MODELLING AND CONTROL OF PAM UNDER LOW PRESSURES AND AT SHORT LENGTHS

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Abstract. *Nowadays, the development of a control system for a pneumatic artificial muscle is of great interest, because it is an important application in robotics, and this actuator is presents the most similar behavior to human muscle behaviour. In this paper it will be considered the modeling of PAM (Pneumatic Artificial Muscle), as well as its control. Two types of modeling are presented, the first one with focus on the geometric model of the muscle and the second one, based on the physics involved in the process. Two different kinds of control are presented, the first one based on the inverse model of the actuator and the second based on fuzzy logic. Model parameters are estimated from data obtained experimentally in the laboratory, and later processed. Thus, besides the theory used, the practice will not be neglected, showing comparisons between the values obtained by simulation and experimentally.*

Keywords: Control, Artificial, Muscle, Fuzzy

1. INTRODUCTION

Pneumatic Artificial muscles (PAM) are actuators with linear motion, operated by the pressure difference, where an increase of the pressure inside the tube results in a contraction of its fibers. Then, its diameter may increase about 25% of the original size, causing a decrease in axial length. Thus, the resulting deformation pulls both ends of the PAM together. The difference between internal and external pressures gives the energy for muscles to increase or decrease its volume and to exert a contraction on its own axis. In most cases, it is much easier to increase the pressure inside the tube rather than decrease it; then, positive relative pressure levels are used.

Figure 1. Pneumatic Muscle MAS-20 from Festo.

In this paper, a model based on the pneumatic artificial muscle produced by Festo, model MAS20-200 is presented. A pneumatic apparatus was built to test the muscles at different loads and pressure levels. Model parameters values extracted from experimental data in different situations are used to develop fuzzy models for the parameters of the analytical model of the PAM. This work also aims to provide support for a general application of this pneumatic actuator; therefore, control techniques based on Fuzzy Logic are presented.

2. THE EXPERIMENT

A test bench was implemented in laboratory to verify the results obtained in numerical simulations. This apparatus keeps the muscle in a horizontal position, clamped in a way to allow only horizontal movement at one end, called the free end, which is coupled to a load cell. A platform, with vertical movement, is attached to the load cell by a cable, which drives a rotation encoder, to measure the system displacement. Thus, whenever the pneumatic muscle is pressurized, it moves only one end, contracting and pulling on the entire system, causing the platform to rise according to the contraction force exerted by muscle.

Load Cell

Different gymnastic rings were used to vary the load on the system. The total load, that means, the weight of platform, rings and connection parts, was measured by a load cell model CS50 Líder, which was calibrated to the load range used in the experiments. After calibration experiments, it was observed that the load cell presents a linear behavior, thus, a linear regression was used to obtain its calibration curve, given in Eq. 1, where S_{cc} is the electric signal sent by the load cell and the mass M is the total load mass.

$$M = 274.26 \times S_{cc} - 211.4 \quad (1)$$

Rotation Sensor

The rotation encoder Pasco Model CI-6538, with a resolution of 0.25 ° (can be converted to 0.055 mm) was employed. The program of Pasco, Data Studio, recognizes the sensor and interfaces it and the data acquisition board used, generating automatically graphs of the measured data, which can be later exported as text data.

Solenoid Valve

The solenoid valve used in this work is manufactured by Metal Work, model 7C10020200. This valve is used to trigger the pneumatic artificial muscle in this work.

Acquisition Board

To provide communication of the solenoid and the load cell with the computer, it was used a data acquisition board model Data Translation DT9802 from Pasco, which could simultaneously drive the actuator (the solenoid valve) and read the sensor (rotation encoder).

3. MODELING

The model presented in Fig. 2 was initially applied to represent a simplified cardiac muscle, as proposed by Y.C. Fung (1993), later for some other kinds of muscle and, finally for artificial ones. Actually it consists on a spring-damper model, with both elements in parallel, widely used in mechanical engineering.

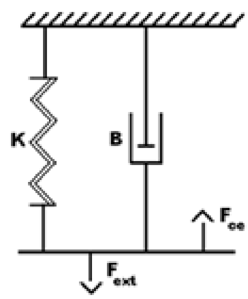

Figure 2. PAM's Model.

The mathematical model of this system is well known and widely explored, and here, shown in Eq. 2. There, K represents the elastic constant, B is the damping constant, F_{ce} is the muscle contraction force, F_{ext} is the external force applied at the free end of the muscle, M is 1/3 of the PAM mass, since it is fixed at one end and X is the displacement produced by the actuator. Measured the contraction, it is possible to calculate the values of muscle stiffness and damping. In order to get a faster response from the simulated model, the model of Eq. 2 was simplified to Eq. 3, using the Laplace Transform and neglecting the inertia. In Serres (2008), a study on the influence of inertia in the system concluded that this can be discarded, since it represents about 1% in the final result.

$$\begin{aligned} &M\ddot{X} + B\dot{X} + KX = F \\ &F = F_{ce} - F_{ext} \end{aligned} \tag{2}$$

$$X(t) - \frac{F}{K}\left(1 - e^{-\frac{K}{B}t}\right) \tag{3}$$

4. EXPERIMENTAL METHODOLOGY

During the experiment, the pressure is varied from 300 kPa to 600 kPa in steps of 50 kPa, because the solenoid valve doesn't work properly for pressures under 300 kPa and the maximal pressure for the pneumatic muscle is 600 kPa according to the manufacturer. The load applied at the free end was varied from 2.7 kg to 36.7 kg.

The pressure regulator is adjusted to the operating pressure and then, the solenoid valve is fired by the computer, during 5 or 90 seconds. Each of these two different time intervals corresponds to a different experiment: the shorter interval is used to evaluate the rise time, whereas in 90 seconds, the steady state is analyzed. For each applied pressure level and mass, two groups, with five experiments in each, are tested, in a total of 700 experiments successfully completed.

Only the standard deviation is used to eliminate spurious data, no other post-processing was carried out. Later, these data is used to adjust the values of stiffness and damping based on the model of Eq. 3.

5. FUZZY PARAMETERS

Fuzzy logic was employed to implement inference systems which could in an easy way to reproduce the relation between load, pressure and contraction force. Two systems were implemented, one for the stiffness and another for the damping, both with the same structure: Mandani inference with two entries and one output, all of them with triangular membership functions. Then, the system parameters are adjusted based on the experimental data.

5.1. Fuzzy Stiffness

Values for stiffness were calculated from Eq. 2, considering steady state, therefore, only the long term experiments (90s interval). The values so obtained are shown in Table 1, which express the relation between stiffness coefficient, pressure and load:

Table 1. Experimental Stiffness

Valores de K					
Pressão	2,7kg	12,5kg	20,6kg	28,6kg	36,7kg
300	10800	10800	12200	10500	11800
350	12050	11900	12900	12650	15100
400	13350	13250	14100	14100	16050
450	14600	14600	15400	15400	17350
500	15750	15900	16650	16850	18600
550	17300	17300	18250	18600	20100
600	18550	18750	19500	20000	21700

In order to state a function to reproduce the relation of Table 1, a fuzzy inference system is used to model the stiffness of the system. The entries were the pressure and the mass; and the stiffness K was the only output. The system has 3 membership functions for the mass, 2 for the pressure and 3 for the stiffness. In Fig. 3, it is shown the resulting surface obtained by this model.

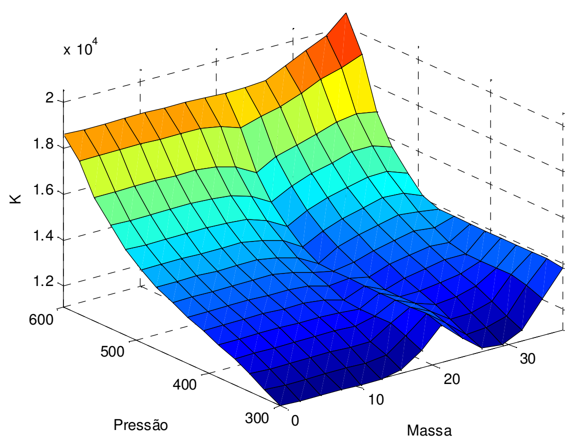

Figure 3. Fuzzy Stiffness

5.2. Fuzzy Damping

The data collected in short time interval experiments were used to train a fuzzy inference system for the damping (B), to capture the characteristics of rising, where the damping has more influence. Eq. 3 was used to calculate the values for each experiment.

Just as in the fuzzy stiffness, the fuzzy damping has two entries, one for pressure, another for mass, and the damping as output. To implement both of the inference systems, Fuzzy Systems Toolbox of MATLAB was used, and the obtained function for damping is shown in Fig. 4.

Table 2. Experimental damping

2,7 kg						12,5 kg					
Pressão	K p/ 5s	Força	B	Soma erro	Erro médio	Pressão	K p/ 5s	Força	B	Soma erro	Erro médio
300	12300	386,52	5500	0,0087		300	11400	290,09	4500	0,0061	3,04E-05
350	13000	480,36	5000	0,0111		350	12700	383,93	4500	0,0072	3,62E-05
400	14200	574,20	5000	0,0104	5,13E-05	400	14000	477,77	4500	0,007	3,47E-05
450	15300	668,04	5000	0,0111	5,44E-05	450	15400	571,61	4500	0,0077	3,87E-05
500	16400	761,88	5000	0,0118	5,85E-05	500	16700	665,45	4500	0,0076	3,79E-05
550	17900	855,72	5000	0,0102	4,99E-05	550	18200	759,29	5000	0,0074	3,67E-05
600	19200	949,56	5000	0,0069	4,68E-05	600	19700	853,13	5000	0,0071	3,54E-05
20,6 kg						36.7 kg					
Pressão	K p/ 5s	forca	B	Soma erro	Erro médio	Pressão	K p/ 5s	Força	B	Soma erro	Erro médio
300	14600	211,10	5500	0,0043	2,18E-05	300	16100	53,32	10000	0,0027	1,41E-05
350	14900	304,94	5500	0,005	2,55E-05	350	15500	127,56	5500	0,0041	2,15E-05
400	15700	398,78	5000	0,0055	2,78E-05	400	16400	221,40	5500	0,0062	3,16E-05
450	16800	492,62	5000	0,0068	3,42E-05	450	17900	315,24	5500	0,0051	2,60E-05
500	18200	586,46	5000	0,006	3,03E-05	500	19000	409,08	5000	0,0057	2,90E-05
550	19200	680,30	5500	0,0077	3,50E-05	550	20800	502,92	5000	0,0061	3,10E-05
600	20600	774,14	5500	0,007	3,50E-05	600	21800	596,76	5000	0,0063	3,18E-05

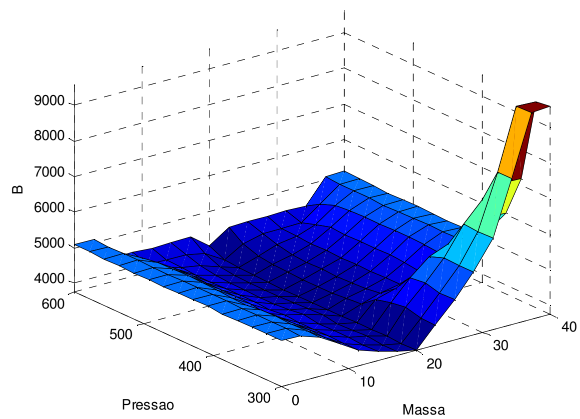

Figure 4. Fuzzy damping

6. CALCULATION OF CONTRACTION FORCE

To calculate the force exerted by muscle contraction, different loads were attached to the free end of the muscle and see when it would return to the previous position, i.e., no mass attached. Thus one can determine a ratio between the pressure required for muscles to sustain a given load, then finding the strength of this artificial muscle contraction. The figure below presents the experimental result found. Then we used a linear regression to formulate the ratio of contraction force and pressure exerted by the muscle.

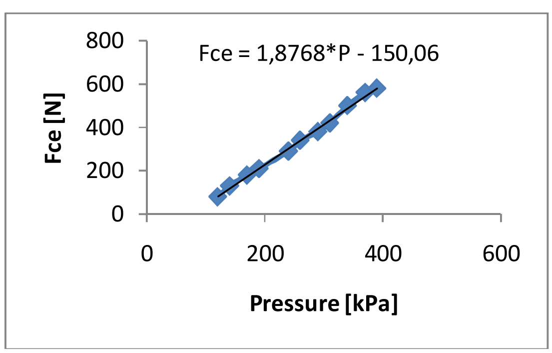

Figure 5. Linear regression for Contraction Force

7. CONTROL

7.1. Model-based Control

It is of interest to know the pressure needed so that the system meets some intended change. Thus, the equations used to control it, should be the inverse of the model presented. To use the inverse model, all the formulas are modified to express pressure as function of desired contraction. From equation 3, one can write:

$$\mathrm{F} = \frac{\mathrm{X} \times \mathrm{K}}{1 - \mathrm{e}^{-\mathrm{K}t/\mathrm{B}}} \tag{4}$$

$$\mathrm{P} = \frac{\mathrm{F} + \mathrm{Mg} + 150{,}06}{1{,}88} \tag{5}$$

Where:

$$\begin{aligned} &\mathrm{F} = \mathrm{F}_{\mathrm{ce}} - \mathrm{F}_{\mathrm{ext}} \\ &\mathrm{F}_{\mathrm{ce}} = 1{,}88 \times \mathrm{P} - 150{,}06 \end{aligned} \tag{6}$$

The fuzzy systems were modified too. In Fig. 3 and Fig. 4 the inputs were the mass and pressure. The new system needs to receive as inputs and the mass and the desired displacement. Thus the surface can be found in the figure below:

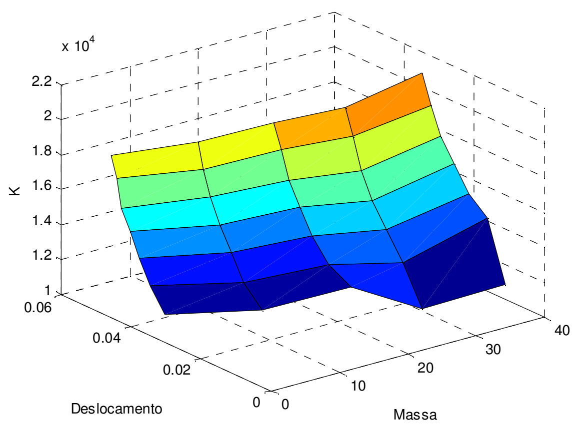

Figure 6. Stiffness surface

The new fuzzy system adopted requires treatment before entering the program MATLAB toolbox for fuzzy logic. The angle between the figure and the axis of mass was calculated, to apply a rotation to the system, adjusting the data to the program. From Fig. 6 we have as rotation angle $\theta = \mathrm{atan}(0{,}0312/34)$, what lead us to the system of Fig. 7 (left).

For the damping, a new system is generated without the need to rotate it, obtaining the response of Fig. 7 (right). In Fig. 7 is possible to see that the damping is less sensitive to the pressure than the stiffness, since stiffness directly affects the steady state value, ie directly on the pressure required.

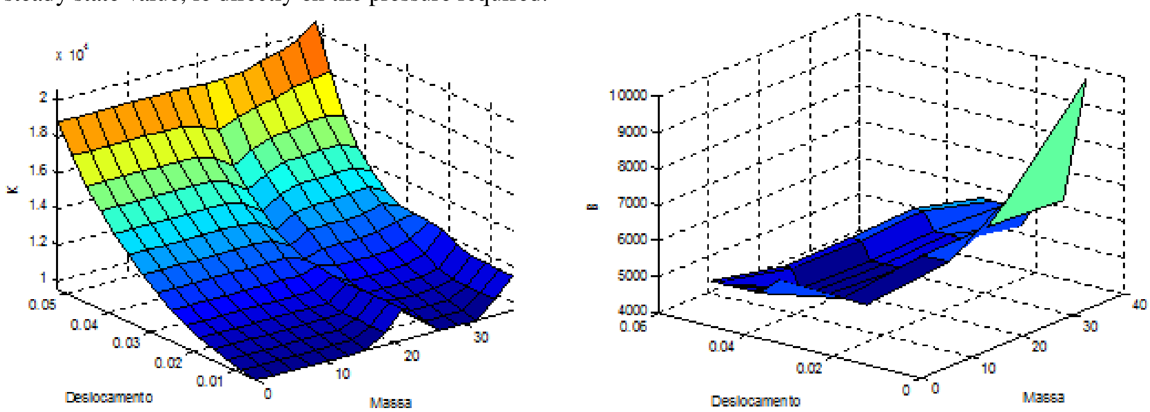

Figure 7. Fuzzy stiffness (left) and damping (right)

7.2. Results

Table 3 shows a preview of the pressure values (in kPa) for the executed experiments as result of the inverse fuzzy models and Eq. 5. For each experiment, the displacement value was applied to Eq. 4 and the calculated value applied in Eq. 5, together to the load mass value (in kg). Then, theoretical pressure values for control are obtained and compared to the real values (measured), which are on the right column of Table 3.

Table 3. Comparison between Experimental and Simulated Pressure

Pressão/Massa	2,70	12,54	20,60	28,60	36,70
300,00	359,97	347,75	306,48	325,21	304,44
350,00	415,19	412,65	366,78	378,38	351,33
400,00	461,93	469,90	428,57	445,23	416,47
450,00	512,90	531,33	501,31	502,32	481,56
500,00	568,06	566,57	540,08	534,83	521,82
550,00	591,60	585,13	560,06	558,87	554,06
600,00	606,42	601,50	584,01	585,82	576,75

8. FUZZY LOGIC CONTROL-BASED

A second fuzzy control system is developed, which uses directly the mass and displacement as inputs and has the pressure as output, instead of calculating stiffness and damping to apply to an analytical model. Without calculation of intermediate variables it becomes faster and doesn't suffer from model approximations errors. In Fig. 8 (right) the trained system is shown and in Fig. 8 (left) a rotation of angle θ = 0.0526 ° is applied in order to adjust the axis.

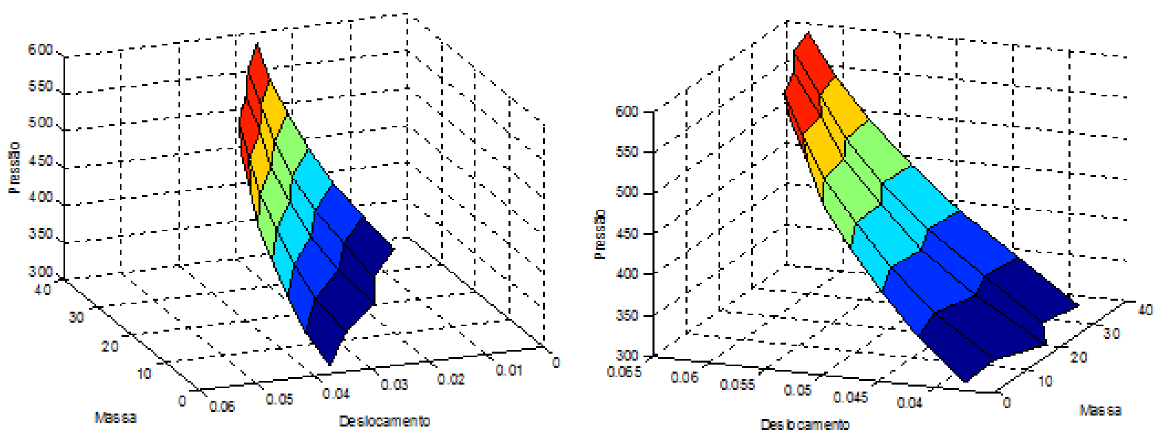

Figure 8. Normal (left) and Rotated (right) Fuzzy Controller with Mandani structure.

For the input variables, four membership functions were created for the load mass, and four for the the displacement. This system follows the Mandani structure, then six membership functions were used in the output (pressure). A second system, which follows the Sugeno structure was implemented, with the same inputs and seven output functions. Thus, it was found the following surface for the fuzzy controller:

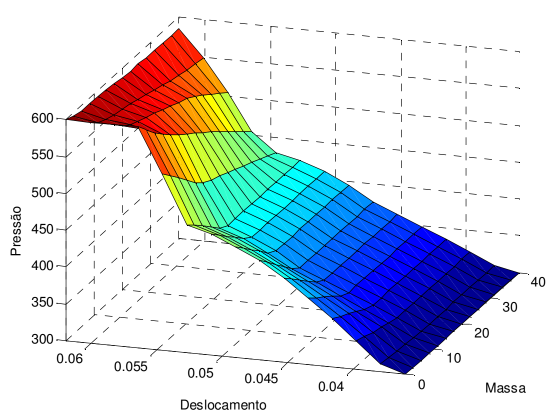

Figure 9. Fuzzy Controller with Sugeno Structure

8.1. Results

The same calculation used to obtain Table 3 is repeated to obtain Table 4 with the Fuzzy system of Fig. 8 (Mandani structure). There, the real values of pressure are on the right column, and the values measured for each load mass are presented in the table. Table 5 shows the percentage of errors found between the measured and the calculated pressure values:

Table 4. Experimental vs. Simulated Pressure Results

Pressão/Massa	2,70	12,54	20,60	28,60	36,70
300,00	314,92	312,14	300,00	315,10	309,05
350,00	369,41	354,18	342,20	353,99	349,14
400,00	406,31	384,94	378,33	396,42	392,15
450,00	433,62	412,73	411,13	425,76	424,64
500,00	451,93	432,55	454,44	492,95	473,17
550,00	461,03	518,74	515,68	546,18	543,42
600,00	474,10	554,32	559,73	565,18	587,30

Table 5. Simulated Error Value

Pressão/Massa	2,70	12,54	20,60	28,60	36,70
300,00	4,97	4,05	0,00	5,03	3,02
350,00	5,55	1,19	-2,23	1,14	-0,25
400,00	1,58	-3,77	-5,42	-0,89	-1,96
450,00	-3,64	-8,28	-8,64	-5,39	-5,63
500,00	-9,61	-13,49	-9,11	-1,41	-5,37
550,00	-16,18	-5,68	-6,24	-0,70	-1,20
600,00	-20,98	-7,61	-6,71	-5,80	-2,12

After analyzing Table 5, is verified that the difficulty remains: in critical cases (low pressure and low mass load), high error is found. The results for the Sugeno system are still worse, therefore, they were omitted.

9. CONCLUSION

From the obtained results it is easy to conclude that at low pressures, to control the pneumatic muscle is a difficult task, as well as for low load mass. The control system presents an acceptable error for all other situations, with both controllers: the pure fuzzy controller and the inverse model controller. The nest step in this work is the implementation of a proportional valve in the test bench, to implement and test the different controllers.

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