EVALUATION OF PNEUMATIC ARTIFICIAL MUSCLE MODELS FOR ROBOTIC APPLICATIONS

Elif Tuğba DEVECI[1*] and Cabbar Veysel BAYSAL[2]

[1] Cukurova University, Faculty of Engineering, Biomedical Engineering, Adana, Turkey
(etdeveci@cu.edu.tr)

[2] Cukurova University, Faculty of Engineering, Biomedical Engineering, Adana, Turkey
(cvbaysal@cu.edu.tr)

ABSTRACT
Pneumatic Artificial Muscles (PAM) are used in robotic applications due to their advantages such as high force to weight ratio, soft and flexible structure. However, PAMs have some disadvantages because of the inherent non-linearity in their structure and modeling difficulties. In this paper, an evaluation of Pneumatic Artificial Muscle Models to be used for robotic applications is presented. The modeling approaches such as empirical, static and phenomenological are analyzed in simulation and tests are performed on an experimental setup. The results indicate that models are not generalizable and highly nonlinear. Hence, there is still a strong requirement for simpler and the more conceptive models. To conclude, further modeling studies would resolve this problem.

Keywords: *Pneumatic Artificial Muscle (PAM), PAM Modeling, Robotic Applications*

* Corresponding author

1. INTRODUCTION

A pneumatic artificial muscle (PAM) is an actuator that mimics behavior of skeletal muscle by contracting and generating force in a nonlinear manner when pressurized. PAM was invented in 1950s firstly by Joseph L. McKibben and it was used for used in artificial limbs (Tondu, Lopez). In 1980s it was redesigned by Bridgestone Company and it was used for some applications to assist disabled individuals (Daerden, Lefeber). PAM is a radially inflated and axially contractionary shear which produces high tensile forces along the longitudinal axis. The most well-known feature of PAM is the force, which is a function of pressure and contraction (Wickramatunge, Leephakpreeda, 2009).

PAM is currently used different areas such as robotic and rehabilitation (Hall,2011). Improvement of modeling and control will increase the use of PAM.

Although PAMs have many advantages such as high force to weight ratio, soft and flexible structure, low cost and extreme safe for human use they have many disadvantages like difficult modeling and controlling. These difficulties exhibit due to compressibility of the air, inherent properties of visco-elastic material and geometric structure of PAM (Wickramatunge, Leephakpreeda, 2009).

In this study different modeling approaches are investigated. And then some tests are done in experimental setup for finding properties of each one.

2. MODELING APPROACHES OF PAMS

In modeling approaches of PAM, the aim is to relate the pressure, and length change of the pneumatic actuator along the entire axis. Variables such as tensile force, actuator length, air pressure, diameter and material properties play an important role in modeling approaches and mathematical models attempt to define the relationship between these factors (Kelasıdı, Andrikopoulos, Manesis). Modeling approaches are based on PAM's static and dynamic behavior.

2.1. Static Modeling Approach

When developing a static model of the muscle, the basic approach is based on the energy model. This approach is based on the relationship between virtual work and loss-free energy conservation by providing an association between actuator force, pressure, and length (Jouppila).

The Chou and Hannaford model is the simplest geometric model for the static performance of a PAM. With this approach the PAM actuator is modeled as a cylinder with length L, thread length b, diameter D and the number of thread turns n as shown in Fig. 1. θ angle is defined as the angle between longitudinal axis and thread.

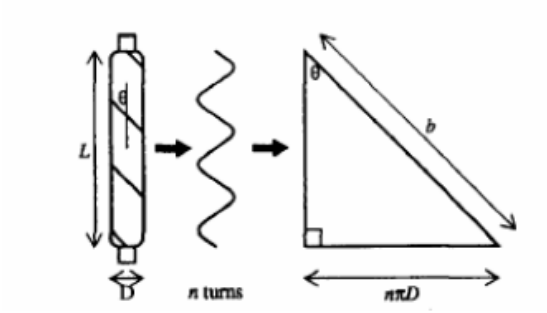


Fig.1. Geometric model of PAM actuator (Chou, Hannaford)

According to the Chou and Hannaford suggest the force produced is expressed as:

$$F = p' \frac{b^2}{4\pi n^2}\left(3\cos^2\theta - 1\right) \quad (1)$$

2.2. Dynamic Modeling Approach

Dynamic models in other words phenomenological models aim to capture the dynamic behaviors of pneumatic muscles better when compared to static behaviors focused on geometric models. The three elements phenomenological model used to describe PAM's dynamic is a parallel configuration of a spring element, damping element and contractile element and is shown below in Fig.2. (Serres, Reynolds, Phillips,, Gerschutz, Repperger).

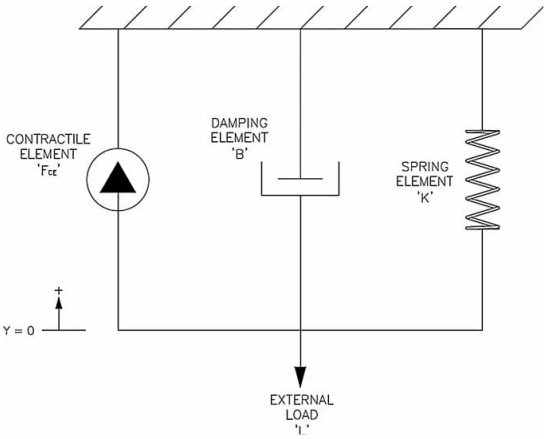


Fig.2.The three elements phenomenological model (Serres, Reynolds, Phillips, Repperger)

In this work done by Seres at al. assuming that there is displacement on the y axis, the equation for the phenomenological model is written as follow:

$$M\ddot{X}_{O-PAM} + B_{PAM}\dot{X}_{O-PAM} + K_{PAM}X_{O-PAM} = F_{CE} - L \quad (2)$$

Here X_{O-PAM} refers to the PAM displacement, M refers to the the mass of moving components, B_{PAM} refers tıo the damping coefficient, K_{PAM} is spring coefficient, F_{CE} is contractile force factor, and L is external load.

2.3. Empirical Modeling Approach

Wickramatunge and Leephakpreeda assumed the PAM system as a mechanical spring system in their study of empirical modeling of PAM.

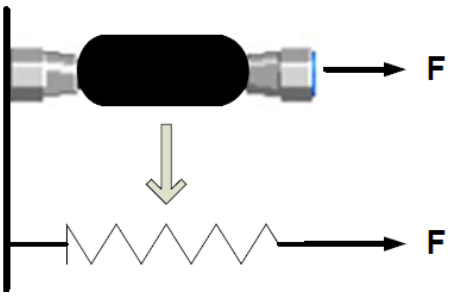


Fig.3.Equivalent system diagram of pneumatic muscle and spring system (Wickramatunge, Leephakpreeda, 2009)

Both the PAM and mechanical system exhibit similar behavior when pulling force is applied. Based on experimental observations it has been shown that the forces acting on the muscles and the force acting on the mechanical spring system can be modeled in the same way. The muscle hardness parameter is determined as K and it is accepted the function of working air pressure P and stretched length Ls.

$$F_{elastic} = K(P, L_s) * L_s \quad (3)$$

$$K = c_3 p^2 + c_2 pL_s + c_1 L_s^2 + c_0 \quad (4)$$

In Eq.4. K is considered to be a second-order polynomial. The c parameters are fixed and can be found from experimental data using least squares estimation method.

It has been shown that the empirical model developed in the present student provides an effective definition for understanding the mechanical behavior of PAM in design and use. And the adaptation of both simulation results and test results show the feasibility of the proposed technique.

In this paper the static, dynamic, and empirical models are evalauted using experimental data. The results obtained indicates feasibilty of each model for robotic applications.

3. EXPERIMENTAL SETUP & TEST BED

In the experimental setup, there are loadcells, encoder(position sensor), pressure sensors, an amplifier circuit, a data acquisition unit and fast electro-pneumatic valves. Fig.4. shows the experimental setup.

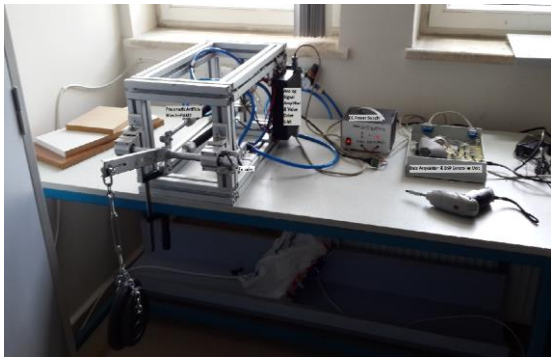


Fig.4. Experimental setup

Sensors and actuators used in the setup is controlled by a desktop PC using Matlab package with "Texas Instruments Code Composer Studio" software package running on Data Acquisition and DSP Controller unit. In addition, a real-time data exchange is possible. The software is prepared in the MATLAB SIMULINK package and is converted to "Code Composer Studio" using various conversion libraries given in Fig.5. After that, the C software is compiled with necessary edit and loaded on the "ezDSP F2812" module. While the control and data acquisition software are running on the DSP processor, real-time data can be collected using the RTDX function. By means of MATLAB GUI prepared in Fig. 6, the user can perform real-time data exchange while performing control functions.

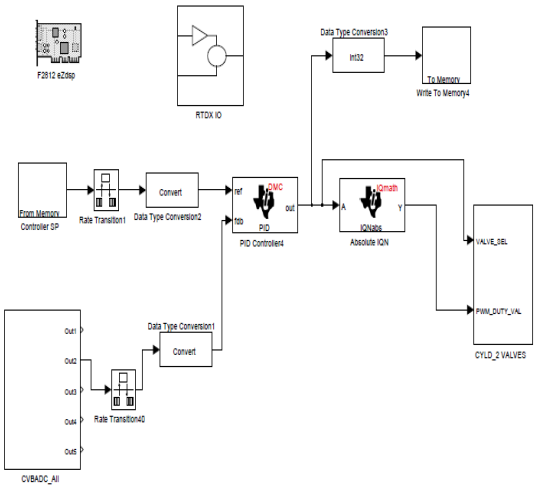


Fig.5. Simulink Control Blocks

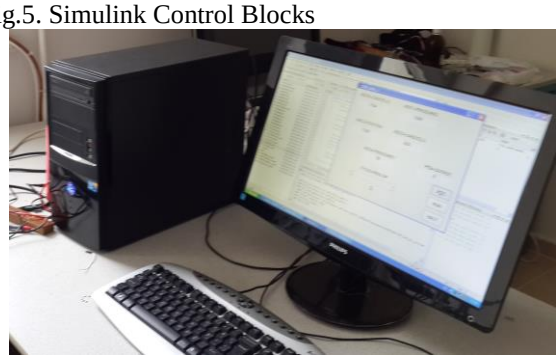


Fig.6. MATLAB GUI in desktop PC

Before modelling and data collection, calibrations for each sensor were carried out. The measurement functions are obtained by using amplifier gains and calibration results for pressure, force and position sensors. The ADC (Analog-to-Digital Converter) on the DSP Controller has a 12-bit resolution. The ADC input analog signal values can range from 0 to 3.3V. In this case, the numerical value of an analog signal between 0-3.3V can have a value of 0-4095. The sensor calibrations were repeated two times, and accuracy was confirmed for measurement errors. The measurement functions are given in table 1.

Table 1. Sensor and amplifier measurement characteristics

Name	Inout(w) Range	Sensor Out(x) mV	Amplifier Out(y) mV
Loadcell	0-100 kg	x=4,1528w +0,53	y=111x-1,153
Encoder (Position Sensor)	25-155 deg	x=13,164w +1067	y=0,5892x
Pressure Sensor	0-100 psi	x=2,839w-0,86	y=7,239x-3,73

4.RESULTS

In order to perform analysis of PAM , experiments are carried out in test bed by applying different gravitational force loads to setup arm.The loads range from 3,5 to 70 kgs. Data sets are obtained while the controlled varying pressure is applied to PAM, that yields a full trajectory motion of the arm. The pressure, force and position are recorded along the full motion for each load. An example of force vs pressure variation graph is given in Fig.7., for gravitational loads F_{I1}=21.6 **Kg**, F_{I2}=36.7 **Kg** and F_{I3}=58.3 **Kg**.

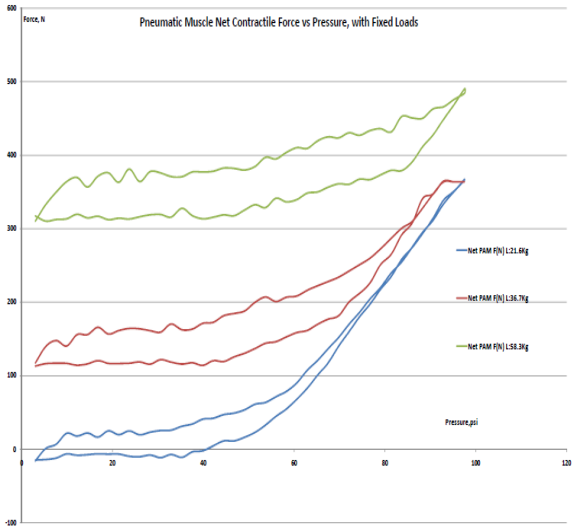


Fig.7.Force vs Pressure performance with different loads.

When the different loads are applied to test arm with same pressure variation, as the contraction of pneumatic muscles varies wrt loads, eventual motion results in different trajectories.

Thus input (pressure) and output (force) functions of the PAM were obtained. In this way, the characteristic plots is obtained in a simpler and more understandable way than the plots given in terms of triple parameters in the literature (force-motion relation according to constant pressure lines). When the data is evaulated, it is seen that the motion trajectory of the low weighted load is completed within the pressure range of 0-60 psi, while the high weighted load is completed in the wider 0-90 psi pressure range. During the movement, the applied load force is constant.

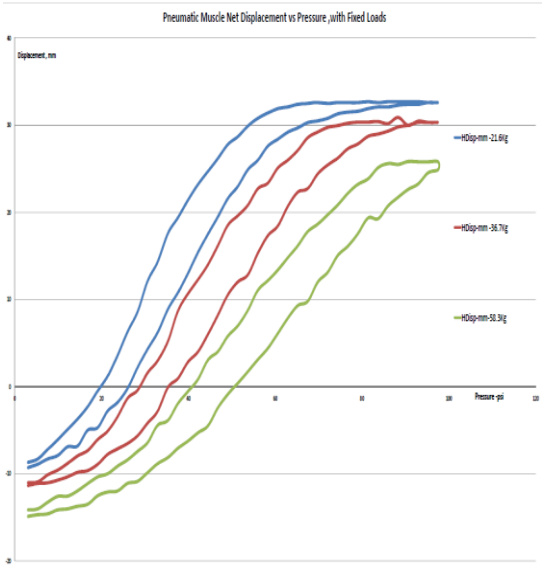


Fig.8.Displacement vs pressure performance with different loads.

In Fig.8., when different loads are applied to the test bed, the net muscle length contraction and elongation plots are given while the controlled varying pressure is applied to PAM. The plot is , produced during full trajectory motion. This feature is very similar to human muscle characteristics and indicating “Phenomenological Model” is more suitable for PAM type actuator.

When the graphs are examined the trajectory shapes are similar for different loads. Despite different loads applied to the system, the trajectories are complete without deterioration of quality. However, hysteresis is also observed when the trajectory is executed. Even though the characteristic functions are linear in a significant part of the motion, the hysteresis at the ends makes the behavior of the system structure non-linear which makes it difficult to be used in robotic applications.

5. CONCLUSION

It has been observed in the experiments that the same PAM generally completes successfully the desired trajectories for quite varying loads. This indicates applicability of PAM as robotic actuators as well as its great compliance. However, when trajectory tests are carried out, excessive hysteresis is observed. This feature makes the behavior of the system structure non-linear, even if the characteristic functions are linear in a significant part of the motion.

In conclusion, according to the experimental results and the analyzed models, “Phenomenological” models are deduced to be more suitable for robotic applications .

For future works, a simpler model is needed for effective use of PAM in robotic application.

6. ACKNOWLEDGEMENT

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7. CITATION AND REFERENCE LIST

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