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Phenomenological Modeling and Classic Control of a Pneumatic Muscle Actuator System

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Abstract

This paper focuses on the parameter characterization of phenomenological modelling for commercially available Festo Fluidic Muscle Actuator. Phenomenological model consists of a spring element, nonlinear damping element and a contractile force element which arranged in parallel. The dynamic model was tested on the experimental setup which allows precise and accurate contraction due to the supply of pressure (P) to the PMA. The open loop data were collected for static load study and contraction study at several constant pressures. Only the contraction experiment was focused in this study by excluding the relaxation phase of the experiment. The result obtained shows that at constant pressure, the muscle actuator behaves like a spring and a nonlinear damping element. The contractile force coefficient element is the corresponding force generated by the muscle during contraction in longitudinal direction. Since, pressure is the main driving element in PMA system, all the coefficient value has a pressure dependent relationship. The model and parameters obtained from the study were further validated by predicting the contraction of the muscle system via simulation and experimental. Then, a classical PID control system was designed and validated in point-to-point positioning motion experimentally. Finally, a brief conclusion of the pneumatic muscle actuator experimental setup and dynamic system modeling is made.

Keywords*: Pneumatic Muscle Actuator, Festo Fluidic Muscle, Phenomenological Modeling, Dynamic model, Classical PID controller*

1. Introduction

The pneumatic muscle actuator (PMA) has the characteristics similar to human skeletal muscle in the size, weight and power output. In contrast with the hydraulic actuators, PMA possess many significant advantages such as compliance, light-weight, low cost, and clean characteristics. Besides this advantages, one of the main reasons PMAs has been widely used in rehabilitation and exoskeleton robots is due to its high power/weight ratio of 1W/g and high power/volume ratio of 1 W/cm^3 [1]. This advantages has drawn a need for developing an accurate mathematical model (called as a dynamic) which holds all the quantitative properties of the actuator. The accurate dynamic model of a PMA system will contribute towards the controller design and utilization. However, the main drawback of the system is its difficulties to obtain a precise modeling of the PMA system, due to its high nonlinear characteristics. Furthermore, inaccurate model parameters determination will deteriorate the accuracy of PMA positioning system.

Many researchers have devoted to the research of pneumatic muscle actuator system, especially the modeling of the dynamic actuator. The modeling work begun with the model based on the geometric construction of the PMA [2]. The main idea of geometric models was to describe the static behavior of the actuator. Static models relate the length

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changes of a PMA, the pressure inside the actuator and some of its geometrical parameters which contributes towards force generation at steady state condition. Thus, various geometrical models were proposed and developed with several assumptions done by the researchers. The model created by Chou and Hannaford [3] and Tondu and Lopez [4] were the most widely used to date. Unfortunately, this model has its limitations of predicting the behaviors of the PMA in no-load conditions [5]. Some of the theoretical model of PMA can be found in [6]. Recent works on PMA modeling have concluded that the phenomenological model aims to better capture the dynamics of PMA as compared to the geometrical models which focuses only on the static behavior of the actuator [7]. Phenomenological model uses visco-elastic parameters to describe the behavior of pneumatic muscle actuator. This model consists of a spring element, a damping element and a contractile force element arranged in parallel improved by Reynold [8]. The name phenomenological model was first derived from the name biomimetic model which uses the principle of human skeletal muscle to model the actuator. According to the comparisons have been made between the biological skeletal muscle and the pneumatic muscle; where both contract and expand in radial direction resulting in a tensile force. The pulling force, length, air pressure, diameter and material properties are the important parameters in a PMA and it is the main parameters which effects in the mathematical modeling.

The evolution of a phenomenological model begun with the researcher Colbrunn [9] where he developed a pneumatic muscle model consisting of a spring, viscous damper and Coulomb friction element arranged in parallel. The verification test showed the potential of phenomenological model to predict the dynamic behavior of the PMA. Another dynamic model was constructed by Repperger [10] which used a stiffness-viscous model consisting of a spring element, damping element and contractile force element that arranged in parallel too. Reynold in [11] has improved the modeling by adapting the Voight viscoelastic model [12] into the mathematical model. The validation experiment was conducted for an in-house build PMA on a vertically aligned test system. Validation tests showed significant results in predicting the PMA dynamic behavior. Since then, the utilization of phenomenological model has increased and been used for motion control purposes.

The main aim of this paper is to characterize the pneumatic muscle actuator system using the phenomenological model and to validate its PTP positioning performance with a classical PID controller. The static load and contraction study results were used to individually characterize the contractile force coefficient, spring coefficient and damping coefficient as function of pressure. This paper is organized as follows: Section 2 describes the phenomenological modeling that has been focused in this study. Section 3 introduces the experimental setup used in the study, and Section 4 shows the experimental and simulation open-loop results of the PMA system for phenomenological model validation. Furthermore, the positioning performance of the PMA system with PID controller is validated in Section 4 too. Finally, Section 5 presents the conclusion and recommendation.

2. Phenomenological Modeling

The three element phenomenological modeling is the topic of interest in this research. Assuming that x is the contraction of the PMA, the governing equation of motion for the three element phenomenological model is written as:

$$M\ddot{x} + B\dot{x} + Kx = F_{ce} - F_L \tag{1}$$

where M is the mass at one end of the PMA, K is the spring coefficient, B is the nonlinear damping coefficient, F_{ce} is the contractile force coefficient and F_L is the external load acting on the system. The contractile force coefficient is the contraction force that has been generated by the muscle due to pressurization. The contractile force coefficient is assumed to be equal to the external load applied to the PMA which results in zero contraction of the muscle actuator.

Note that when $F_{ce}=F_L$ which results in zero initial contraction and velocity $[x(0)=\dot{x}(0)=0]$, no motion occur in the system. When $F_{ce} > F_L$, the right hand side of the (1) is the driving force for the system.

The dynamic experiments in this study have been conducted in a horizontal experimental setup. The following assumption has been made to neglect the initial term, mass M in the data collections. In the horizontal setup, one end of the muscle is fixed with the load cell and the other end is fixed with the table/mass. This is reasonable to assume that half of the muscle weight is supported by the load cell. It only contributes less than 1% of the total contraction of the PMA. Since this is a low mass system, the element M can be neglected [19]. Once, neglecting the initial term in the model, the simplified equation is shown in (2). Figure 1 presents the three element phenomenological model of PMA.

$$B\dot{x} + Kx = F_{ce} - F_L \tag{2}$$

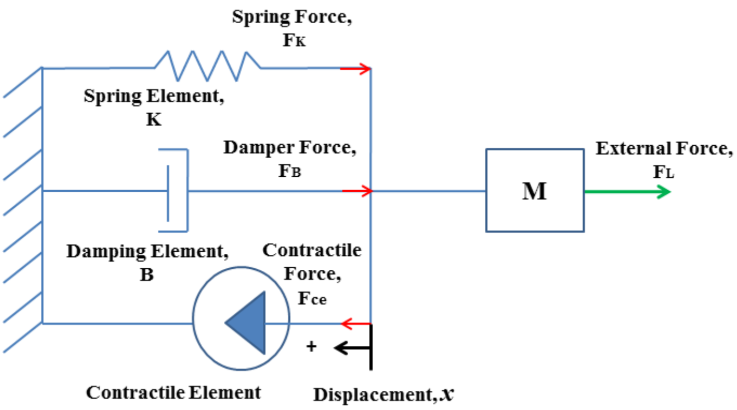

Figure 1. Three-Element Phenomenological Model of PMA

3. Experimental Setup

An experimental setup for motion control of the pneumatic muscle actuator system has been developed as shown in Figure2. Figure 3 visualizes the schematic view of the PMA system. The pneumatic muscle used for the study is the Festo Fluidic Muscle Actuator (MAS-20-250N-AA-MC-K) as the main driving element. The actuator has a nominal length of 250mm and diameter of 20mm. The experimental setup for carrying out the testing procedure was based on the one used in the previous study [20], but with some modification in the sensing part as shown in Figure 2. The PMA system is investigated using an experimental setup that allows precise and accurate actuation pressure controlled by a Festo Proportional Pressure Regulator (PPR) model (MPPE-3 1/8-6-010B) that manufactured by Festo. The PMA system is tested, by observing the contraction of the muscle actuator for different step input of pressure. The length change of the PMA is measured using a Linear Variable Differential Transducer (LVDT) (SR-Series VR 100.0SBLS, manufactured by Solartron metrology) with the resolution of 500nm.

The PMA is pressurized with compressed air controlled by a proportional pressure regulator which has a response time of 0.22s. The inlet pressure to the PMA is maintained below 650kPa to protect the PMA from excessive pressure. The outlet from the regulator is connected to the PMA and to a Festo Pressure transducer model (SDE1-D10-G2-W18-L-PU-M8) to measure/monitor the exact pressurization inside the actuator. The pressure transducer and proportional pressure regulator are fixed near to the actuator for better performance. A Futek load cell (model LCF451) is mounted at the fixed end of the PMA to obtain the pulling force/contractile force generated by the pneumatic muscle. The air supply to the system is supplied by a mini air compressor model Kinki (KAC-14 6L 1/4HP 100PSI). The low friction of the table is assumed to be neglected. Therefore, it is routinely lubricated to ensure minimal friction in the data collection process. Data is collected at a 500Hz sampling frequency and the pressure range for the experiments is 50-550kPa (0.5-5.5bar).

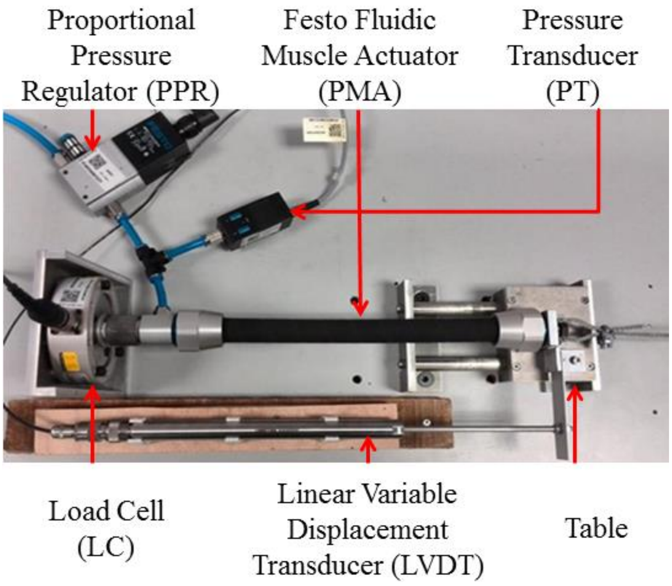

Figure 2. Experimental Setup of a PMA System

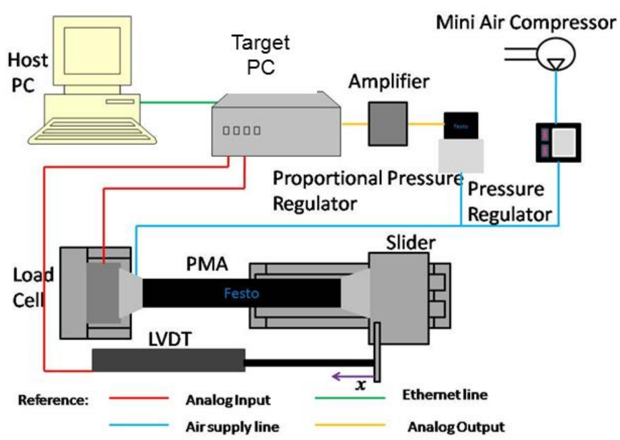

Figure 3. Schematic View of a PMA System Setup

4. Experimental and Simulation Result

4.1. Static Load Study

The main goal of this study is to find the contractile force coefficient as a function of pressure. In this experiment, a vertical load stack is used to supply the required load. This setup consists of a steel weight device weighing 10.79N (1.1kg) which is fastened to one free end of the PMA by a steel cable hung over a steel pulley. The additional steel weight is added to the experiments. Pressure in the range of 100-550kPa and loads in the range of 0-554.26N (0-56.5kg) are tested. The experimental procedure is arranged as follows:

Step 1: Before starting up the experiment, the LVDT and pressure transducer are calibrated to its initial position. Then the LVDT and the pressure transducer are powered and preheated for 10 minutes. The initial end position of the PMA is selected as the reference point. The PMA is then tested under different desired contraction.

Step 2: The muscle is pressurized to a selected value. Then the load is placed on the PMA, the corresponding contractile force generated by the muscle to support the load is read by the load cell. After 10s, the loading support is removed and the pressure at which the muscle returns to its original position is recorded. The load placed on the PMA is the corresponding F_{ce} for the recorded pressure. Each trial is repeated for 5 times. The loads tested are 58.86-545.44N with the increment of 50N and the pressure tested is 100-550kPa with the increment of 50kPa.

Figure 4 presents the result from static loading study conducted. The relationship between the contractile force coefficient F_{ce} N and pressure P kPa is shown in (3).

$$F_{ce} = 0.94P + 94.38 \tag{3}$$

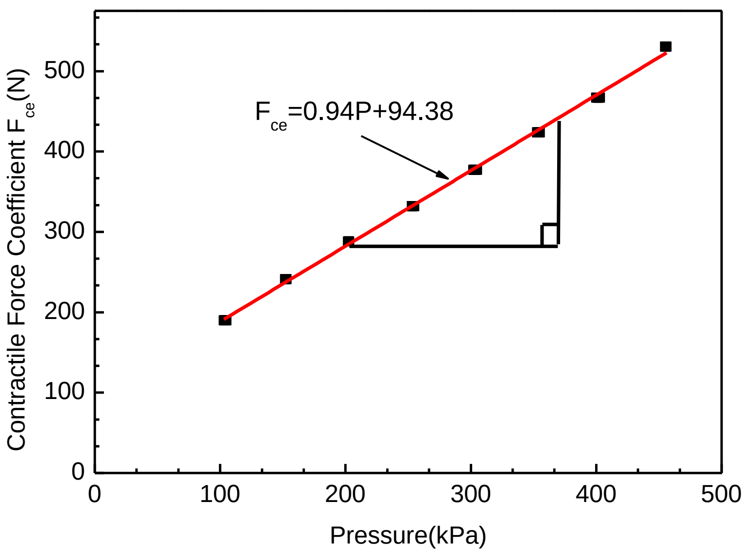

Figure 4. Mean Contractile Element Force Coefficient F_{ce} as a Function of Pressure is Denoted by Square Dot (The Solid Red Line Represents the Regression Line)

4.2. Contraction Study

A contraction study has been conducted on the experimental setup to estimate the value of spring coefficient, K and damping coefficient, B as a function of pressure. During contraction study, the load supply was provided through the steel weight device. The setup was designed similar to the static load study, but different in procedures. To provide independent estimations of K and B as a function of pressure, the pressure was commanded to the proportional pressure regulator at a different step of pressure with the same load. The displacement and pressure data were recorded when pressure reaches steady state. The procedure was repeated for pressure range from 150-500kPa with step increment of 50kPa and the tested loads are 58.86-545.44N with the step increment of 50N.

$$[\ F_{ce}(P) \quad K(P)\ ]\begin{bmatrix} 1 \\ -x \end{bmatrix} = Mg \tag{4}$$

The maximum contraction of the muscle data x_{max} , and the predicted force that generated by the muscle F_{ce} were used to calculate the spring coefficient, K for different load tested under constant pressure. According to (4), the contraction and load data in the same pressure were used to estimate the K by using the least-squares technique. The different pressure will generate a different contractile force and spring coefficient. Based on the changing trend of F_{ce} and K with P, the mean of the spring coefficient K N/mm, versus pressure, P was established. There was a time delay before the contraction starts. This time delay was determined from the sampled data as measured by the pressure transducer at the initial motion of the PMA. The delay is estimated at the average of ±40ms. This is caused by the Coulomb friction of the PMA. The displacement curve is then fit to the general solution shown in (2) to solve for the damping coefficient, B. The exponential curve fit analysis has been used to obtain the damping coefficient value for the pressure tested. Since the transient portion of the contraction data is related to the damping coefficient element and the steady state data is related to the spring coefficient K, it is easy to predict the coefficient values from the PMA displacement curve.

Figure 5 presents the mean of the spring coefficient K N/mm, tested with the different pressure P kPa, on the PMA system. Figure 6 presents the mean of the damping coefficient, B Ns/mm, as a function of pressure P kPa, which has been determined by using exponential fit analysis. The scatter plot of spring coefficient and the damping coefficient is plotted by using the nonlinear curve fit technique.

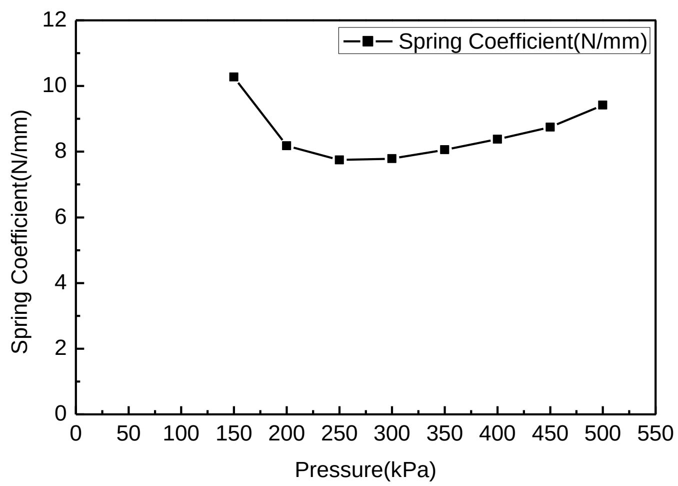

Figure 5. Mean Spring Coefficient *K* (N/Mm) as a Function of Pressure

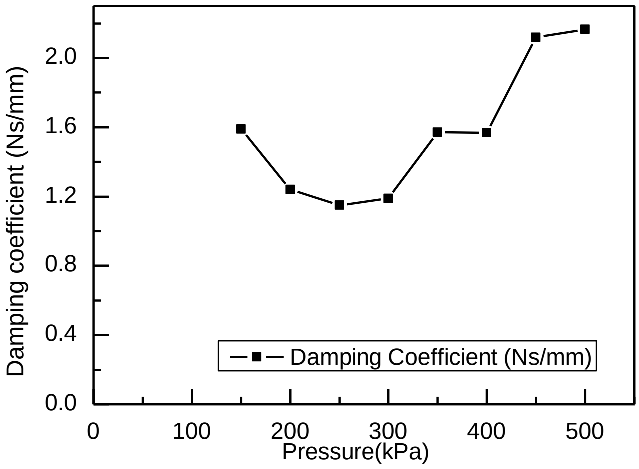

Figure 6. Mean Damping Coefficient *B* (Ns/Mm) with Standard Error Bars is Shown as a Function of Pressure (The Data Shown Is For Contraction Phase Only)

4.3. Validation Study

The experimentally determined K, B and F_{ce} coefficients are verified in simulation. The coefficients values are used to predict the muscle contraction in the simulation environment. As studied in [21], the linearized equation which has been used in the validation study produces a large amount of error during steady state. In order to reduce the linearization influence, the experimental data has been fed in the form of nonlinear curve fit to predict the PMA contraction. The PMA system was tested with the step input of pressure for 200 kPa, 300kPa, 400kPa and 500kPa under 0 N loading conditions.

Figure 7 illustrates the validation result in simulation based on phenomenological model, where the coefficient value were obtained experimentally. The model was tested for a step input of pressure at 200kPa, 300kPa, 400kPa and 500kPa under 0N external loads correspondingly. The solid blue line in the graph indicates the experimental result and the blue dashed-line indicates the simulation result (phenomenological model).

The results in Figure 8 show that the difference between the simulation and experimental results (steady state error) are 0.05%, 0.02%, 0.02% and 0.03%. The steady state error has been collected at the ending of contraction, which is between 8-10s.The result indicates that the phenomenological model is able to predict the contraction of the PMA with the characterized parameters, by maintaining the steady state error below 0.10% as compared to the exact PMA contraction (experimentally). The steady state errors occurred between the simulation and experimental study is due to the nonlinear characteristic of the PMA. The result shows that the steady state error for lower pressure is larger as compared to the higher pressure. This situation existed due to the lighter table and the nonlinear effect of the PMA system. The difference between the static and coulomb friction forces gives an unexpected force to the table and leads to a large steady state error. The nonlinear characteristics also caused by the high static friction ("stiction") between the sheath and the bladder of the PMA. However, it is significant to conclude that the three element phenomenological model is able to predict the dynamic contraction of the PMA under different pressure tested. Therefore, the phenomenological model characteristics depends on the working range and the frictional force ("stiction") of the PMA.

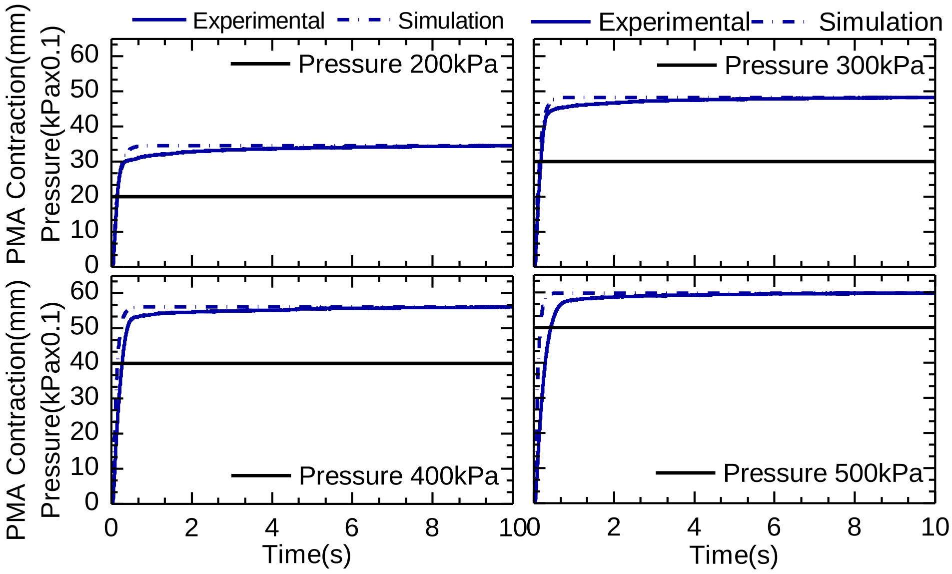

Figure 7. PMA Contraction/Displacement Result for a Step Input in Pressure for 200kpa, 300kpa, 400kpa and 500kpa Under 0N Constant Load

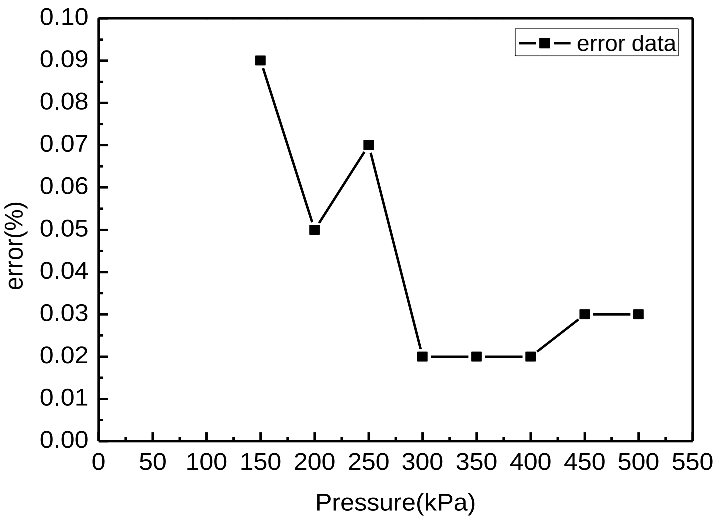

Figure 8. PMA Contraction Error Result under Different Pressure with 50kpa Interval Pressure

4.3.1. Classical Control System Design

After validating the model in the simulation environment, this section will cover the classical control design and its performance evaluation. A classical Proportional-Integral (PI) controller is designed by using the Ziegler Nicholas tuning method 1 as shown in Table 1. The PI controller is designed based the following procedures: First, the mechanism is driven with a proportional gain only. Then, the proportional gain is increased until the sustained oscillation achieved. The optimum proportional gain is defined as K_c (critical proportional gain) (see Figure 9).Then, the ultimate period T_c, which is the time required to complete a one full oscillation while the system is at steady state is noted. By using the K_c and the T_c, the values of K_p and K_i can be determined by referring to Table 1.

Table 1. Ziegler Nicholas Tuning Method 1 Chart

PID Type	K_p	K_i	T_d
P	$0.5K_c$	Inf	0
PI	$0.45K_c$	$T_c/1.2$	0
PID	$0.6K_c$	$T_c/2$	$T_c/8$

Figure 9 shows the response of the system where the critical gain, K_c was determined. The determined K_c is 7.1 and T_c is at 9 seconds. According to Table 1, the calculated proportional gain, K_p is 2.195 and the integral gain, K_i is 3.

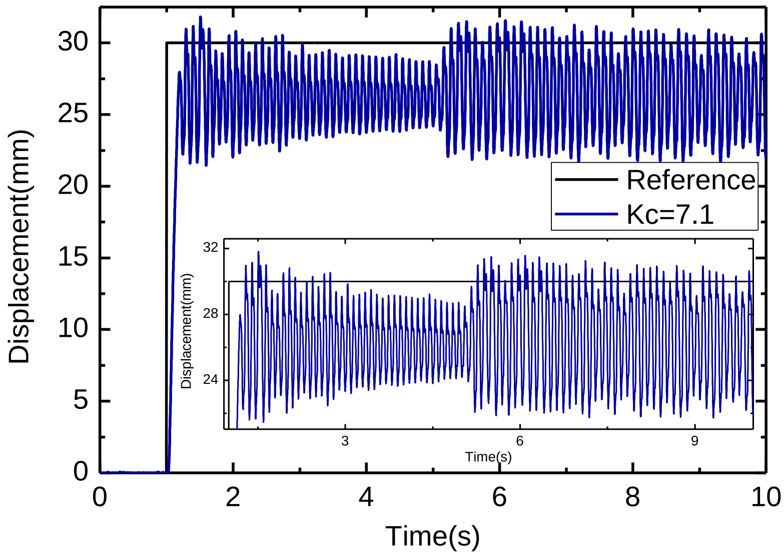

Figure 9. Response of the System with Critical Gain K_c

Figure 10-12 show the positioning responses of the PMA system with PI controller. The blue solid line represents the experimental result; the red dashed-line represents the simulation result and the black solid line represents the reference input. The positioning performance of the PMA system was examined at the contraction range from 10-mm to 60-mm, with step increment of 5-mm. However, only the positioning results of the lowest contraction, mid contraction and highest contraction are presented in this paper.

The positioning results in Figure 10-12 obviously show that the PMA system exhibits oscillation (limit cycle) due to the static friction effect. Due to the high nonlinear characteristics, the static friction in the PMA system exhibit limit cycles when the controller includes an integral term. The limit cycle is an isolated closed trajectory; which means the system oscillates towards or away from the set-point. Whereby, the integral term is considered as the history of the error over time, where the integrator will be summed up with the controller error to minimize the error. Besides that, the stick slip effect occurred due to the compressed air characteristics and the low mass table of the system, which caused the oscillation to be very obvious when the air is being exhausted out from the actuator. The stick slip effect is the area where the nonlinear effect can be seen very obvious. This is the main reason the proportional gain and integral gain have been tuned and optimized to a significant value to maintain the overall steady state error below 1%. However, the PI controller is a linear controller, which fail to show sufficient positioning results towards a highly nonlinear system. Due to the above mentioned reason, future work will focus on proposing a practical and robust control system for the PMA system.

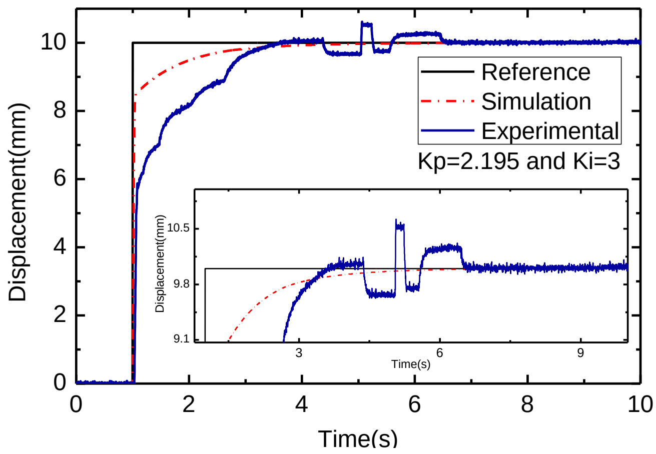

Figure 10. Response of the PI Control System to a 10mm Step Input

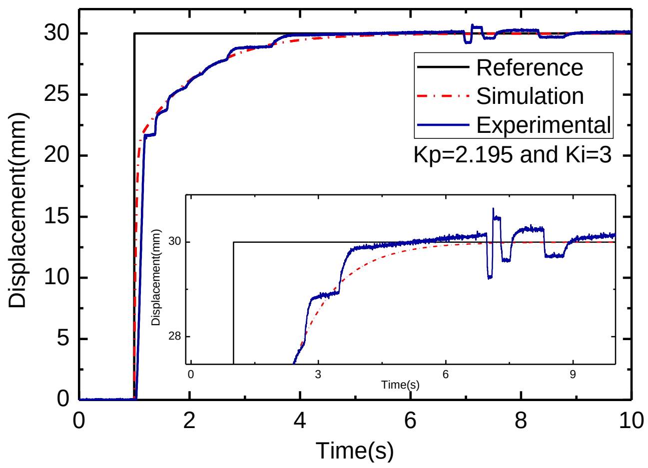

Figure 11. Response of the PI Control System to a 30mm Step Input

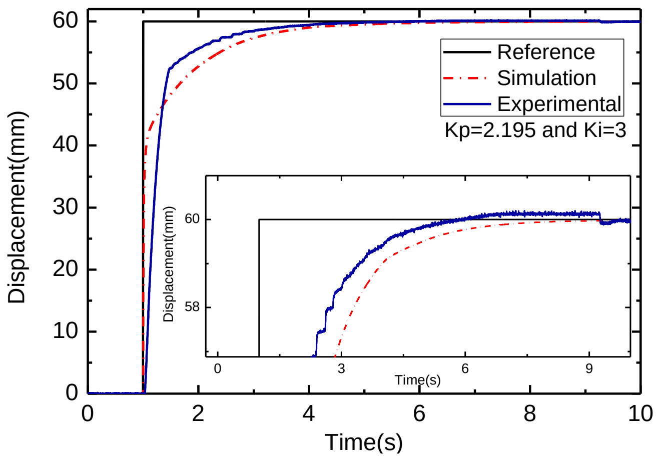

Figure 12. Response of the PI Control System to a 60mm Step Input

5. Conclusion and Recommendations

In the present paper, the three element phenomenological model has been characterized and validated on a PMA system. The characterized model was further validated by a PI controller in simulation and experimental environment. The experiments conducted on a horizontally positioned PMA with loads attached at one end of the muscle were used to characterize the phenomenological model presented. Based on the assumptions and experiments, the contractile force coefficient F_{ce}, spring coefficient K and damping coefficient B as a function of pressure were obtained. The least-square method and exponential curve fit analysis approach were used to determine the displacement curve of the PMA. The characterized phenomenological model shows significant results in predicting the dynamic contraction of the PMA. The proposed phenomenological model is able to predict the PMA contraction for the given input pressure by maintaining the steady state error less than 0.10%.

A Ziegler-Nichols tuned PI controller was proposed and validated via simulation and experiment. However, due to the linear characteristic of the PI control, it fails to show sufficient positioning results for the PMA system that contains high nonlinear characteristics. Therefore, a practical and robust controller will be proposed for the PMA system as the future work.

Acknowledgments

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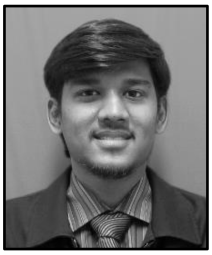

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