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STATIC MODELING OF MCKIBBEN PNEUMATIC MUSCLE

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The Pneumatic artificial muscles - PAMs - also known as rubberactuators, are pneumatic actuators that consist in a tubular elastomer covered by an inextensible braided shell, and, due to the braid pantographic effect, has the ability of contracting itself when a pressurized gas is injected into its interior. Its main characteristics, such as low weight, direct connection to the structure and excellent weight/power ratio has increased its application importance in the field of robotic actuators in the last years. However, its behavior is similar to human muscles, presenting non linearities in all its operation range. Therefore, these non linearities difficult the force control that must to be applied to the actuator. The main objective of this paper is to perform the identification of a self made exemplar, relating the pressure to the force and to the deformation (relation between final length and starting length) using a least squares estimation approach, and compare it to a given known mathematical model. The behavior presented by the self made muscles is similar to others found in the bibliography. Besides, the present paper also seeks to deal with the not treated in bibliography case of pneumatic muscles with lengths bigger than the starting length. So, an enhanced model is proposed for this case and the performance of the real system was compared to this mathematical modified model too. An example of practical application is also presented.

Keywords**: Pneumatic actuators; Mckibben muscle; modeling**

1. INTRODUCTION

Pneumatic artificial muscle is a technology that started in the 1960s for use as artificial limbs. It is also known as McKibben artificial muscles. The power/weight performance of the system and the inherent compliance were seen as positive features but control was a problem, and then development was then discontinued (Davis, 2002, Perondi, 2002). However, interest on pneumatic muscles has increased in the last years because the microcontrollers processing capacity have achieved higher levels, allowing the implementation of more complex mathematical models and control systems (Perondi, 2002).

According to Oarden, 2002, pneumatic actuators are commonly used in industrial and robotic fields, and its mainly attractive characteristics are the low cost and resilient behavior, i.e., they have a great capacity of absorb and store energy. A less known type in this gamma of actuators is the ones called pneumatic muscles. Still in according to Oarden, 2002, and Chou, 1996, its working characteristics differ from the usual actuators (pistons composed by a plunger, rod and cylindric braid) by the existence of contraction when insufflated and that the forces actuating are dependant not only on the internal pressure, but also on the insufflating state.

This actuator class presents lower weight, when compared to the pneumatic cylinders (Chou, 1996). This characteristic is due to the materials used on its assembly. Its main elements are an inner elastomeric tube wrapped by a braided shell, which is composed of inextensible flexible fibers, having connectors in both endings. Again, according to Oarden, 2002, these elements can transmit the same amount of energy as conventional actuators, when both are operating under the same pressure and volume levels.

The modeling of the case in which the muscle is stretched beyond its length at rest is not addressed in most of works in this area. In this situation, however, the muscle develops its maximum force, due to the minimal volume in its interior and due to the mechanical reaction of the interlaced fibers. So, in this paper it is proposed to achieve an expression that intents to deal also with this important condition. That region is important due to the future application of these muscles: a six-legged robot powered by pneumatic muscles, using revolute joints to work under hazardous environmental conditions and rough terrain. For some angle joints configuration, the muscles will be stretched beyond its length at rest, enabling the robot to take advantage of the maximum force which these muscles can provide.

2. WORKING PRINCIPLE

The pneumatic muscle's working principle is based on the pantographic principle (Tondu**,** 2000), as shown in Fig.1 (Geremia, 2007). The pantographic movement is made up by a four-linked bar mechanism, which are kept parallel in pairs. The smaller bars are placed below the bigger ones, and they are articulated to each other. The bigger bars are placed above the smaller ones with their articulation placed along its length (the position may be regulated in order to obtain the desired displacement and force proportions), and articulated one to the other pair in one end (McGraw-Hill, 2002).

When submitted to pressure, the elastomer tends to inflate, but its volume is limited by the braided shell. The shell, therefore, has to increase its diameter to follow the increasing elastomer volume. However, due to the fact that the braided shell's fibers are inextensible, it contracts itself in order to keep the surface constant, thus making the whole muscle to contract, in a similar way to the real human muscles (Chou, 1996, Davis, 2006 and Perondi, 2004),. Therefore, the braided shell is responsible for the traction force, and not the elastomer.

This physical configuration causes the muscle to have characteristics similar to those found on a spring, but with a non-linear passive elasticity (anisotropic behavior), with high physical flexibility and extremely low weight, when compared to most of other artificial actuators (Hannaford and Winters, 1990).

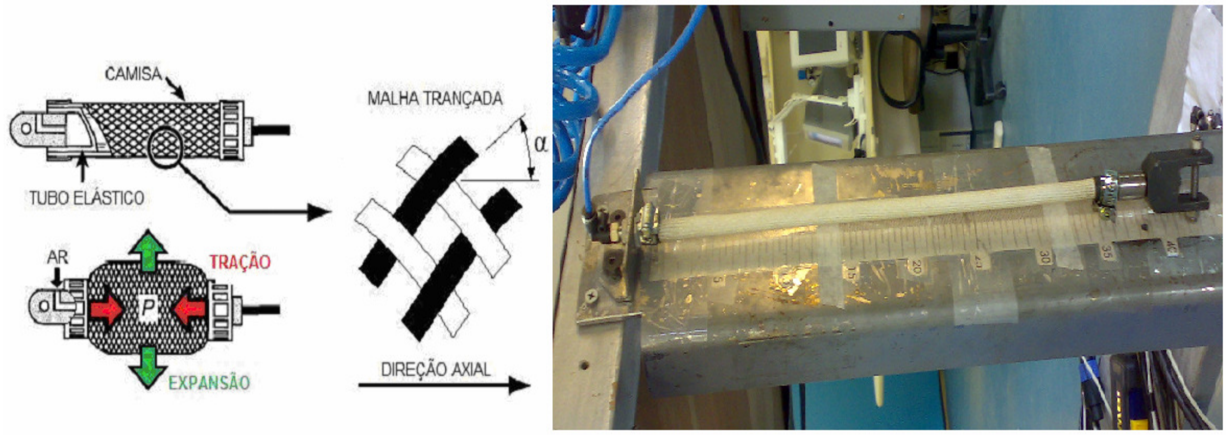

Figure 1 – Pneumatic muscles working scheme and detail of the braided shell (Geremia, 2007), and a picture of the pneumatic muscle used on the present work.

The maximum muscles length is determined by its length at rest and by the space between the interlaced fibers. When the muscle is stretched, the fibers start to press each other, limiting the minimum angle α (see Fig.1). The maximum angle is limited by the same cause.

Experimental studies presented by Caldwell ett alli, 1993, has shown that the maximum volume (and consequently its minimum length) when the angle between the threads on the braided shell is approximately 56.5º.

3. MATEMATICAL MODELING OF A PNEUMATIC MUSCLE

The pneumatic muscle is a highly non-linear element, mainly due to the air compressibility, the elastomer's non-linear behavior and the reaction of the braided shell, which is dependant on its actual length. The traction force exerted by it varies in a non-linear way along the inner pressure and its length (Takuma, 2006).

To observe the muscles behavior and acquire the data needed to mathematically identify the system that represents the muscle, was performed a force test (as a function of pressure and length).

The experiments were performed in a bench composed by a pressure valve, a length regulator and a load cell. The test was accomplished by setting a specific length and linearly varying the pressure, ranging from its maximum value to zero. Then, the data from the load cell was acquired. After that, the actual length was increased and the overall process was repeated. Following this procedure for different lengths, ranging from 75% to 1.05% of the muscles length at rest, it was obtained a tridimensional surface relating pressure, length and force. The correspondent surface is shown in Fig.2, for a 465mm muscle and variation between tests equal to 0,001 m (1 mm).

As already commented, in the pneumatic muscle, the element responsible for the contraction force is the braided shell, not the elastomer. So, as the amount of the fibers on the braided shell that involves the muscle is the same in any transversal section, and these fibers are the parts that effectively contracts the muscle, one can infer that the exerted force does not depends only on the fibers length, but mainly on the number of fibers and on the relation between the initial and actual angle between them. Thus, as a consequence, the force depends also on the amount of pantographic elements along the muscles transversal sections. To verify this theory, the test described above was performed for muscles with different lengths. The results are show in the Fig.3 and Fig.4.

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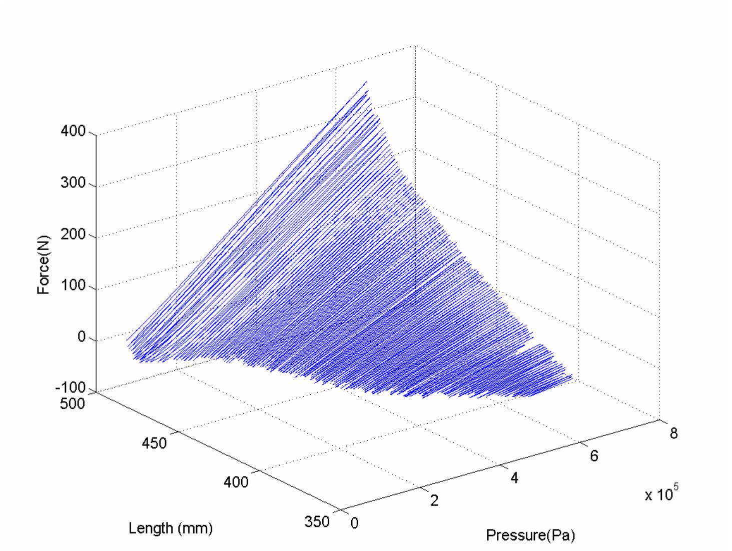

Figure 2. Surface that relates pressure, length and force for a 465mm muscle.

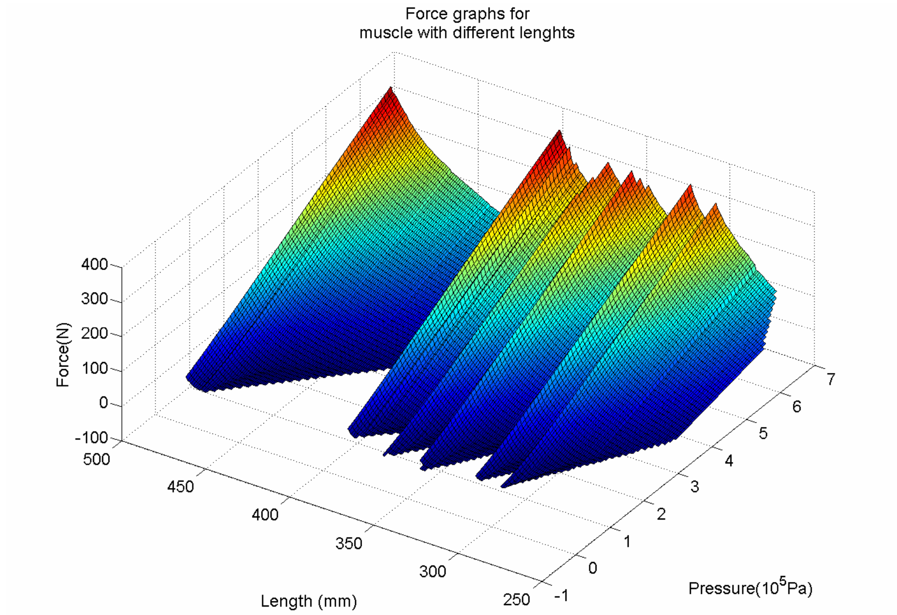

Figure 3: Force measured for muscles with different lengths. The muscles lengths', from left to right, are: 465mm, 378mm, 355mm, 335mm, 310mm e 295mm.

In Fig.4, the surfaces were graphed in relation to the muscles deformation (L/L_0), instead of its length. To ease the visualization, lines were drawn in each pressure level from the maximum force to the level of force equal to zero. The several lines almost overlaid are from muscles with different lengths, proving the fact that the exerted force does mainly depends on its deformation (and the dependence on the length in practically imperceptible).

In order to the muscle to be utilized as an actuator in control systems – such as on a servoposition system – a mathematical model that describes the behavior of the exerted force by the muscles as a function of pressure and length must be known, in order to allow the implementation of a model-based controller. To accomplish that, it was performed the identification of the pneumatic muscle referred in this paper and experimental results were compared whit the theoretical ones provided by the use of the model proposed by Tondu, 2000.

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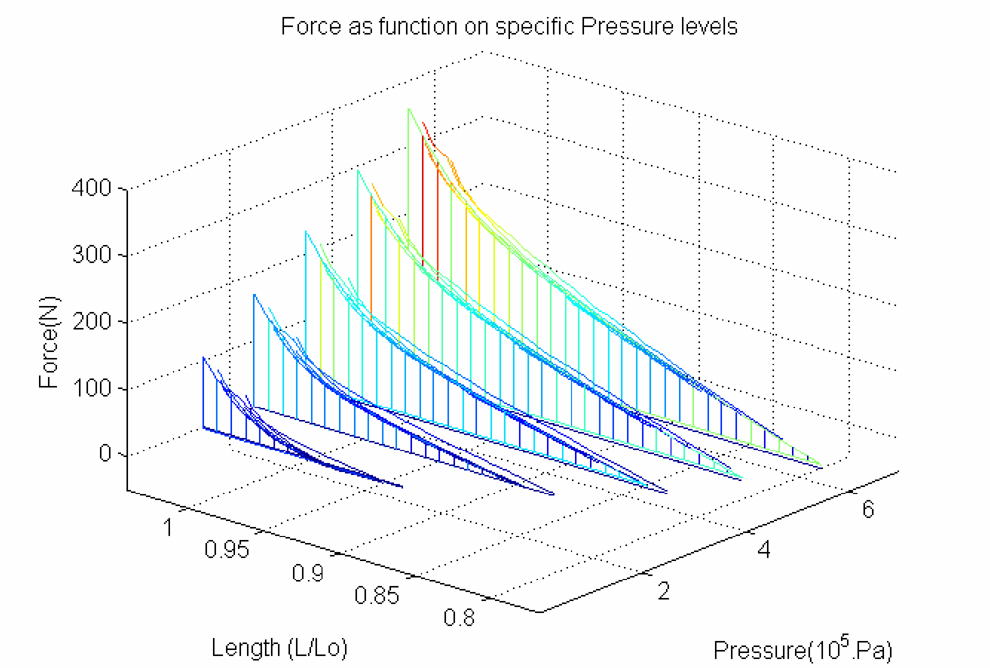

Figure 4 – Force graphs for the muscles of Fig.3, but graphed using deformation (L/L_0) and specific pressure levels. These pressures are (in MPa): 0.55,0.45,0.35,0.25 and 0.15.

3.1 Model based on physical concepts:

In order to verify the similarity between the muscles built at LAMEF – RCA labs, a physical model already published was used to compare the measured and the calculated force exerted by this pneumatic actuator. The chosen model is from a paper published by Tondu, 2000, because the muscle used by the author is similar to the muscle used on the present paper. This equation is based on the principle of Virtual Works, and its development is not in the scope of this work, therefore won't be shown here.

The calculated forces exerted by the pneumatic muscle are given by the Eq.(1), (2),(3) e (4):

$$F(\varepsilon, P) = \pi . r_0^2 . P(a(1-\varepsilon)^2 - b) \tag{1}$$

Where

$$a = \frac{3}{\tan^2(\alpha_0)} \tag{2}$$

$$b = \frac{3}{\sin^2(\alpha_0)} \tag{3}$$

$$\varepsilon = \frac{L_0 - L}{L_0} \tag{4}$$

α_0 is the initial angle between threads of the braided shell in radians, r_0 is the braided shells radius in meters, L is the length, in meters, , L_0 are the initial length and P is the systems pressure, in Pa.

The force calculated by the expression (1) uses the same pressures and lengths shown in Fig. 2. The graphics on Fig 5 and 6 shows the calculated force and the difference between the calculated and measured forces.

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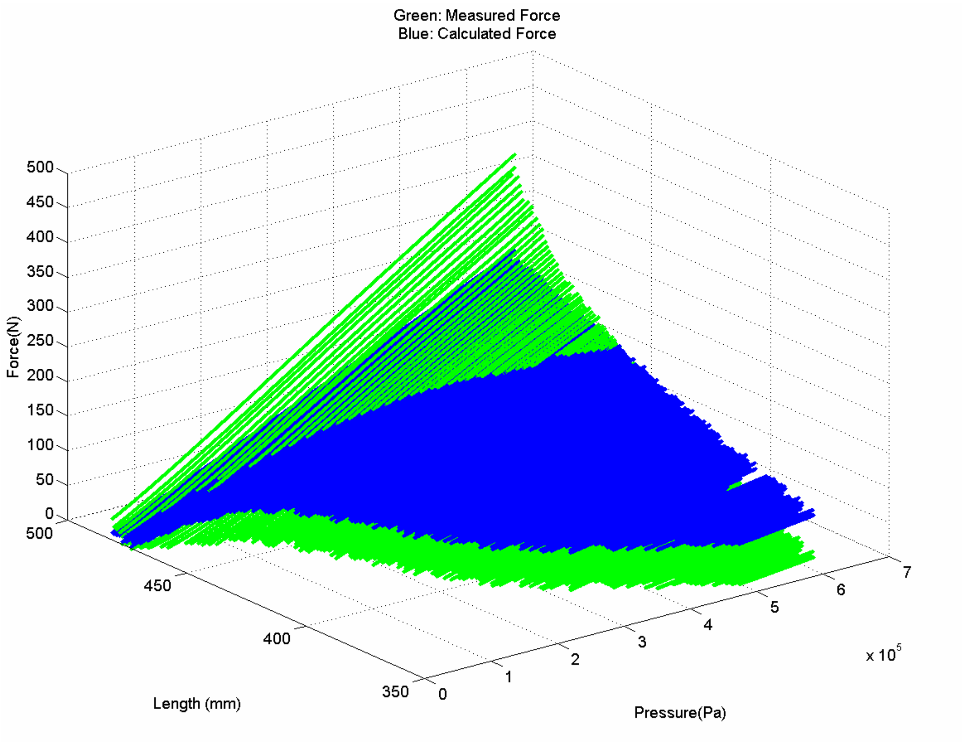

Figure 5: Calculated and measured forces using Eq.(1).

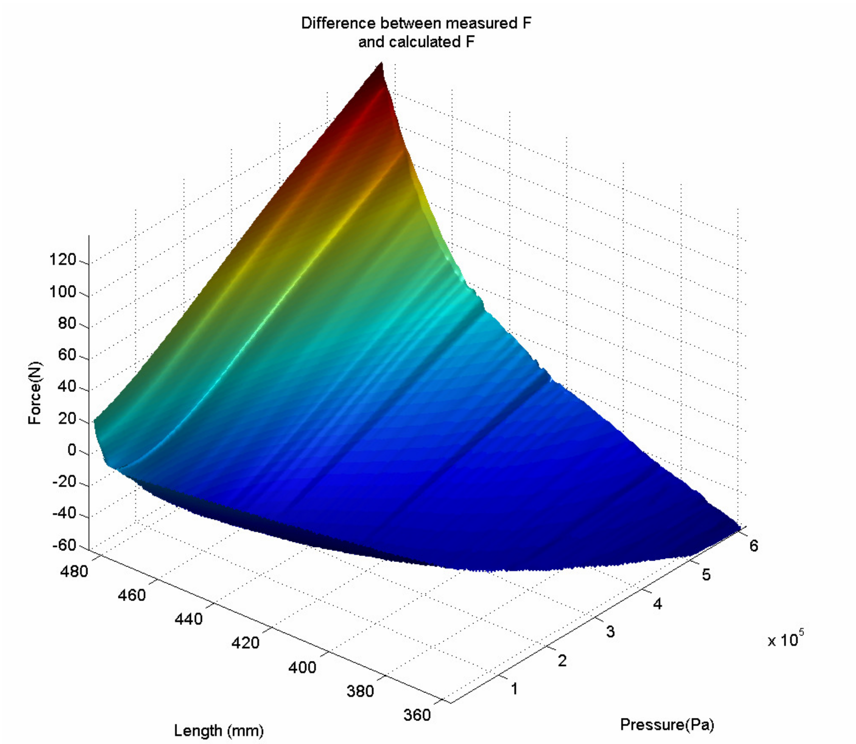

Figure 6. Difference between the measured and calculated forces - note that the largest error occurs when the length is bigger than the length at rest, i.e., when the muscle is stretched.

From the figures 5 and 6 it can be see that the proposed model does not represents the muscle with accuracy; the maximum error, when the muscle is stretched and the pressure is at its highest value, is about 40%. The arithmetic mean of the modules sum in the surface of Fig. 6 is 89,15 N. The percentage error is 9.09%.

Since the pneumatic muscle will be applied in a precise system (an inspection robot), it is desired that the error on the muscle's model be as close to zero as possible in a way that a model based controller be more accurate. In order to accomplish this, a new model must be developed.

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3.2. System Identification

Due to the increase in the computers processing capacity (Ferris, 2006), it has become possible to perform experimentations to obtain the value of the systems parameters and its behavior. This process is known as system identification, and is highly dependant on the subject that will be identified. Therefore, many expressions schemes were tested, in order to obtain an expression as close as possible to the real system and in the simplest form feasible. This is desired if the equation is to be embedded in a microcontroller, because a simple expression will probably not overload the control hardware system.

Thus, analyzing the graphics in Fig. 2, it can be found that the force exerted by the muscle raises when it is stretched and when it is submitted to pressure. It can also be found that the growth in exerted force with the increase of the pressure is slightly linear, and the slopes coefficient of the curve with a constant length varies with the actual muscle's elongation. It is also visible that a variation in pressure results into a curve similar to a parabola for small force levels. Thus, an expression containing simple, quadratic and cross terms were proposed. Yet, after some experimentation, the whole expression was divided by simple terms. Then, the Eq. (5) was obtained.

$$F = \frac{c_1.P^2 + c_2.\varepsilon^2 + c_3.P + c_4.\varepsilon + c_5.P/\varepsilon + c_6}{c_7.P + c_8.\varepsilon} + c_9 \tag{5}$$

The constants c_1, $c_{2,...}$, c_9 were calculated by the least squares estimation approach and MATLAB software. However, when the muscle is stretched beyond its length at rest, the increase in the force is almost exponential, due to the braided shells reaction. Then, to include this change in the forces behavior in the Eq. (5), an exponential term depending on ε was added to it. Then, the Eq. (6) was obtained.

$$F = \frac{c_1.P^2 + c_2.\varepsilon^2 + c_3.P + c_4.\varepsilon + c_5.P/\varepsilon + c_6}{c_7.P + c_8.\varepsilon} + c_9 + c_{10}.e^{(\varepsilon\text{-}0.7)} \tag{6}$$

The expression term "(ε-0.7)" was chosen because the exponential parcel becomes significant only when ε is comparable to the unity, i.e., when the muscle is very close to its length at rest.

Figure 7 shows the force surface calculated with the Eq. 6 (green lines) overlaid on the measured surface (black lines). Figure 8 present the difference between the two force surfaces shown in Figure 2.

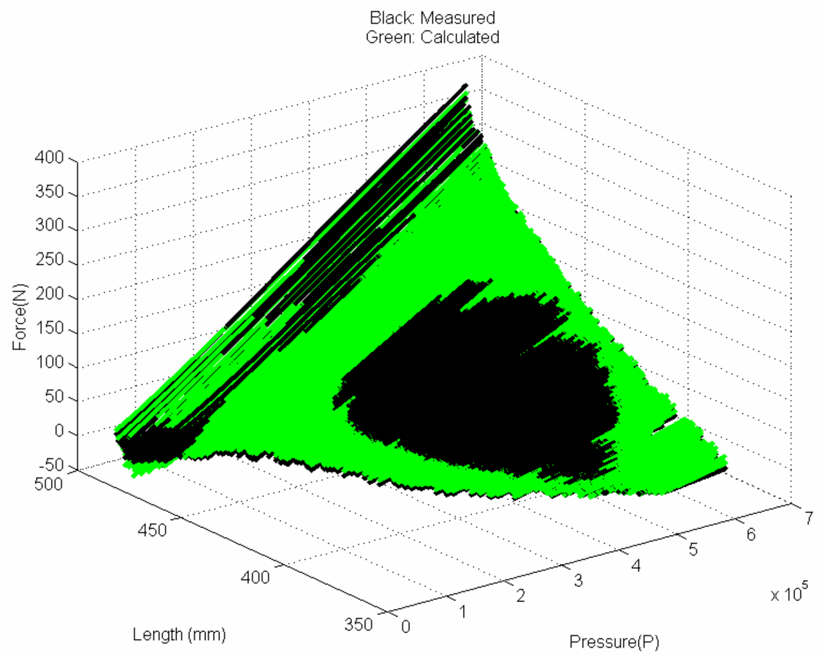

Figure 7. Calculated and the measured curves. The several intersections amongst both surfaces show that the force which was calculated using Eq. (6) is very close to the measured force on Fig. 1.

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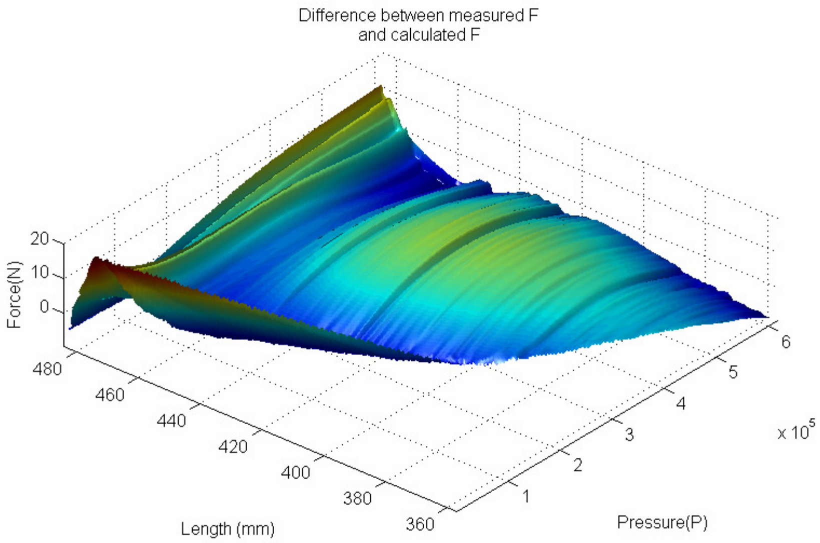

Figure 8. Difference between measured and calculated forces on Fig. 8. Note that the most significant error occurs at low force levels.

The arithmetic mean of the modules sum in the force's surface of Fig. 8 is 3.0695. The percentage error is 0,77%. It can be noted in Fig. 8 that the error is more significant when the force levels are close to zero.

4 – Application:

The objective of mathematically describe the pneumatic muscle here presented and developed at UFRGS-LAMEF (http://www.lamef.demet.ufrgs.br/rca-index.html), with the support of LAMECC_UFRGS (http://www.mecanica.ufrgs.br/lamecc/) is to use it in a pneumatic hexapod robot which can then be used in rough terrain and in hazardous areas with risk of explosion. In such areas, electric motors are not allowed due to the fact that a single spark could start a fire, followed by an explosion.

This robot should be capable of set each leg's position by itself, and the only command issued by the operator will be the general directions, such as forward, back, left and right. RCA-LAMEF laboratory intends to develop the overall robot, including its mechanics and control system. A picture of this robot is shown in Fig. 9.

This robot is still in early development and only one prototype leg has been constructed, in order to gain the necessary knowledge to construct and control the whole system. The equations of kinematics (Denavit-Hartenberg), reverse kinematics and Dynamics (Euler formulation) are already implemented.

In the Fig. 9 it can be seen the sets of muscles that will be used as actuators to move the robot. The blue cables are the pressure lines that provides the pressurized air needed to contract the muscle. The hardware can be found in the metal box on the right side of the picture.

For a single pair of antagonistic muscles, the control system can be implemented using a PID with feed-forward term or a model-based adaptative control, for better performance, as shown at Medrano-Cerda, 1995, and Karnjanaparichat, 2008. However, these techniques suffer from variation on physical parameters, such as supply pressure fluctuations, pipe length, temperature and muscle characteristics, thus making the overall performance insufficient for a precise motion control.

To improve the system's response, advanced control techniques must be included, such as feedback linearization, equations of dynamics, actuator model (Spong, 1989), state observers, cascade control (Perondi, 2002) and so on.

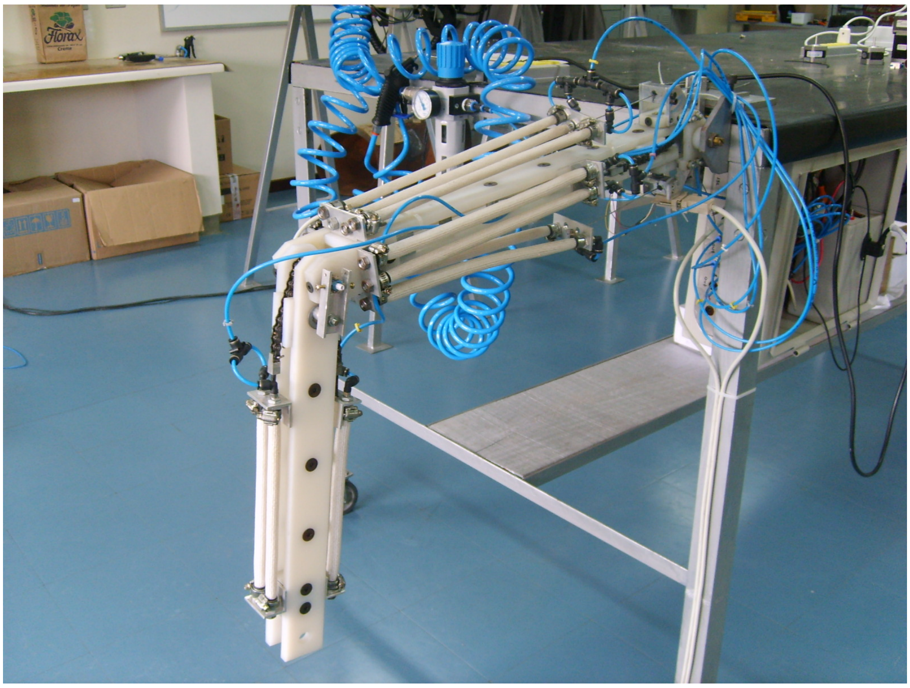

Figure 9: Leg of the pneumatic robot

5 – Conclusions:

It was already discussed the importance of a precise and simple expression to describe the behavior of the pneumatic muscle, so it can be successfully used in a microcontroller in order to control it, i.e., a servoposition system. After comparing the modeling methods described before, the mathematical model takes serious advantage in both aspects over the physical model: it is simpler, because it uses just multiplications and divisions, and it is much more precise.

To measure the time needed to evaluate the physical model of Eq. (1-4) and the identified system of Eq. (6), the expressions were implemented on the software MATLAB and the points on the surface on Fig. 2 were used on both equations. To evaluate all the data with the expression from physical concepts, 0.004183 s were needed. The identified system, represented by the Eq. (6) took 0,004025 s, about 4% faster than the physical model. Besides, several microcontrollers do not support trigonometric functions, making the task of embedding these expressions much more difficult and costly, since more peripheral hardware must be used in order to evaluate these expressions.

6. ACKNOWLEDGEMENTS

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