# FUNCTION APPROXIMATION FOR THE FORCE GENERATED BY DIFFERENT FLUID MUSCLES

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**ABSTRACT**

The main disadvantage of the pneumatic artificial muscles (PAMs) is that their dynamic behaviour is highly nonlinear. Designing an adequate control mechanism for this highly non-linear system needs precise modelling. This paper presents our new, accurate and simple approximation model of PAM, comparing with measured and literary data.

## 1. INTRODUCTION

Many researchers have tried to find an actuator similar to human muscles. The most promising actuator in this field of research is undoubtedly the McKibben pneumatic muscle actuator. The McKibben muscle was invented in the 1950's by physician Joseph L. McKibben to help the movement of polio patients and to motorize pneumatic arm orthotics. There exists several types of artificial muscles that are based on the use of rubber or some similar elastic materials, such as the McKibben muscle, the Rubbertuator made by Bridgestone company, Air Muscle made by Shadow Robot company, Fluid Muscle (Figure 1.) made by Festo company, Pleated PAM developed by Vrije University of Brussel, ROMAC (RObotic Muscle ACtuator), Yarlott and Kukolj PAM and some others [1].

A pneumatic actuator consists of an internal rubber bladder surrounded by a braided shell with flexible yet nonextensible threads according to a helical weaving that is attached at either ends. When inflated, the internal bladder tends to expand, with a consequent increase in the angle between the helical woven fibres of the braid and the axis of the tube and a decrease in axial length [2].

*Figure 1. Fluid Muscles made by Festo*

The Fluid Muscles type DMSP-20-400N-RM-RM (with inner diameter of 20 mm and initial length of 400 mm) and DMSP-10-250N-RM-RM (with inner diameter of 10 mm and initial length of 250 mm)produced by Festo company were selected for our newest study.

The layout of this paper is as follows. Section 2 (Materials and Methods) is devoted to display our test-bed for investigation of pneumatic muscle and to demonstrate the model of force as a function of pressure and length (contraction). In section 3 (Results and Discussion), we presents our new approximation algorithm and gives some comparisons for measured and literary data. Finally, section 4 (Conclusions and Future Work) gives the investigations we plan.

## 2. MATERIALS AND METHODS

Good descriptions of our test-bed (Figure 2.) and experimental results can be found in [3].

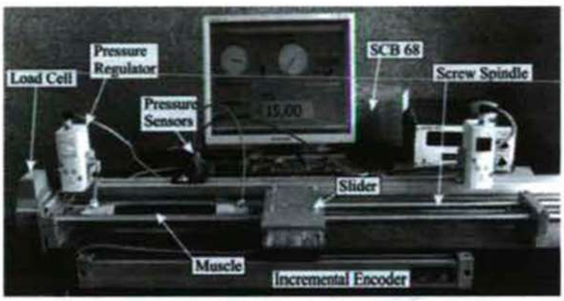


*Figure 2. Experimental setup for investigations of PAMs*

With the help of this test-bed we can investigate one muscle and two muscles or muscle-spring system in antagonistic setup.

The general behaviour of PAM with regard to shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and of the braid at rest, and on the materials used (Figure 3.) [4].

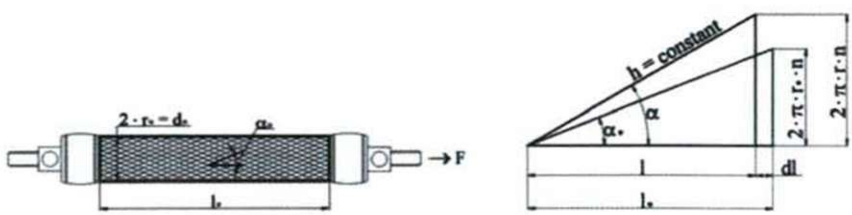


*Figure 3. Geometry parameters and orthotropic material layers of PAM*

On the basis of [5] and Figure 3., the force can be calculated:

$$F = \pi \cdot p \cdot r_0^2 \cdot \left( \frac{3}{tg^2 \alpha_0} \cdot \frac{l^2}{l_0^2} - \frac{1}{\sin^2 \alpha_0} \right) = \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1-\kappa)^2 - b) \tag{1}$$

$$\text{with } a = \frac{3}{tg^2 \alpha_0}, \quad b = \frac{1}{\sin^2 \alpha_0} \text{ and } \kappa = \frac{l_0 - l}{l_0}$$

*Where:* $F$ the pulling force, $p$ the applied pressure, $r_0$, $l_0$, $\alpha_0$ the initial inner radius and length of the PAM and the initial angle between the thread and the muscle long axis, $r$, $l$, $\alpha$ the inner radius and length of the PAM and angle between the thread and the muscle long axis when the muscle is contracted, $h$ the constant thread length, $n$ the number of turns of thread and $\kappa$ the contraction.

Equation 1 is based on the admittance of a continuously cylindrical-shaped muscle. The fact is that the shape of the muscle is not cylindrical on the end, but rather is flattened, accordingly, the more the muscle contracts, the more its active part decreases, so the actual maximum contraction ration is smaller than expected.

Tondu and Lopez in [5] consider improving equation 1 with a correction factor ($\varepsilon$), on the one hand, it does not pay attention to the material that the muscle is made of, and on the other hand, it predicts for various pressures the same maximal contraction. This new equation is relatively good for higher pressure ($p \geq 2$ bar). Kerscher et al. in [6] suggest achieving similar approximation for smaller pressure another correction factor ($\mu$) is needed, so the modified equation is:

$$F(p,\kappa) = \mu \cdot \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1-\varepsilon \cdot \kappa)^2 - b) \qquad (2)$$

$$\text{with } \varepsilon = a_\varepsilon \cdot e^{-p} - b_\varepsilon \text{ and } \mu = a_\kappa \cdot e^{-\kappa \cdot 40} - b_\kappa$$

## 3. RESULTS AND DISCUSSION

The working principle of the Festo Fluid Muscle is similar to the McKibben muscle, so the previous models for the dependence between force, pressure and contraction of the McKibben can be used. Firstly, we compared the measured data and force model using equation 1.

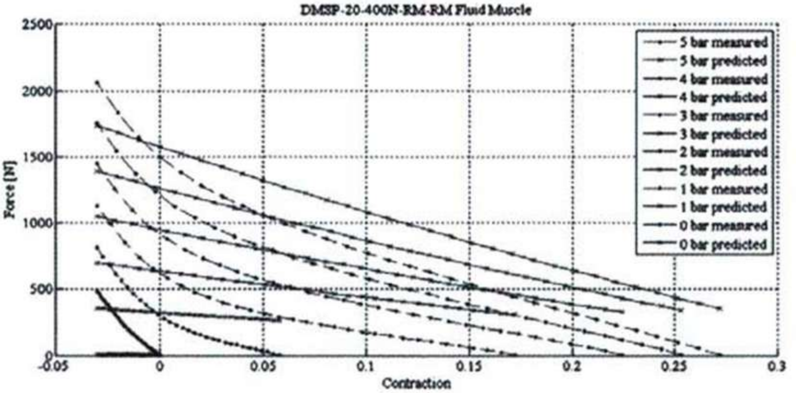


***Figure 4. Comparison of measured data and force model using equation 1***

As it is shown in Figure 4., there is only one intersection between the measured and calculated results and no fitting.

In the interest of fitting we repeated the simulation with equation 2. The coefficients ($a_\varepsilon$, $b_\varepsilon$, $a_\kappa$ and $b_\kappa$) of equation 2 were found using genetic algorithm in MATLAB (Figure 5.).

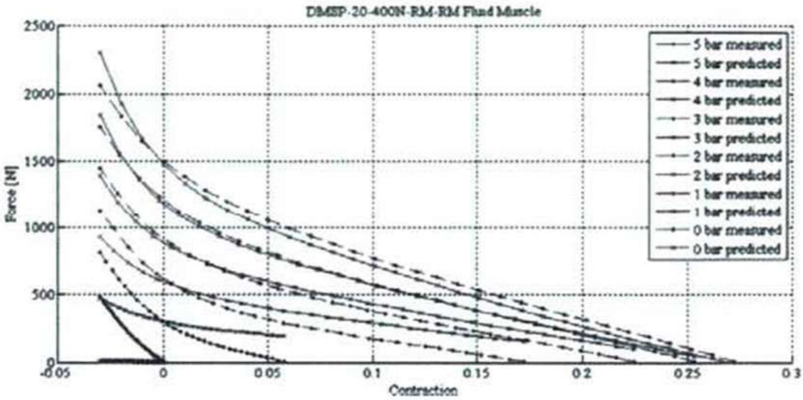


*Figure 5. Comparison of measured data and force model using equation 2*

Figure 5. shows the measured and predicted results still do not fit, for this reason we had to widen the search parameters of the genetic algorithm. With the help of it, a better fitting was attained (Figure 6.), but at a pressure of 0 bar we still have a rather substantial inconsistency.

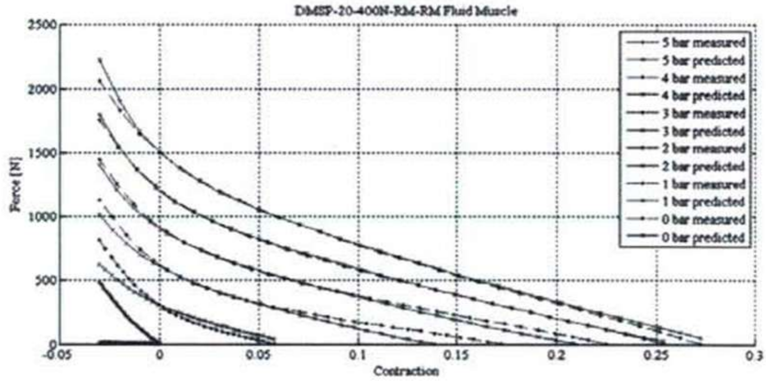


*Figure 6. Comparison of measured data and force model using equation 2 with the widening of the search parameters*

In the interest of better fitting under different pressures including 0 bar we have introduced a new approximation algorithm:

$$F(\kappa) = a \cdot e^{(b \cdot \kappa + c)} + d \cdot \kappa + e \tag{3}$$

Under fixed pressure the contraction to force function can be approximated with a general exponential function with first order correction polynomials of contraction.

To make our equation 3 universal meaning usable under various pressures we needed to make the algorithm vary from pressure:

$$F(p,\kappa)=(a\cdot p+b)\cdot e^{(c\cdot\kappa+d)}+(e\cdot p+f)\cdot\kappa+g\cdot p+h \tag{4}$$

The unknown *a, b, c, d, e, f, g* and *h* parameters can be found using genetic algorithm, too. The fitting with the 8 parameters received from the algorithm can be seen in Figure 7.

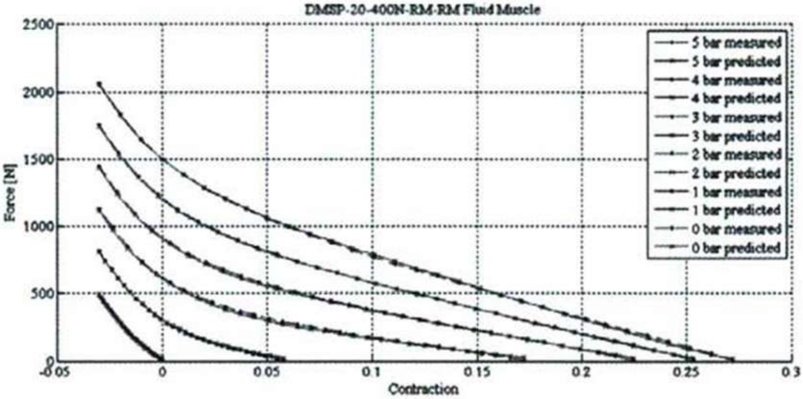


***Figure 7. Comparison of measured data and force model using equation 3***

As we can see we have consistent fitting even at a pressure of 0 bar.

Chou and Hannaford in [7] report hysteresis to be substantially due to Coulomb friction, which is caused by the contact between the bladder and the shell, between the braided threads and each other, and the shape changing of the bladder. An experiment was made to illustrate the hysteresis (Figure 8.).

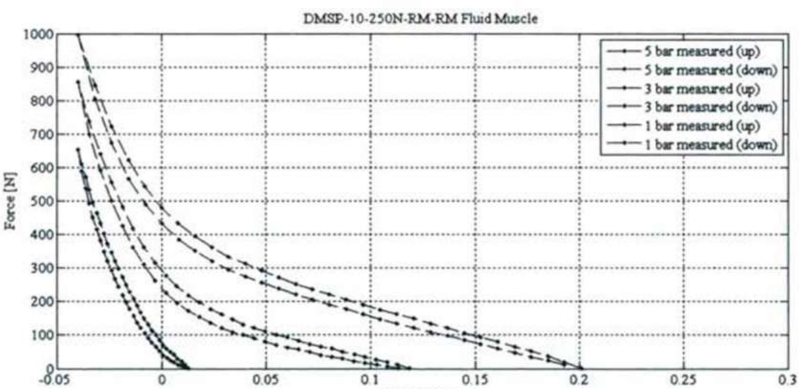


***Figure 8. Hysteresis in the tension-length (contraction) cycle***

To prove versatility of equation 4, another comparison was done between the measured data and force model. The accurate fitting is demonstrated in Figure 9.

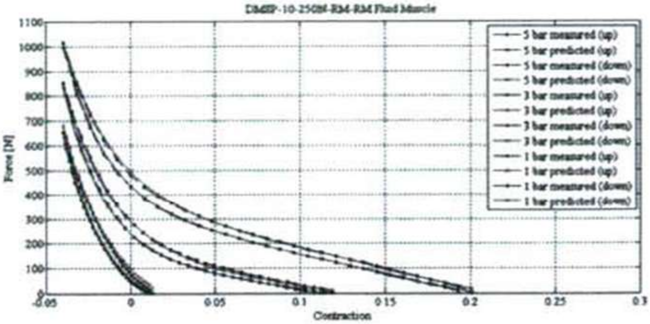


*Figure 9. Approximation of hysteresis loop*

## 4. CONCLUSION AND FUTURE WORK

In this work a comparison of theoretical and measured forces generated by pneumatic artificial muscle has been shown. As we can see there is a substantial difference between the measured and predicted forces, for this reason we had to develop a radically new equation based on purely statistical approach. With the help of it precise curve fitting can be proven for any fluid muscles. Our goal is to develop a new mathematical model for pneumatic artificial muscles on the basis of our approximation model and to construct a prosthetic arm with PAMs, because these muscles seem a better choice than present day electric or other drives.

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