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NEWEST APPROACH TO MODELING HYSTERESIS IN THE FORCE-CONTRACTION CYCLE OF PNEUMATIC ARTIFICIAL MUSCLE

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ABSTRACT: *Electric, hydraulic and pneumatic drives are widely used in industrial environment. In robotics different types of pneumatic actuators - e. g. cylinders and pneumatic motors - can be found commonly to date. A less well-known type is that of the so-called pneumatic artificial muscles (PAMs). Different designs have been developed, but the McKibben muscle is the most popular and is made commercially available by different companies, e. g. Fluidic Muscle manufactured by Festo Company. This paper presents the static model of PAM and our newest model for the force generated by Fluidic Muscle. The accuracy of this new model for the hysteresis loop is analysed by mathematical methods of statistics.*
KEYWORDS: *Fluidic Muscle, Static Model, Hysteresis, MS Excel Solver. Correlation*

INTRODUCTION

The working principle of different pneumatic muscles is well described in [1.], [2.], [3.], [4.], [5.] and [6.]. PAM's have various names in literature: Pneumatic Muscle Actuator, Fluid Actuator, Fluid-Driven Tension Actuator, Axially Contractible Actuator, Tension Actuator, etc. [3.], [4.] and [7.].

Most types of PAM's consist of a rubber bladder enclosed within a helical braid that is clamped on both ends. A PAM's energy source is gas, usually air. The muscle will expand radially and contract axially when inflated, while generating high pulling forces along the longitudinal axis. The tensile force depends on the contraction and the pressure of actuator (Figure 1). This feature is totally different from pneumatic cylinders, because a cylinder develops a force that depends on the applied pressure and piston surface area and independent from displacement [4.]. Typically, the air muscle can contract by about 25 % of its initial length.

In the force-contraction cycle hysteresis can be observed. Chou and Hannaford in [2.] 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.

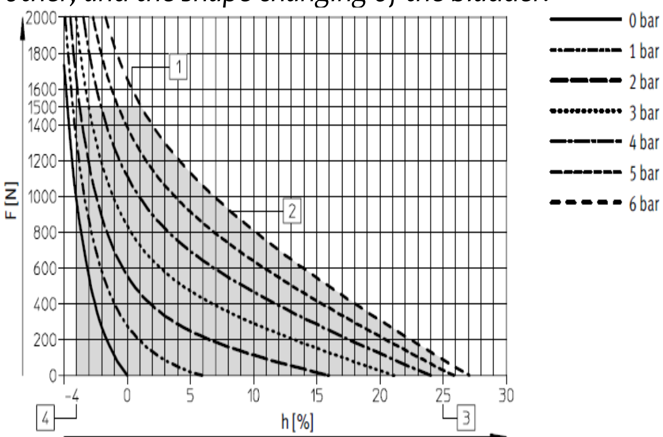

Figure 1. Isobaric force-contraction characteristics of Fluidic Muscle with inner diameter of 20 mm [8]

where: 1 - Maximal force, 2 - Maximal operating pressure, 3 - Maximal deformation (contraction), 4 - Maximal pretensioning.

Many researchers have investigated the relationship of the force, length and pressure to find a good theoretical approach for the equation of force produced by pneumatic artificial muscles, e. g. [2.], [3.], [5.], [9.], [10.] and [11.]. In most cases, significant differences have been noticed between the theoretical and experimental results. [12.] proves the accuracy of fitting using mathematical method of statistics (correlation index R = 0.998-0.999), only, but it is valid for SAM (Shadow Air Muscle) made by Shadow Robot Company.

The layout of this paper is as follows. Section 2 (The Study) is devoted to illustrate the static models on the basis of professional literature and our new force models. Section 3 (Results and Discussion) presents comparison between the measured and theoretical data for the hysteresis loop. Finally, section 4 (Conclusion) gives the investigations we plan.

For this study Fluidic Muscle type DMSP-20-400N-RM-RM (with inner diameter of 20 mm and initial length of 400 mm) produced by Festo Company is selected.

THE STUDY

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 (Figure 2), and on the materials used [3].

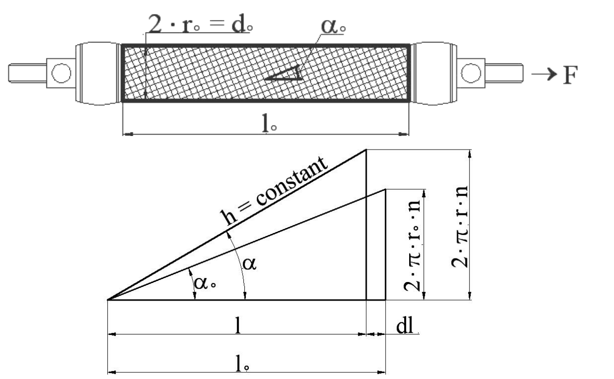

Figure 2. Geometry parameters of PAM

where: F the pulling force,
r_0 the initial inner radius of PAM,
l_0 the initial length of PAM,
α_0 the initial angle between the thread and the muscle long axis,
r the inner radius of the PAM when the muscle is contracted,
l the length of the PAM when the muscle is contracted,
α the 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.

Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres. Figure 3 shows the materials of Fluidic Muscles.

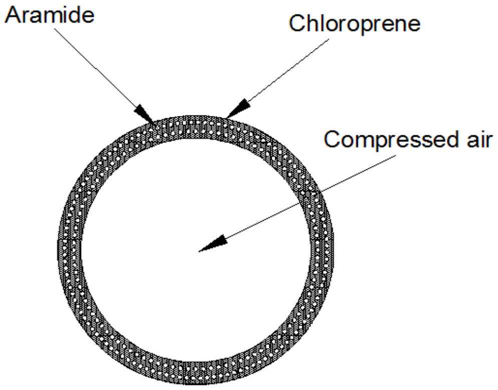

Figure 3. Materials of Fluidic Muscles

Good description of the general static model of PAMs can be found in [2.], [3.], [5.] and [13.]. On the basis of them the force equation is found:

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

where: $a = \dfrac{3}{tg^2\alpha_0}$, $b = \dfrac{1}{\sin^2\alpha_0}$, $\kappa = \dfrac{l_0 - l}{l_0}$ *and*

p the applied pressure,
ϰ the contraction.

Equation 1 was modified by Tondu and Lopez [5.] and Kerscher et al. [11.] with correction factors ε and μ:

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

Significant differences between the theoretical and experimental results using equation 1 and equation 2 have been proved in [13.] and [14.]. To eliminate the differences new approximation algorithms with six and five unknown parameters has been introduced for the force generated by Fluidic Muscles:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{c \cdot \kappa} + d \cdot p \cdot \kappa + e \cdot p + f \qquad (3)$$

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

Equation 3 can be generally used with high accuracy for different Fluidic Muscle independently from length and diameter under different values of pressure and equation 4 can be used with high accuracy for Fluidic Muscle with inner diameter of 20 mm, only.

The unknown parameters of equation 3 (a, b, c, d, e and f) and equation 4 (a, b, c, d and e) can be found by Solver in MS Excel 2010.

RESULTS AND DISCUSSION

Our analyses were carried out in MS Excel environment. Tensile force of Fluidic Muscles under different values of constant pressure is a function of muscle length (contraction) and air pressure.

The force always drops from its highest value at full muscle length to zero at full inflation and position. The hysteresis in the force-contraction cycle is shown in Figure 4.

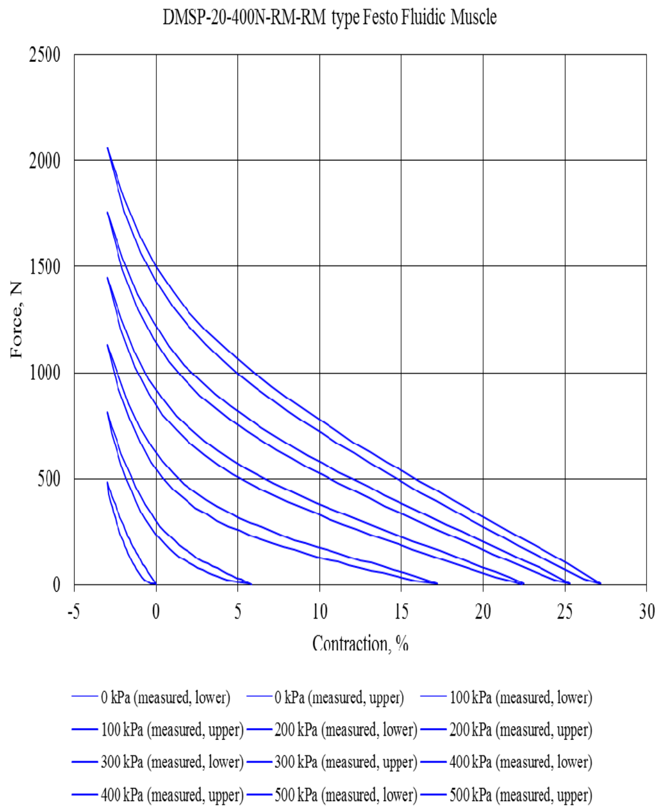

Figure 4. Hysteresis in the tension-contraction cycle

Firstly, the measured data and force model using equation 4 were compared. The unknown parameters of equation 4 were found using Solver in MS Excel. Values of these unknown parameters are shown in Table 1.

Table 1. Values of unknown parameters of equation 4

Parameters	Values	
	Upper	Lower
a	274,794472	235,183308
b	-0,3262381	-0,3803548
c	-9,07369268	-9,0612216
d	296,3161451	293,793153
e	-254,042379	-282,57012

The accurate fitting of equation 4 for the hysteresis loop can be seen in Figure 5.

Figure 6 and Figure 7 illustrate the relationship between the measured force and calculated force. The R^2 = 0.9993 → R = 0.9996 correlation index and R^2 = 0.9991 → R = 0.9995 correlation index prove the tight relationship between them.

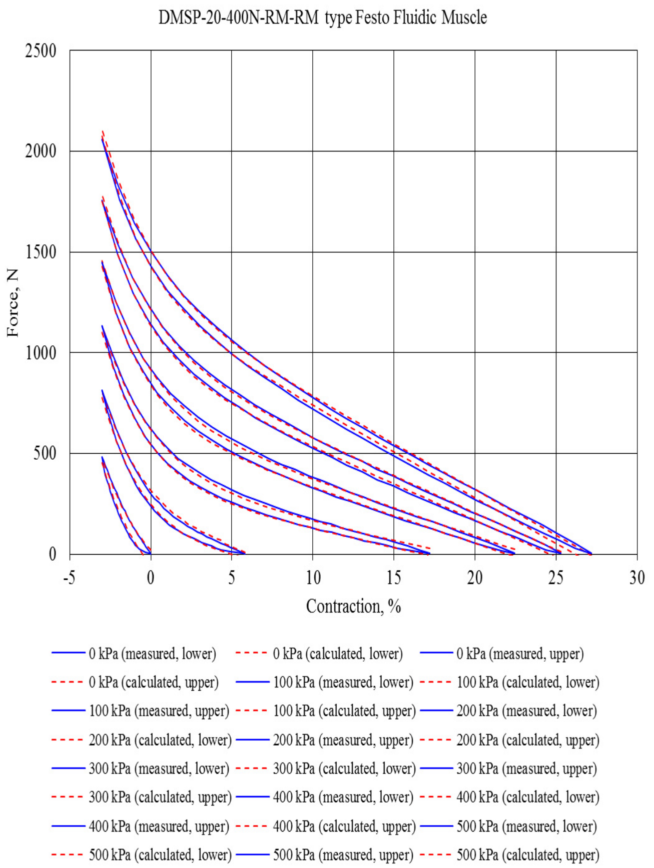

Figure 5. Approximation of hysteresis loop using equation 4

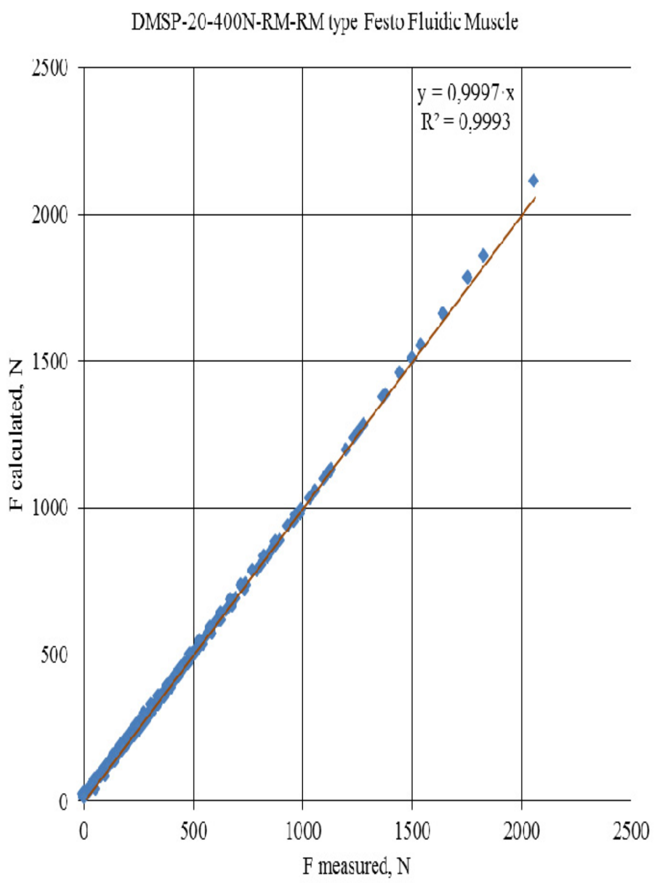

Figure 6. Relationship between the measured force and calculated force (upper)

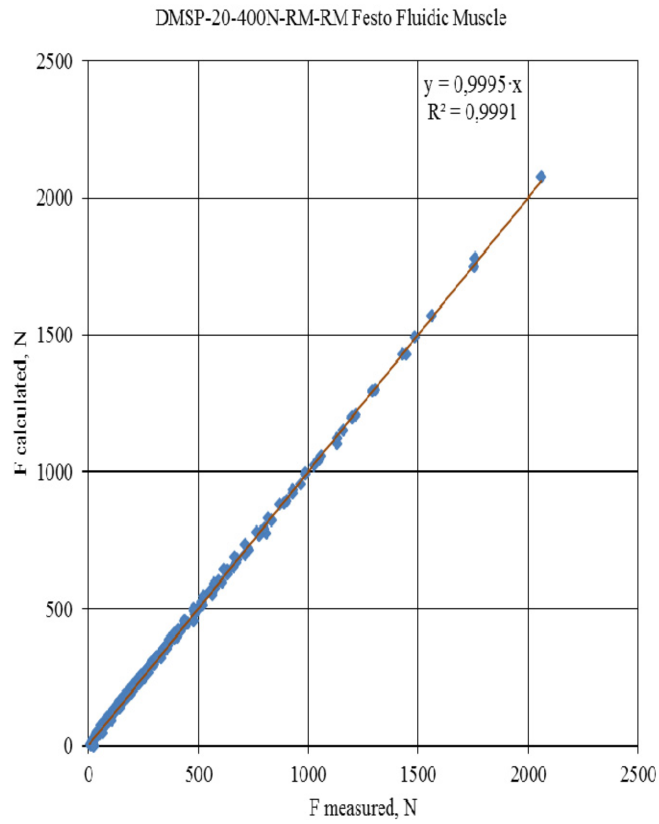

Figure 7. Relationship between the measured force and calculated force (lower)

CONCLUSIONS

In this work a new function for the force generated by Festo Fluidic Muscle was introduced and the accuracy of this approximation algorithm was proved. The investigations were carried out in MS Excel environment. Our main aim is to develop a new general mathematical model for pneumatic artificial muscles applying our new models and results.

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