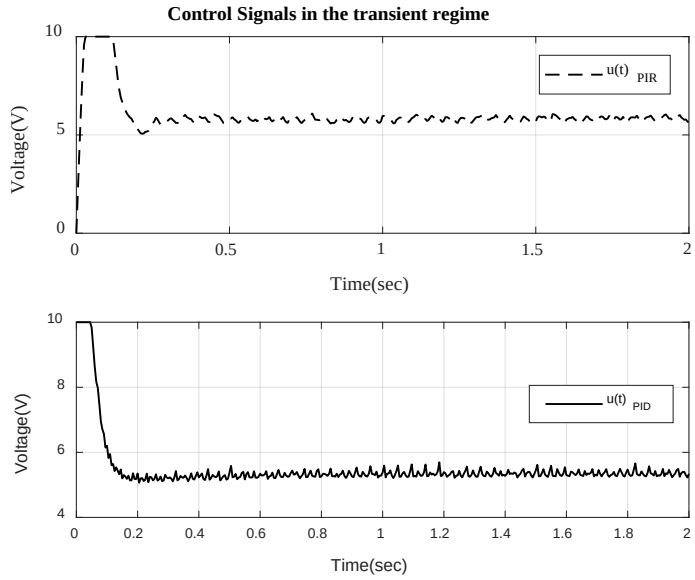


Figure 5.58 The control signal of PIR and PID control

It is observed that the control signal of the delay-based controller is slightly better than PID control in terms of total variance as well as chattering.

The tracking performance of the proportional integral delay control and conventional PID controller is demonstrated in Figure 5.59 and the corresponding control signals are shown in Figure 5.60.

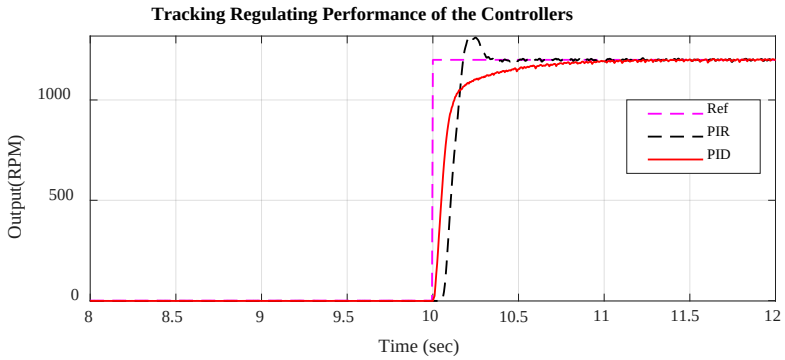


Figure 5.59 Tracking performance of the controllers

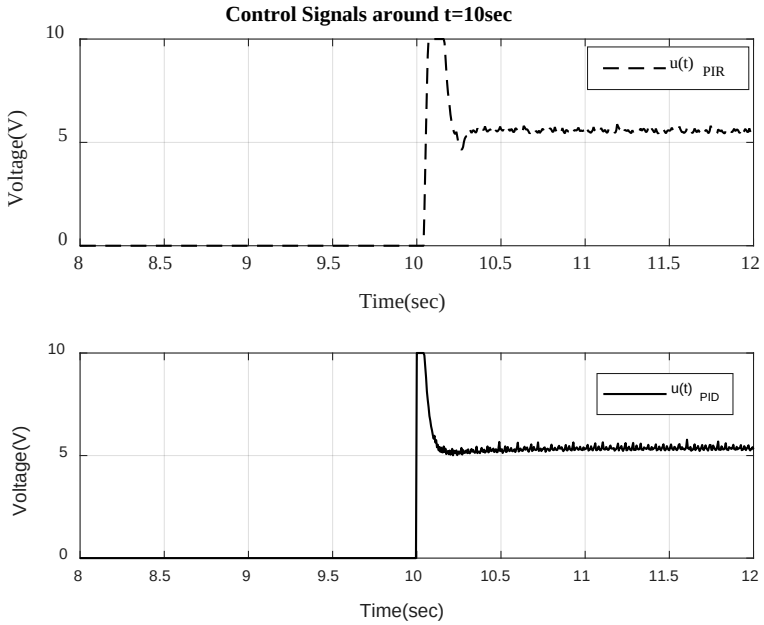


Figure 5.60 The control signal of PIR and PID control in transient regime

Moreover, the disturbance rejection capability of the controller technique is given in Figure 5.61. It is to be noted that the disturbance rejection performance of the delay-based controller is slightly better than the PID controller. The control signal around t=13 seconds is shown in Figure 5.62.

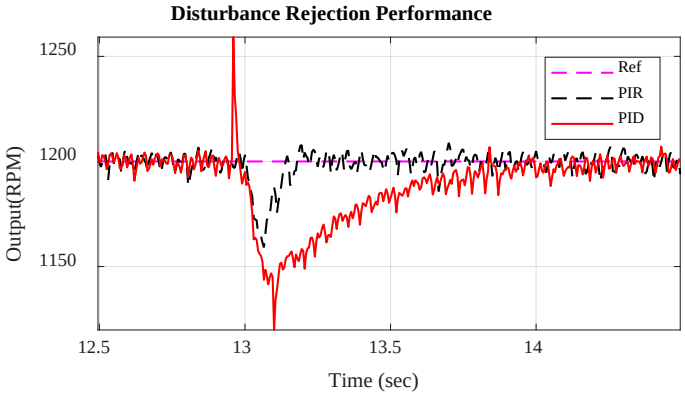


Figure 5.61 The control signal of PI-R and PID control

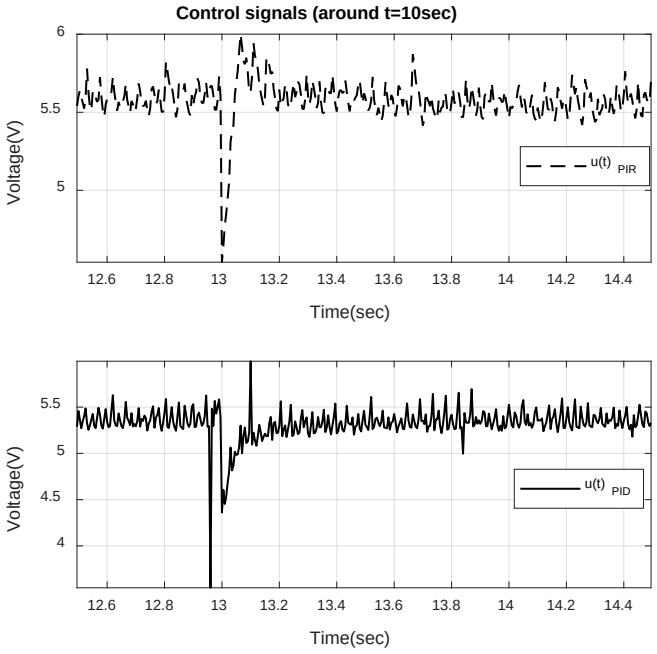


Figure 5.62 The control signal of PI-R and PID control

5.6.2. Proportional Integral Proportional Delayed Control Application to the DC Motor: Simulation and Experimental Results

The closed-loop control performance of the elaborated control technique is investigated. Furthermore, the present technique is compared with conventional PI-PD and PID controllers to highlight the advantages and disadvantages. From the realization point of view, delayed controller is more advantageous since it requires only memory registers, which make it easier to implement. From another aspect, it would not be noise amplification problem since the controller does not contain any derivative term. Thus, in some cases, it is not necessary to consider any additional filter during the experimental realization (Ozbek and Eker, 2017).

By considering the results presented above, the controllers' gains are chosen as in Table 5.18. It should be pointed out that the decay rate has to be

chosen carefully according to the actuator and experimentation limits such as sampling, quantization.

Table 5.18 Measured performances of the elaborated controllers

	PI- PR	PI-PD		PID	
K_p	7.84	K_p	4.86	K_p	3.089
K_i	80.32	K_i	16.26	K_i	8.3896
K_r	0.00518	K_d	1.293	K_d	0.0014
K_f	16.32	K_{p2}	7.823		
τ	1.9231				
σ	0.501A				

Figure 5.63 illustrates the transient performance and Figure 5.64 shows the control signal for each control technique. From the results, it can be concluded that PI-PR controller perform better results according to the quality of the control input as well as disturbance rejection. The tracking performance of the controllers are given in Figure 5.65. The corresponding control signals are shown in Figure 5.66.

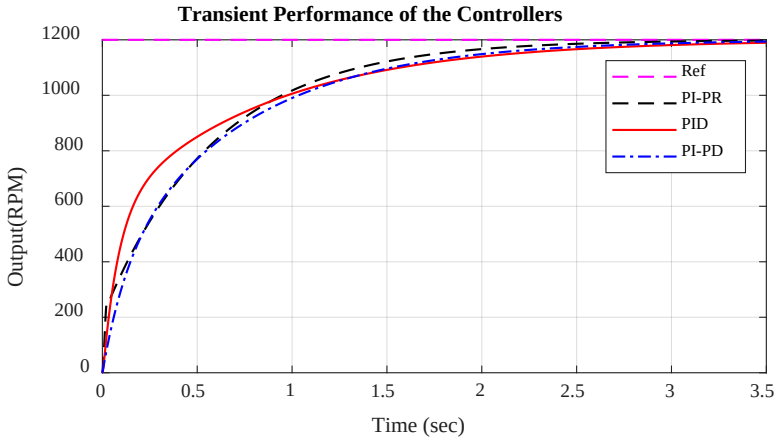


Figure 5.63 Transient performance in simulation

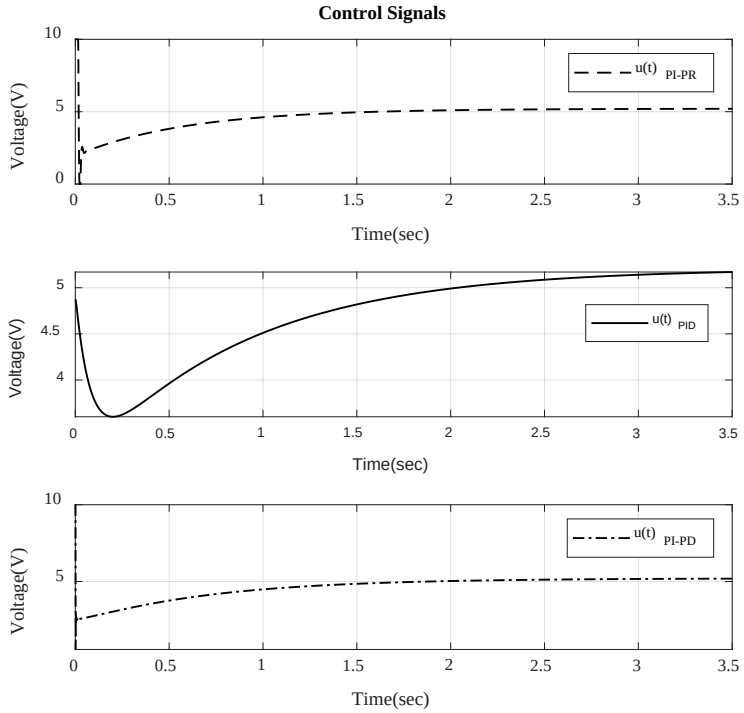


Figure 5.64 Control signals in transient regime

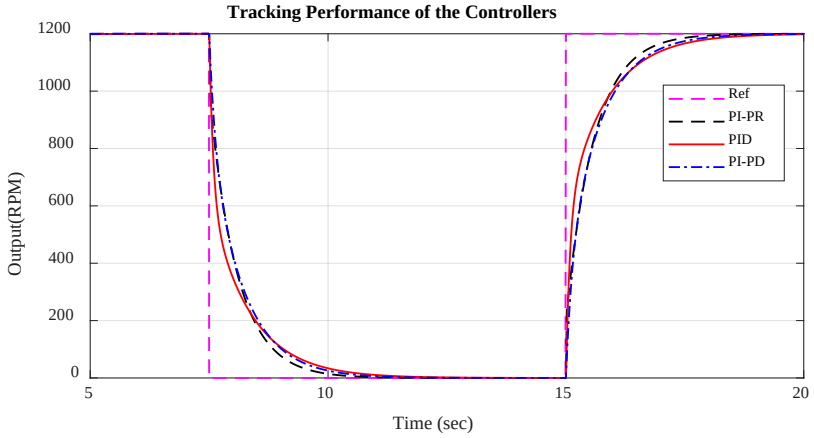


Figure 5.65 Simulation based comparison of control techniques

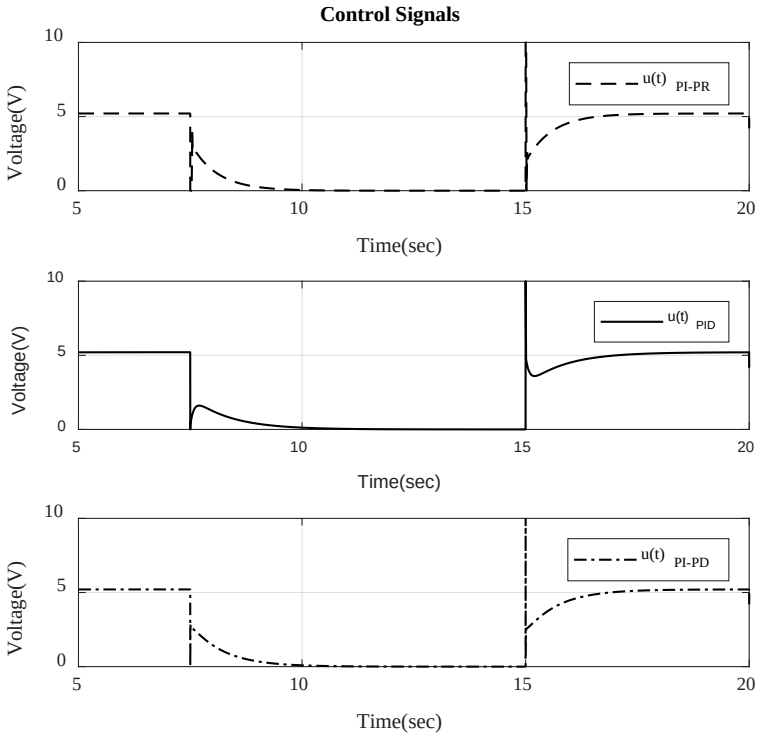


Figure 5.66 Control signals in simulation

The disturbance rejection performances are given in Figure 5.67, and the corresponding control signals are presented in Figure 5.68.

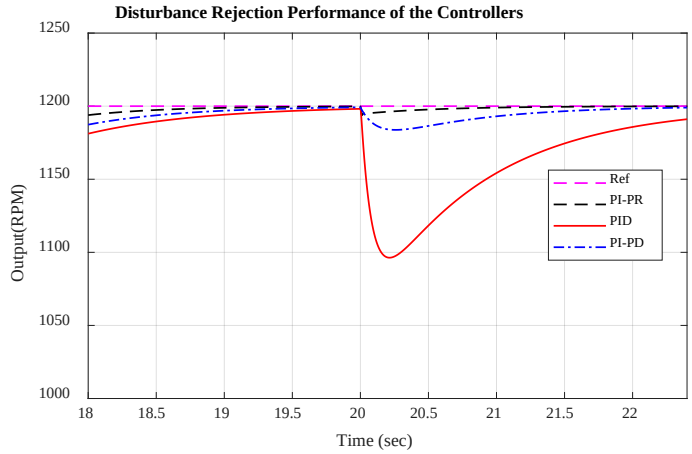


Figure 5.67 Disturbance rejection performance in simulation

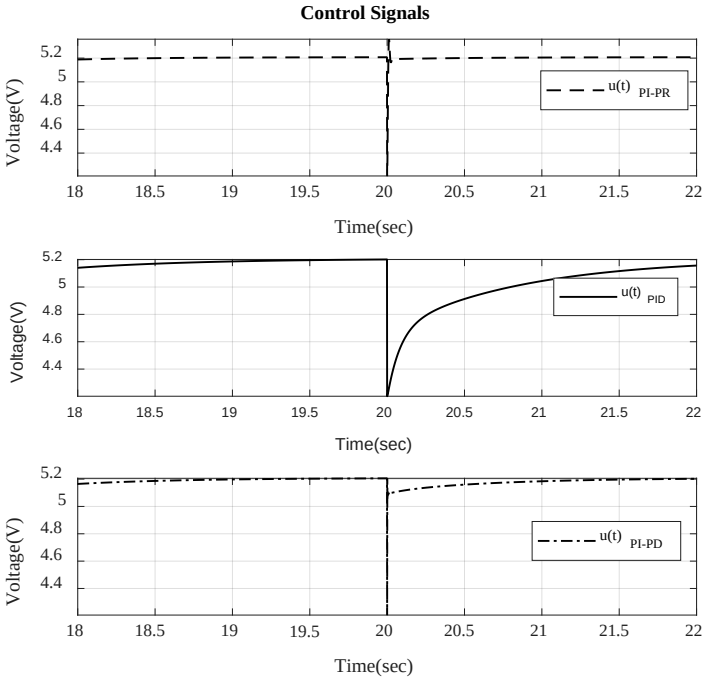


Figure 5.68 Control signals for the systems subject to disturbances

Finally, the tracking errors for the simulations are given in Figure 5.69.

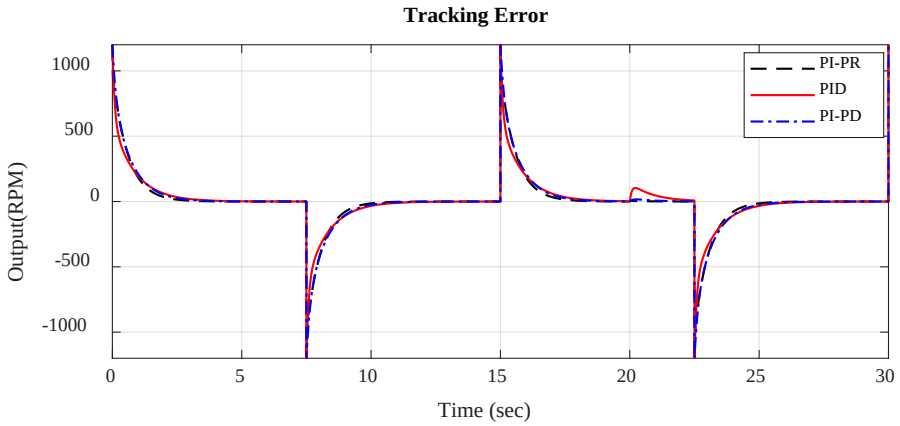


Figure 5.69 Tracking error in simulation

The transient performance of real-time experimental results are presented in Figure 5.70 and the control signals are presented in Figure 5.71. According to the results, proportional integral proportional delayed controller provides betters control response in terms of settling time, rising time.

The measured time domain performances for the transient regime are tabulated in Table 5.19

Table 5.19 Measured performances in transient regime

Criterion	PI-PR	PI-PD	PID
Settling Time	0.256	0.8996	1.1452
Rising Time	0.2242	0.5532	0.7853
Overshoot	No overshoot	No overshoot	No overshoot
EV	0.2354	0.5313	0.36183

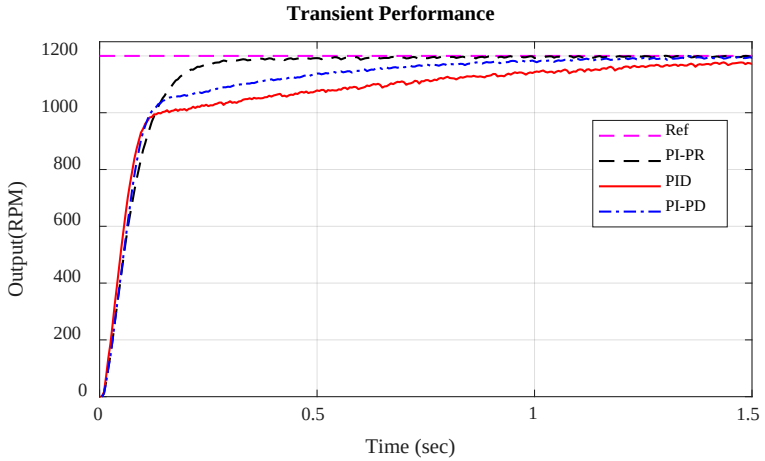


Figure 5.70 Transient performance in experimental application

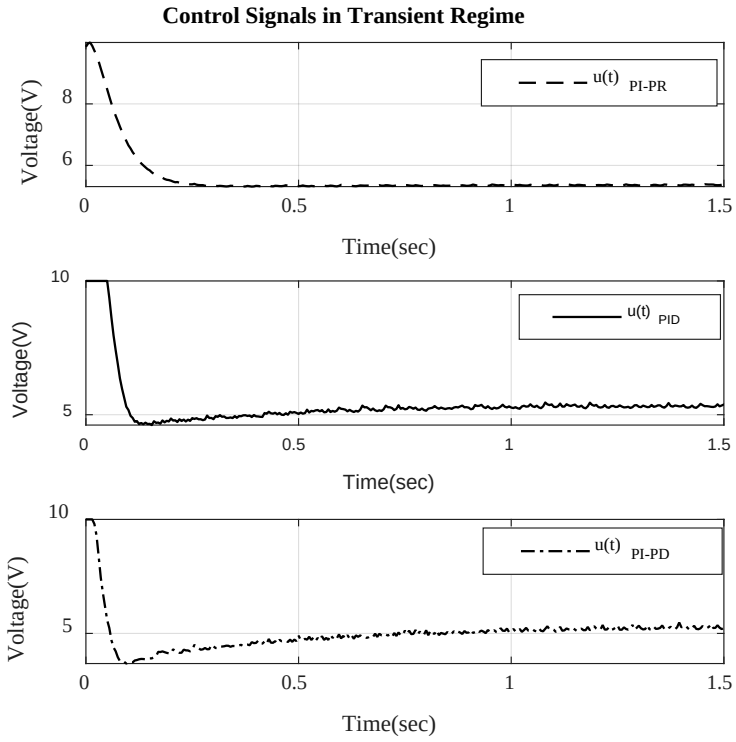


Figure 5.71 Simulation based comparison of control techniques

It is concluded that the best transient performance is achieved by delay-based control technique.

The outcomes of the experiments show a robust behavior of the closed-loop system under delay-based control with respect to disturbances and noise. It is observed that the delay-based controller has a simpler control input that makes it more convenient for experimental applications. Because of failing to produce a smooth control input, the poorest results are obtained with the classical PID controller in terms of the EV. Furthermore, the magnitude of the control signal of classical PID control technique is relatively larger than the PI-PD control. The tracking performance is presented in Figure 5.72, and the control signals are given in Figure 5.73.

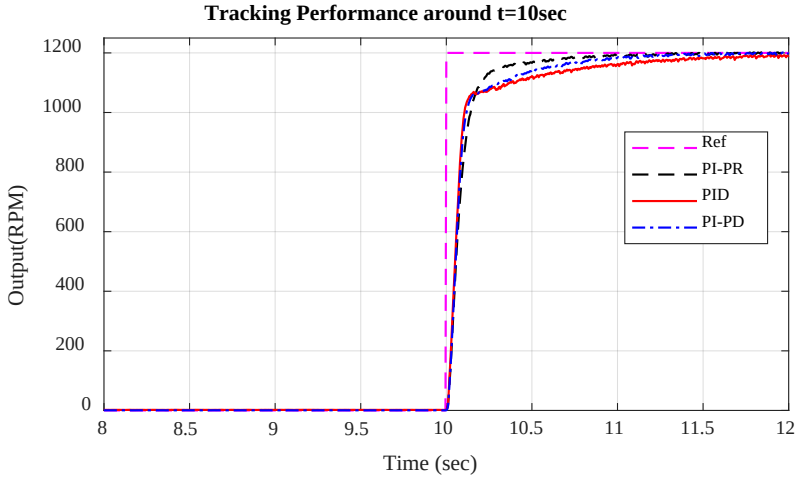


Figure 5.72 Tracking performance of the controllers

It is seen that evidently improved control performance is obtained by the delay-based technique.

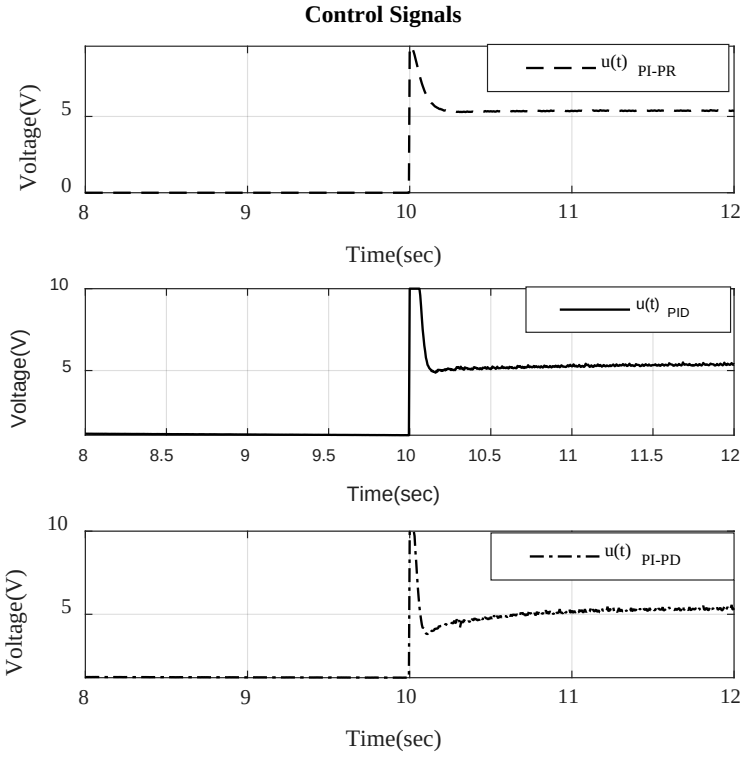


Figure 5.73 Control signals of each controller in transient regime

Then, a disturbance test is performed and the corresponding disturbance rejection performance is shown in Figure 5.74. It is to be noted that fast and smooth control response is obtained by the delay-based control technique. Further, although the PID perform fast response to reject the disturbance, the maximum absolute error of PI-PD is smaller than PID control. This gives an idea about the robustness of the control technique. Moreover, the corresponding control signals are demonstrated in Figure 5.75.

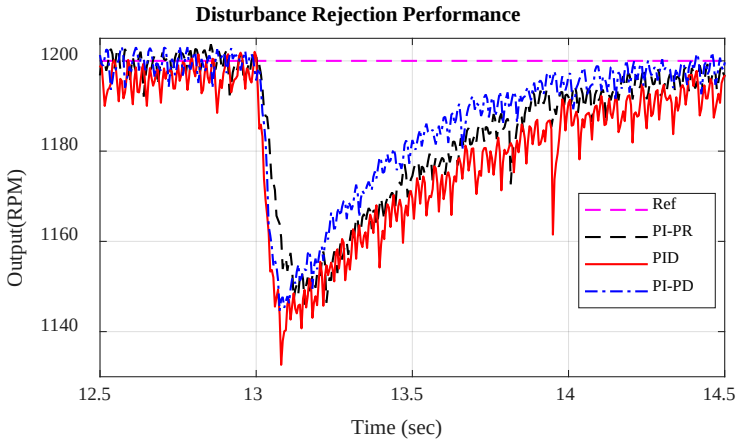


Figure 5.74 Disturbance rejection performances

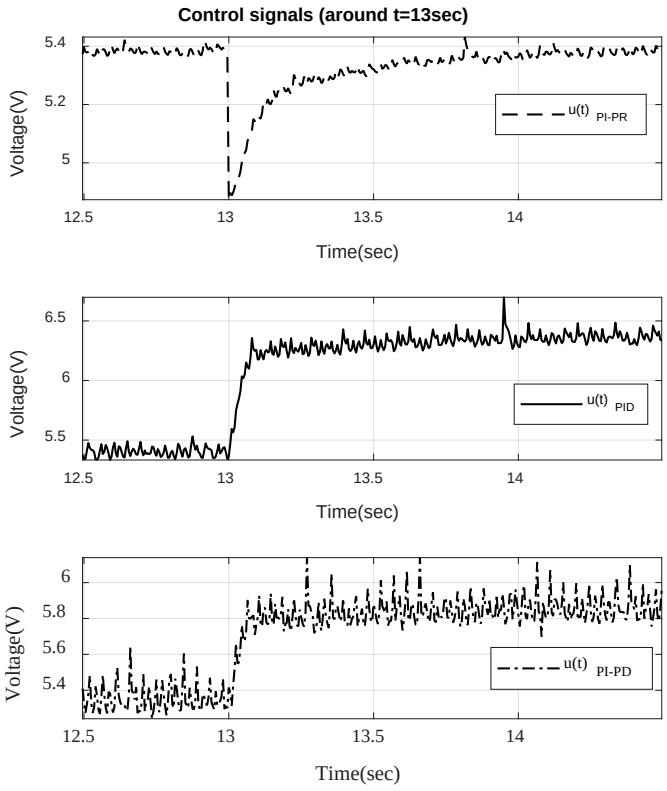


Figure 5.75 Control signals around t=13 sec

According to the disturbance rejection performance, all control techniques are comparable. However, the maximum absolute error is observed by the PID control technique. Further, it can be concluded the delay-based control provide better robustness compared with PID and PI-PD.

However, the PID and PI-PD control techniques are more sensitive to noise and implementation of an exact differentiation is a challenging problem, which can be affected by many factors. Further, from a practical point of view, measured signals are always contaminated with noise. The tracking errors of the controllers are presented in Figure 5.76.

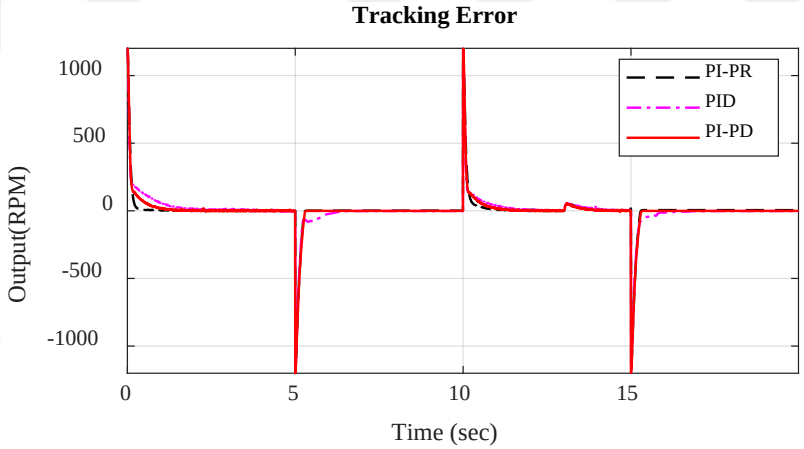


Figure 5.76 The error function of each control technique

The performance comparison in terms of IAE, ISE, ITAE, ITSE is presented in Table 5.20. According to the results, the performance of the PI-PR, PID, and PI-PD controllers is comparable, with a slightly smaller error variance for PI-PR controller, as given in Table 5.20.

The quantitative performance metric (ISCI) for control signals is presented in Table 5.21.

A radar diagram, which presents a visual comparison of the control techniques, is demonstrated in Figure 5.77.

Table 5.20 Measured performances of the elaborated controllers

Criterion	PI-PR	PI-PD	PID
IAE	2.1836	2.2639	2.9860
ISE	4.6823	4.7035	4.7041
ITAE	16.0572	17.7908	23.6701
ITSE	35.4563	37.6335	37.4512
MAE (t=13) RPM	33	36	48

Table 5.21 Measured ISCI for the control signals

Criterion	PI-PD	PI-PD	PI-PR
ISCI	291.5044	296.5662	271.3263

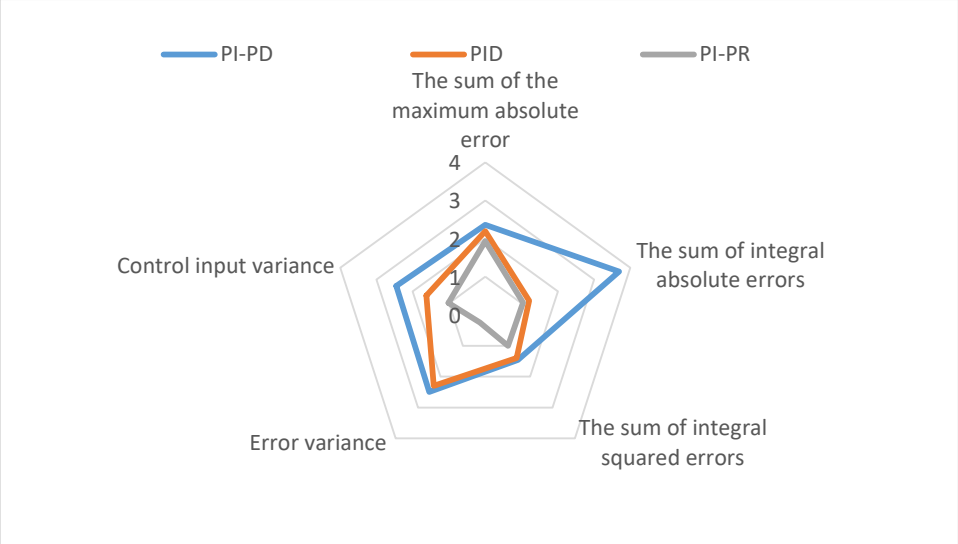


Figure 5.77 The comparison of the control strategies (normalized values)

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6. CONCLUSION AND FUTURE WORK

6.1. Concluding Remarks and Discussion

This thesis investigates the control of time-delayed systems, delay affects and its compensation results in control systems by a number of control strategies. The elaborated control strategies provide a number of benefits for coping with long time-delay systems. The experimental tests with tabulated time domain measures showed that performance enhancement of the closed-loop system enables more robust behaviour, better disturbance rejection capability, and good noise suppression ability while less energy consumption. Furthermore, the sensitivity of control strategies to uncertainties and noise is also explored.

It should be emphasized that the elaborated control techniques may entail comparatively sophisticated hardware and software to implement. However, the control designer may observe the performance enhancement by the proposed control techniques over the classical one, then decide whether it is beneficial for his specific application or not.

A set of fractional order control design techniques with analytical tuning rules are investigated with real-time experiment for controlling a thermal process. An experimental evaluation is presented through a number of performance criteria. The effects of controller gains, as well as the fractional order term, are discussed in detail.

In order to investigate the closed loop control performance and the robustness of elaborated control strategies, numerous experimental studies have been conducted under different set-points and disturbances. Moreover, complimentary comments are highlighted on the advantages and drawbacks of each modified SP structure.

A second order sliding mode control (SOSMC) with Smith predictor (SP) scheme is adopted to control a time-delayed process.

The simulation results and experimental tests with tabulated time domain measures showed that performance enhancement of the closed-loop system enables more robust behaviour, better disturbance rejection capability, and good noise suppression ability while less energy consumption in comparison with the first order SMC based SP scheme. It is also showed that the present controller provides better time domain specifications compared with the classical SMC in both tracking and disturbance rejection.

The elaborated control strategies provide a number of benefits for coping with long time-delay systems. Further, the controller shows improved robustness performance by means of second order sliding mode control technique while reducing the chattering phenomenon.

As stated previously, various SP based design options have been offered to handle the delay phenomenon. In this study, a small-scale version of an industrial air heater system is employed. The motivation of the paper is to design a SOSMC scheme considering the real-life operational conditions of an air heater process. Performance evaluation is illustrated through a set of performance measures.

In this study, we consider the SMC technique based SP as its robustness against disturbances and modelled dynamics.

Future works will focus on the application of FOSMC with fractional order PID type sliding surface. To mention a few, it can be noted that most of the research on FOSMC has focused designing of the fractional-order switching manifold. However, there are several ways to design a FOSMC such as: i) choosing a fractional order sliding surface, ii) using a fractional order model of the system, iii) employing a fractional order signum function in FOSMC (Corradini, Giambò, & Pettinari, 2015; P. Roy, Sarkar, Roy, & Singh, 2017)

As a conclusion, the proposed gain-scheduled controller may provide several advantages by reducing the cost, providing a simplicity of the tuning of the controller, as well as improving the robustness. The merits and demerits of the controllers are highlighted in Table 6.1.

Table 6.1 Advantages and drawbacks of gain-scheduled control strategies

Strategy	**Advantages**	**Drawbacks**	**Improvements**
PI-PD based SP	• Simple structure • Easy parameter tuning	• Poor performance if the linearised system behaviour is dissimilar to true system • Lack of robustness • Cannot cope with model parameter changes • Needs an exact model	• Parameter optimisation and automatic tuning can be adapted
FPI-PD based SP	• Model free design • Wide operation range • Nonlinearities can be eliminated or reduced	• Larger error variance • High sensitivity to parameter changes • Analytical stability proof is missing • Needs an expert for a good initialisation	• Strong robustness can be provided
FFPI-PD based SP	• Robust • Fast response • Reduce control effort and smooth control signal • Less energy consumption • Low computation cost	• Heavy computational burden • Use of expert knowledge	• Fractional order model can be utilized

It should be emphasized that the proposed control scheme may entail comparatively sophisticated hardware and software to implement. However, the control designer may observe the performance enhancement by the proposed

control schemes over the classical one, then decide whether it is beneficial for his specific application or not. It is to be noted that, to obtain satisfactory control performance in the presence of disturbances and uncertainties is a tedious task for approaches that entail precise plant models. Bearing these ideas in mind, this study addresses a number of controllers and gives some insight into the capabilities of the controllers and their real-time implementation costs.

Furthermore, the degree of robustness is more if the external disturbance is rejected quickly with a less oscillatory transient. Hence, after the disturbance is applied, the settling time and the overshoot and undershoot during disturbance rejection gives an indirect measure of robustness. From this perspective, the deviation between the experimental results on the real plant and the simulation result is within an acceptable limit indirectly justifies that the proposed controllers are adequately robust with respect to the parametric uncertainty.

The FFPI-PD control scheme performs satisfactory results over the classical PI-PD, and the integer order fuzzy PI-PD control under different operating conditions. The proposed control scheme also shows more robust behaviour against disturbances and modelling uncertainties. Since it covers uncertainties and disturbances in the solution algorithms. With this in mind, the proposed algorithm can be used alternative to conventional controllers in industrial applications.

Yet another point is that the performance metrics elaborated with simulations are less than those of experimental applications are. This is due to the simplified model of the heating process, which may cause a slight difference. It is worth mentioning that the response of the temperature output from the power input could be fractional (Caponetto et al., 2016). In view of the foregoing, our future research efforts will focus on fractional order modelling and fractional control of the thermal process (Zhang et al., 2017). Furthermore, it might be interesting to investigate the stability limit experimentally, which gives an insight into networked control applications (Batista and Jota, 2018).

Considering the above observations, and after a comparison with the integer order case, the proposed control scheme provides: i) high tracking performance ii) less sensitivity to measurement noise. Further, it avoids the model sensitivity problem of SP scheme. It benefits the advantages of the fractional order control to compensate the uncertainty and disturbance; it does not require an exact model of the system. Furthermore, the controller is able to compensate the effect of the delay variations.

The present study investigates delay-based control techniques to obtain better control performance for controlling of second-order linear time-invariant systems in the presence of noise and disturbances. A modified delay-based control technique is applied for an electromechanical system represented by a second-order transfer function. Based on this, a proportional integral controller and a proportional delayed controller are combined. In fact, the proportional derivative part is modified by the proportional and delayed output feedback. The performance of this modification is discussed carefully. Table 6.2 presents merits and demerits of the elaborated control structures.

A set of experiments have been conducted in order to assess the performance of the elaborated control methodology. It is also validated that the delay-based control increases the control system performance. However, the design of an efficient real-time control technique, which is strictly dependent on the internal/external factors, is not straightforward.

According to the results, the proposed control scheme provides satisfactory performance in terms of several performance metrics. Further, the controller can be easily implemented for practical applications. The main advantage of inserting a delay in the controller is that the closed-loop control system does not need any additional filter to attenuate noisy measurements.

As a conclusion, the proposed controller may provide several advantages by reducing the cost, providing a simplicity, as well as improving the closed-loop performance. It is observed that the PI-PR control scheme performs better transient

response, and tracking ability. It also produces a smooth control signal in the presence of noise and disturbance.

Table 6.2 Advantages and drawbacks of the delay-based control techniques

	Advantages	**Drawbacks**	**Improvements**
PID	-Simple structure -Easy parameter tuning -Fast response	-Poor performance with wide operation range -Lack of robustness -Cannot cope with model uncertainties	-Parameter optimisation and automatic tuning can be adapted
PI-PD	-Wide operation range -Suitable for unstable integrated processes	-Larger error variance -Needs an exact model -High control input variations in the presence of noisy measurements	-Strong robustness can be provided -Fractional controller can be designed
PI-PR	-Reduce control effort -Smooth control signal -Less energy consumption -Low computation cost -Needs no additional filter	-To obtain analytical stability is a tedious task -Controller parameter tuning is a challenge	-Optimal parameters can be selected

6.2. Future Work

Several original contributions have been tested and accomplished in this thesis. In addition, various interesting future research can be recommended. In order to improve the control performance of time-delayed systems, various subjects are recommended for future studies as follows:

- The design and implementation of digital adaptive Smith predictors and their application in networked control systems.
- The relation between sampling and delay. Further, its effect to the stability and control performance of closed loop systems.
- The application of SP based fractional order SMC with fractional order PID type sliding surface. It can be noted that most of the research on fractional order SMC has focused designing of the fractional-order switching manifold (Corradini, Giambò, & Pettinari, 2015; P. Roy, Sarkar, Roy, & Singh, 2017). However, the design and application of fractional order SMC with fractional-order switching manifold has not been studied yet.
- Analytical controller parameter tuning of proportional integral proportional delayed control can be investigated. Further, stability regions can be investigated according to delay and controller parameters changes, then robustness of the control scheme will be addressed.
- The design of controller for nonlinear time-delayed systems such as unmanned aerial vehicles applications in the presence of delay and communication constraints.

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BIOGRAPHY

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APPENDIX

Publications

Özbek N.S., Eker İ., "An Interactive Computer Aided Instructional Strategy and Assesment Method for System Identification and Adaptive Control Laboratories", IEEE Transaction on Education, vol. 9, 1, pp.285-300, October 2015

Özbek N.S., Eker İ., "A set of Identification and Control Design Methods for an Industrial Air Heating Process", Journal of Automation and Control Engineering, vol 6, pp.152-157, June 2016.

Özbek N.S., Eker İ., "An Experimental Comparative Evaluation of Various Fractional Order Control Based Smith Predictor Control Techniques for Time Delay Systems" International Journal of Embedded Systems, accepted, to appear in 2019.

Özbek N.S., Eker İ., "Design of an Optimal Fractional Fuzzy Gain-Scheduled Control for a Time Delay System" Accepted with Major Revision, In Revision, ISA Transactions. submitted 6 June 2017.

Özbek N.S., Eker İ., "A Novel Modified Delay-Based Control Design for an Electromechanical System with Experimental Application" Information Technology and Control, Accepted with Minor revision, submitted 18.09.2017

Özbek N.S., Eker İ., "Second order Sliding Mode Control Based Smith Predictor with Experimental Application" Transactions of the Institute of Measurement and Control, to be submitted 2018.

Özbek N.S., Eker İ., "A Comprehensive Evaluation of Networked Control Systems with Networked Induced Constraints: Stability Analysis and Control Design Methods" Transactions of the Institute of Measurement and Control, to be submitted.