Proceedings of Factory Automation 2012

21-22nd May, 2012
Veszprém

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New Model for the Force of Fluidic Muscles

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Abstract: The newest and most promising type of pneumatic actuators is the pneumatic artificial muscle (PAM). 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). The most often mentioned characteristic of PAMs is the force as a function of pressure and contraction. In this paper the newest function approximation for the force generated by Fluidic Muscles is shown that can be generally used for different muscles made by Festo Company.

Keywords: PAM, Fluidic Muscle, Force, Function Approximation, Matlab, MS Excel

1 Introduction

Pneumatic artificial muscle is a membrane that will expand radially and contract axially when inflated, while generating high pulling force along the longitudinal axis. PAMs have different names in literature: Pneumatic Muscle Actuator, Fluid Actuator, Fluid-Driven Tension Actuator, Axially Contractible Actuator, Tension Actuator, etc. ([1] and [2]).

The working principle of pneumatic muscles is well described in [1], [2], [3], [4] and [5].

There are a lot of advantages of PAMs like the high strength, good power-weight ratio, low price, little maintenance needed, great compliance, compactness, inherent safety and usage in rough environments ([4] and [6]). The main disadvantage of these muscles is that their dynamic behaviour is highly nonlinear ([4], [7], [8], [9] and [10]).

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. Some of them report several mathematical models, but significant differences have been noticed between the theoretical and experimental results ([4], [6], [11], [12], [13] and [14]).

The force depends on length (contraction) under constant pressure. This force decreases with increasing position of the muscle and the muscle inflates. The goal was to develop a precise approximation algorithm with minimum numbers of parameters for the force of different Fluidic Muscles.

The layout of this paper is as follows. Section 2 (Static Modelling of PAMs) describes several force equations. Section 3 (Experimental Results) compares the measured and theoretical data. Finally, Section 4 (Conclusion and Future Work) gives the investigations we plan.

Fluidic Muscles type DMSP-20-200N-RM-RM (with inner diameter of 20 mm and initial length of 200 mm) produced by Festo Company was selected for this study (Fig. 1).

Fig. 1 Festo Fluidic Muscle

2 Static Modelling of PAMs

The general behaviour of PAMs 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 [1]. Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres.

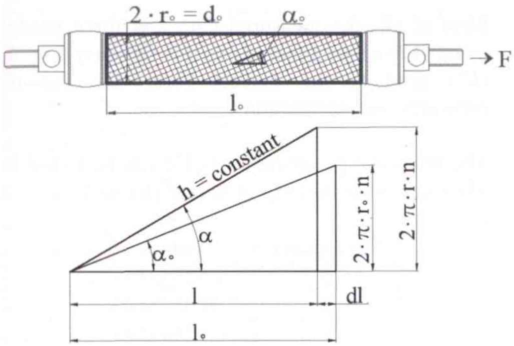

Fig. 2 Geometry parameters of PAMs

With the help of [4] and [6], the input and output (virtual) work can be calculated:

$$dW_{in} = p \cdot dV \tag{1}$$

dW_{in} can be divided into a radial and an axial component:

$$dW_{in} = 2 \cdot r \cdot \pi \cdot p \cdot l \cdot (+dr) - r^2 \cdot \pi \cdot p \cdot (-dl) \tag{2}$$

The output work:

$$dW_{out} = -F \cdot dl \tag{3}$$

By equating the virtual work components:

$$dW_{in} = dW_{out} \tag{4}$$

Using (1) and (3):

$$F = -p \cdot \frac{dV}{dl} \tag{5}$$

Using (2) and (3):

$$F = -2 \cdot r \cdot \pi \cdot p \cdot l \cdot \frac{dr}{dl} - r^2 \cdot \pi \cdot p \tag{6}$$

On the basis of Fig. 2:

$$\cos\alpha_0 = \frac{l_0}{h} \text{ and } \cos\alpha = \frac{l}{h} \tag{7}$$

$$\sin\alpha_0 = \frac{2 \cdot \pi \cdot r_0 \cdot n}{h} \text{ and } \sin\alpha = \frac{2 \cdot \pi \cdot r \cdot n}{h} \tag{8}$$

$$\frac{l}{l_0} = \frac{\cos\alpha}{\cos\alpha_0} \text{ and } \frac{r}{r_0} = \frac{\sin\alpha}{\sin\alpha_0} \tag{9}$$

$$r = r_0 \cdot \frac{\sqrt{1-\cos^2\alpha}}{\sin\alpha_0} = r_0 \cdot \frac{\sqrt{1-\left(\frac{l}{l_0} \cdot \cos\alpha_0\right)^2}}{\sin\alpha_0} \tag{10}$$

$$\frac{dr}{dl} = -\frac{r_0 \cdot l \cdot \cos^2\alpha_0}{l_0^2 \cdot \sin\alpha_0} \cdot \frac{1}{\sqrt{1-\left(\frac{l}{l_0} \cdot \cos\alpha_0\right)^2}} \tag{11}$$

By using (10) and (11) with (6) the force equation is found:

$$F(p,\kappa) = r_0^2 \cdot \pi \cdot p \cdot (a \cdot (1-\kappa)^2 - b) \tag{12}$$

Where $a = \frac{3}{tg^2\alpha_0}$, $b = \frac{1}{\sin^2\alpha_0}$, $\kappa = \frac{l_0 - l}{l_0}$, $0 \le \kappa \le \kappa_{max}$, and V the muscle volume, 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.

Consequently:

$$F_{max} = r_0^2 \cdot \pi \cdot p \cdot (a - b), \text{ if } \kappa = 0 \tag{13}$$

and

$$\kappa_{max} = 1 - \sqrt{\frac{b}{a}}, \text{ if } F = 0 \tag{14}$$

Equation (12) 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 [4].
Tondu and Lopez in [4] consider improving (12) with a correction factor ε, because it predicts for various pressures the same maximal contraction. This new equation is relatively good for higher pressure ($p \ge 200$ kPa). Kerscher et al. in [12] suggest achieving similar approximation for smaller pressure another correction factor μ is needed, so the modified equation is:

$$F(p,\kappa) = \mu \cdot r_0^2 \cdot \pi \cdot p \cdot (a \cdot (1 - \varepsilon \cdot \kappa)^2 - b) \tag{15}$$

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

The significant differences between the theoretical and experimental results were analysed and proved in [15] and [16]. Therefore a new approximation algorithm has been introduced:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{(c \cdot \kappa + d)} + (e \cdot p + f) \cdot \kappa + g \cdot p + h \quad (16)$$

The unknown parameters of (16) were found using genetic algorithm in Matlab. The accuracy of (16) was demonstrated in [16], [17] and [18].

With reduced number of parameters the force can be calculated:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{c \cdot \kappa} + d \cdot p \cdot \kappa + e \cdot p + f \quad (17)$$

On the basis of our investigations and results, (17) can be simplified:

$$F(p,\kappa) = (p + a) \cdot e^{b \cdot \kappa} + c \cdot p \cdot \kappa + d \cdot p + e \quad (18)$$

In this work the unknown parameters of (17) and (18) were found in MS Excel instead of Matlab.

3 Experimental Results

The newest analyses were carried out in MS Excel. Tensile force of Fluidic Muscle under different constant pressures is a function of muscle length (contraction). The force always drops from its highest value at full muscle length to zero at full inflation and position (Fig. 3).

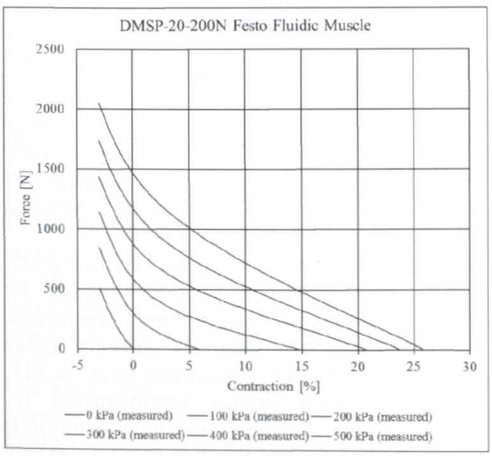

Fig. 3 Isobaric force-contraction diagram

First of all, the measured data and force model using (17) was compared. As it is shown in Fig. 4, (17) predicts the correct force for various pressures and contractions.

The unknown parameters of (17) can be found in MS Excel with the help of Solver (Table 1).

Parameters	Values
a	-4,52882184
b	299,3578643
c	-0,32408548
d	-9,31031059
e	295,035557
f	-287,420111

Table 1 Values of unknown parameters of (17)

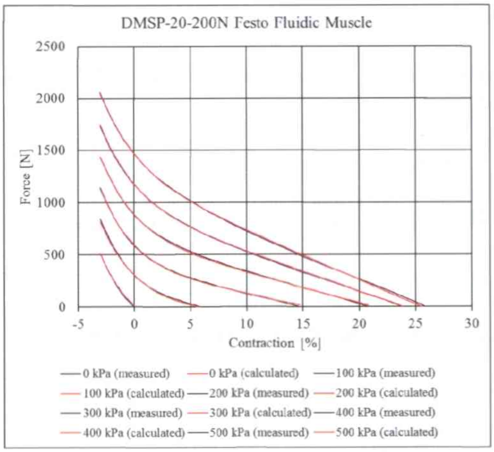

Fig. 4 Comparison of measured data and force model using (17)

Secondly, the investigation was repeated using (18). The results of (18) and measured data can be compared in Fig. 5.

Values of unknown parameters of (18) are listed in Table 2.

Parameters	Values
a	293,3294011
b	-0,32140227
c	-9,07686721
d	289,0857019
e	-278,4611

Table 2 Values of unknown parameters of (18)

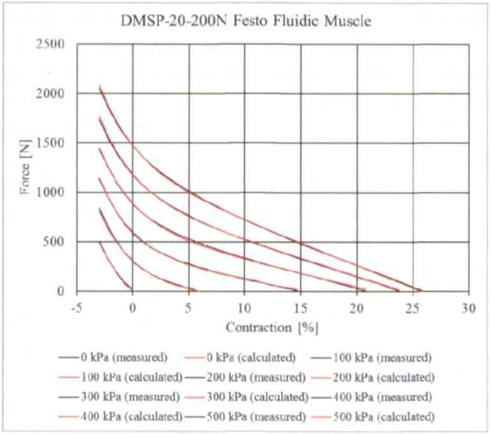

Fig. 5 Comparison of measured data and force model using (18)

The precise positioning of PAMs requires accurate determination of the dynamic model of pneumatic actuators. Therefore the hysteresis in the tension-length (contraction) cycle of PAMs was analysed.

Chou and Hannaford in [6] report hysteresis to be substantially due to the 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. Some experiments were made to illustrate the hysteresis (Fig. 6).

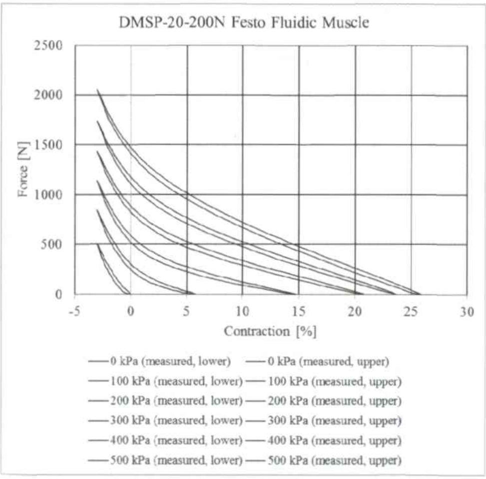

Fig. 6 Hysteresis in the tension-length (contraction) cycle

To approximate the hysteresis loop using (17) and (18), besides the parameters in Table 1 and Table 2, new parameters had to be specified (Table 3 and Table 4).

Parameters	Values
a	2,28453547
b	252,526449
c	-0,3704415
d	-9,0783217
e	283,544241
f	-291,48088

Table 3 Values of unknown parameters of (17)

Parameters	Values
a	253,938042
b	-0,3712419
c	-9,1342021
d	285,066068
e	-293,91895

Table 4 Values of unknown parameters of (18)

The accurate fittings are demonstrated in Fig. 7 and Fig. 8.

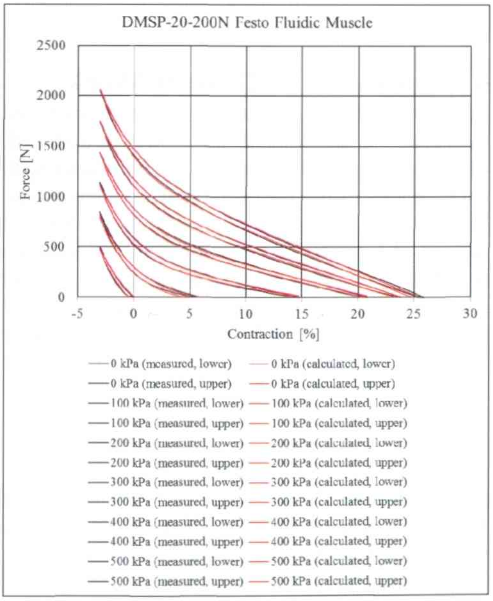

Fig. 7 Approximation of hysteresis loop using (17)

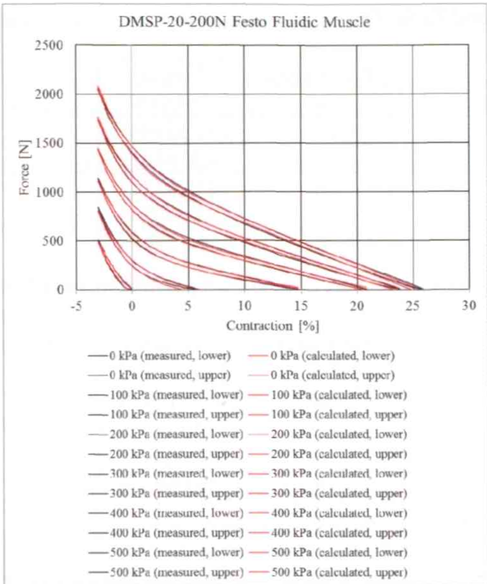

Fig. 8 Approximation of hysteresis loop using (18)

4 Conclusion and Future Work

In this work new functions for the force produced by Festo Fluidic Muscle have been introduced. The accuracy of fittings has been proved with comparisons of the measured and calculated data. These investigations were carried out in MS Excel instead of Matlab. This environment and solution is more favourable, because programming is not required. The main aim is to develop a new general mathematical model for pneumatic artificial muscles on the basis of these new models and results.

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