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NEW MATHEMATICAL MODEL FOR PNEUMATIC ARTIFICIAL MUSCLES

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Abstract

There are several types of pneumatic actuators in industrial environment. The newest and most promising is the pneumatic artificial muscle (PAM).

Many researchers have investigated the behaviour of PAM and some of them have introduced different mathematical models for this actuator. However, we have noticed significant differences between the theoretical and experimental results.

This paper presents our new mathematical model of PAM, comparing with measured and literary data.

Objective

Pneumatic artificial muscle is an actuator, which converts pneumatic energy into mechanical form by transferring the pressure applied on the inner surface of its bladder into the shortening tension. PAMs' source of energy comes from pressurized gas, usually air. The principle of pneumatic artificial muscle is well described in [1] and [2].

There are a lot of advantages of artificial muscles like the high strength, good power-weight ratio, low price, little maintenance needed, great compliance, compactness, inherent safety and usage in rough environments. The main disadvantage of these muscles is that their dynamic behaviour is highly nonlinear ([3], [4] and [5]).

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 made by Festo company, Pleated PAM developed by Vrije University of Brussel, ROMAC (RObotic Muscle ACtuator), Yarlott and Kukolj PAM and some others ([5] and [6]).

The PAM that was selected as the actuator for our study is the Fluidic Muscle (DMSP-10-250N-RM-RM (d0 = 10 mm, l0 = 250 mm, see Fig. 2)) manufactured by Festo. (We have investigated type DMSP-20-200N-RM-RM (d0 = 20 mm, l0 = 200 mm) in [7]).

Methods and materials

A good description of our test-bed (Fig. 1) and experimental results can be found in [8].

With the specially constructed testing machine, we are able to measure the static and dynamic characteristics of several versions of these pneumatic actuators.

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 (Fig. 2), and on the materials used ([6]). Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres.

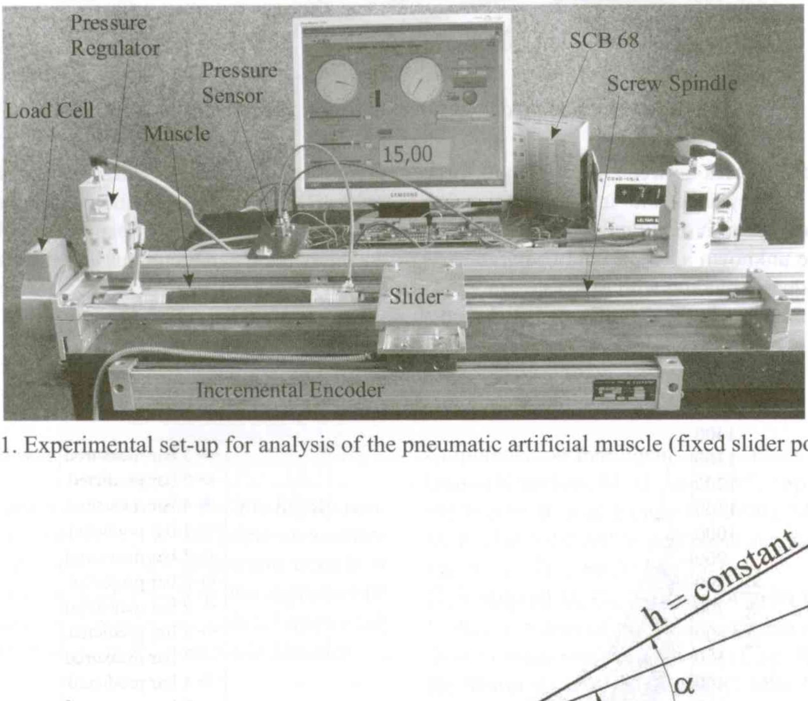

Figure 1. Experimental set-up for analysis of the pneumatic artificial muscle (fixed slider position)

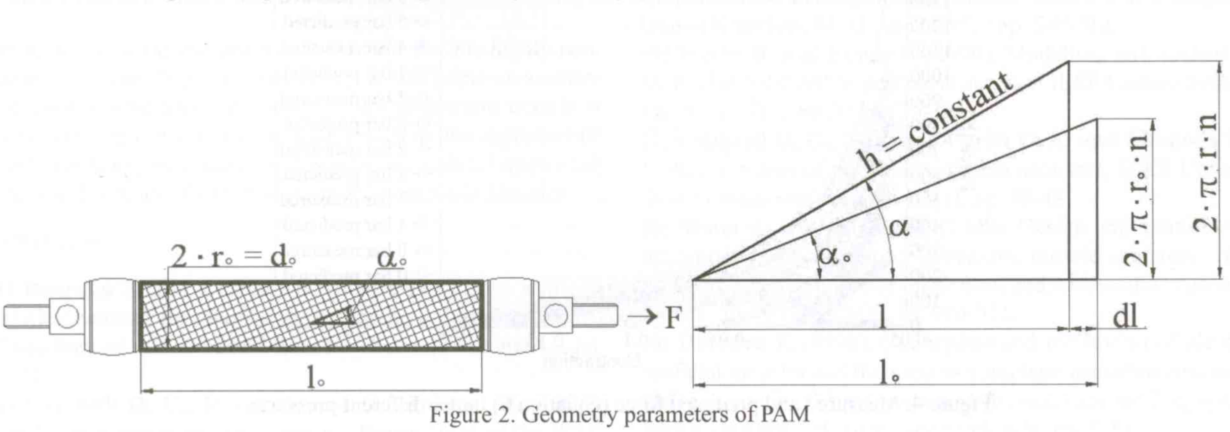

Figure 2. Geometry parameters of PAM

With the help of [3], [9] and Fig. 2, the force can be calculated:

$$\cos\alpha_0 = \frac{l_0}{h} \text{ and } \cos\alpha = \frac{l}{h} \quad \frac{l}{l_0} = \frac{\cos\alpha}{\cos\alpha_0} \tag{1}$$

$$\sin\alpha_0 = \frac{2 \cdot \pi \cdot r_0 \cdot n}{h} \text{ and } \sin\alpha = \frac{2 \cdot \pi \cdot r \cdot n}{h} \quad \frac{r}{r_0} = \frac{\sin\alpha}{\sin\alpha_0} \tag{2}$$

$$\frac{dr}{dl} = -\frac{r_0}{\sin\alpha_0} \cdot \frac{l \cdot \cos^2\alpha_0}{l_0^2} \cdot \frac{1}{\sqrt{1 - \left(\cos\alpha_0 \cdot \frac{l}{l_0}\right)^2}} \tag{3}$$

$$F = 2 \cdot \pi \cdot p \cdot r \cdot l \cdot \frac{dr}{dl} - p \cdot \pi \cdot r^2 \tag{4}$$

$$F = \pi \cdot p \cdot r_0^2 \cdot \left(\frac{3}{tg^2\alpha_0} \cdot \frac{l^2}{l_0^2} - \frac{1}{\sin^2\alpha_0}\right) = \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1-\kappa)^2 - b)$$
$$\text{with } a = \frac{3}{tg^2\alpha_0},\ \frac{1}{\sin^2\alpha_0},\ \kappa = \frac{l_0 - l}{l_0} \text{ and } 0 \le \kappa \le \kappa_{max} \tag{5}$$

F the pulling force, p the applied pressure, r_0, l_0, α_0 the initial inner radius and length of the PAM and the initial angle between the thread and the muscle long axis, r, l, α 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 κ the contraction.

Tondu and Lopez in [3] recommend that to complete this initial approximation with a correction factor (ε), on the one hand, equation 5 does not pay attention to the material that the muscle is made of, 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 [9] suggest achieving similar approximation for smaller pressure another correction factor (μ) is needed, so the modified equation is:

$$F(p,\kappa) = \mu \cdot \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1 - \varepsilon \cdot \kappa)^2 - b) \tag{6}$$
$$\text{with } \varepsilon = a_\varepsilon \cdot e^{-p} - b_\varepsilon \text{ and } \mu = a_\kappa \cdot e^{-\kappa \cdot 40} - b_\kappa$$

Result and discussion

Matlab is common software for modelling, simulating and analyzing. First of all, on the basis of equation 5 we compared the measured data and the force model in Matlab. The results are shown in Fig. 3.

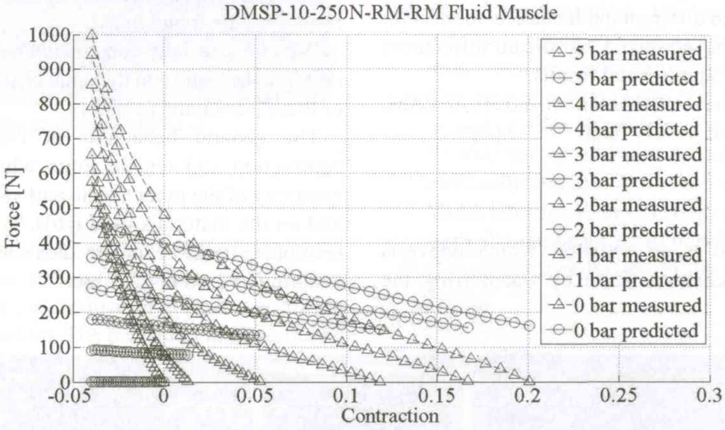

Figure 3. Measured and predicted force (equation 5) under different pressures

We noticed decided differences between experimental force and model. Secondly, we repeated the investigation using equation 6. The results of equation 6 and measured data can be compared in Fig. 4. The unknown a_ε, b_ε, a_κ and b_κ parameters were found using least squares method with Matlab.

Next, with regard to the significant differences between the theoretical and experimental results we have improved this method. A better approximation can be generated with normalized parameters using a new expanded search in Matlab. In this case each unknown parameter has an initial scaling factor to ease the search. This model calculates the correct force for almost every pressure ($p > 0$ bar) (Fig. 5).

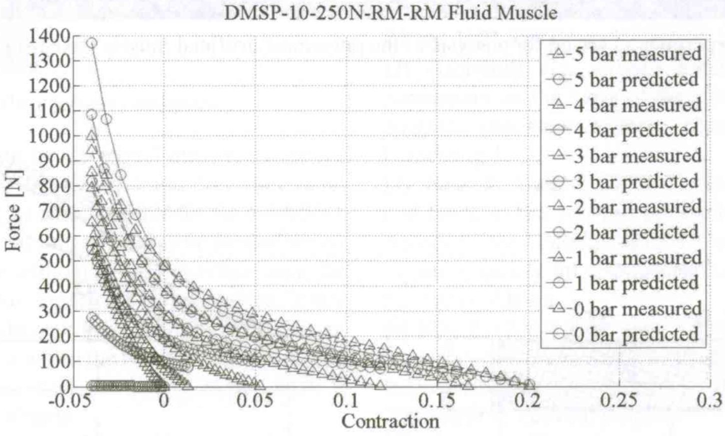

Figure 4. Measured and predicted force (equation 6) under different pressures

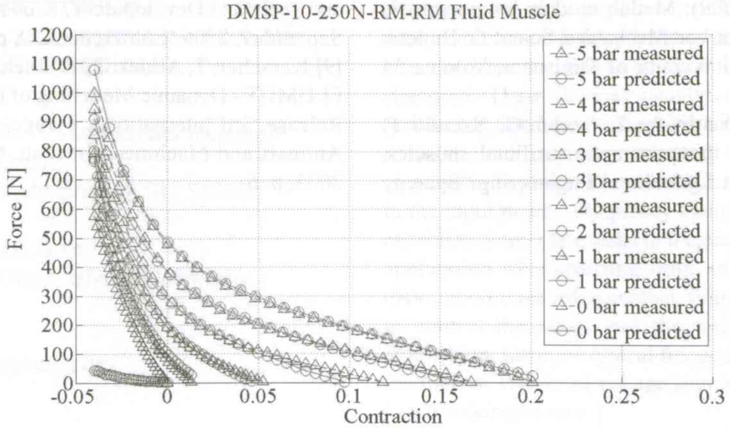

Figure 5. Measured and predicted force (equation 6 by expanded search) under different pressures

Finally, to obtain the best approximation algorithm for the equation of force to reduce the differences between the theoretical and experimental results we have worked out a new mathematical model for Fluid Muscles. Under fixed pressure the contraction to force function can be approximated with a general exponential function with first order correction polynomials of contraction (equation 7):

$$F(\kappa) = a \cdot e^{(b \cdot \kappa + c)} + d \cdot \kappa + e \qquad (7)$$

In order to further generalize equation 7 to attain pressure dependency, variables need to be replaced with first-order polynomes of pressure.

$$F(p, \kappa) = (a \cdot p + b) \cdot e^{(c \cdot \kappa + d)} + (e \cdot p + f) \cdot \kappa + g \cdot p + h \qquad (8)$$

The unknown a, b, c, d, e, f, g and h parameters were found using least squares method in Matlab. The results of equation 8 and measured data can be compared in Fig. 6. Our new equation predicts the correct force for various pressures and contractions.

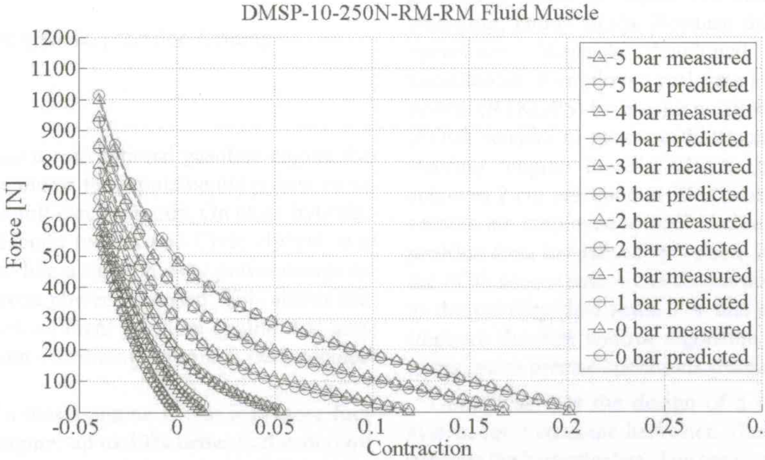

Figure 6. Measured and predicted force (equation 8) under different pressures

Conclusions and future work

Designing an adequate control mechanism for this highly non-linear system needs precise modelling. In this paper an accurate and simple mathematical model of the pneumatic muscle is shown. The agreement of simulation results on the experimental results confirms the viability of the proposed model. Future work is to test this model for hysteresis of different Fluid Muscles.

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