Accurate force function approximation for pneumatic artificial muscles

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***Abstract*—Many papers exist in the literature dealing with the force function approximation for pneumatic artificial muscles (PAM) with different approaches. The aim of this paper was to create a more precise and simple transfer function for the braided fiber reinforced type PAM actuator. For evaluation purpose, 340 measurements were performed on a testbed using the FESTO DMSP-20-400 type artificial muscle. As a result, a new static model was described with 6.44N root-mean-square error (RMSE) in the whole operating range that consist of only six unknown parameters. By using the inverse of this function, it is possible to express the pressure required to maintain a given contraction with a given force. The compactness of the function results in high evaluation speed necessary for fast controllers and for modeling complex systems equipped with PAM actuator. The proposed model can be used in case of a limited number of measurements that is desirable in a practical calibration procedure. This capability can be used to develop a system with real-time calibration inducing longer operating time.**

I. Introduction

Pneumatic artificial muscle (PAM) is a relatively new type of unconventional actuator. There are many advantages of using PAM actuators instead of a conventional one, but mostly the extreme power-to-weight or power-to-size parameter is the deciding factor in practical applications. Accurate modeling of the actuator is necessary to develop a reliable and precise system using PAM component. Three different type of PAMs can be distinguished based on their structure components:

- Pleated muscle [1], [2].
- Straight fiber reinforced muscle [3].
- Braided fiber reinforced muscle [4], [5], [6], [7], [8], [9].

Detailed description about the classification was reviewed in paper [10]. The PAM actuator used in this study is a braided fiber reinforced muscle, that means it consist of a helical braid of rigid fibers surrounding an elastic tubular bladder as seen in figure 1. When the tube is inflated with pressurized gas (usually air) or liquid material like water, the braid diameter is increased and the length of the actuator decreased causing a strong pulling force between the joints.

Although the PAM is a very simple thus cheap construction, controlling them is a difficult problem due to the highly nonlinear characteristics of the generated force.

The models can focus on the static characteristic of the actuator, where the measurements are done in equilibrium states while other models are about to describe the dynamic properties of the actuator. This paper deals with the former one describing only the static behavior of the PAM with a transfer function describing the correlation between the muscle contraction, the relative pressure in the muscle and the generated force.

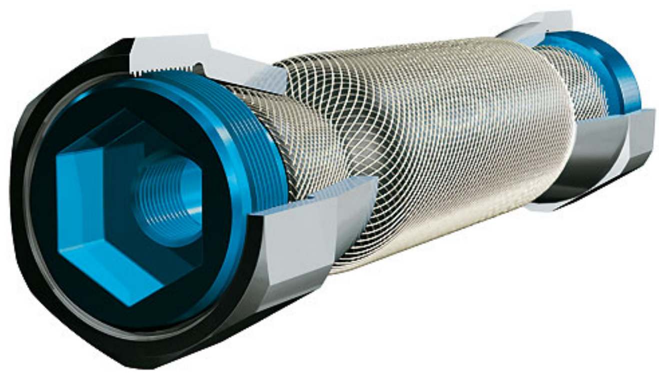

Figure 1. The inner structure of the FESTO fluidic muscle [11]

II. The transfer function

In order to describe the static correlation between the force (y), contraction (κ) and the required pressure (p), an exponential function should be selected first as a core function.

Instead of using trigonometrical or low ordered polynomial, the exponential function provides the best approximation for the highly dynamic change of the measured data points.

The following criteria should be satisfied:

- The function must fit well any isobaric measurement series in the permissible operating range (see the FESTO catalog [12]).
- It should use as few unknown parameters as possible.

The exponential function in equation (1) uses only four unknown parameters and it can express the correlation between contraction and force for a fixed pressure.

$$F_{core}(\kappa) = a\exp^{\left(\frac{1}{\kappa+b}\right)} + c\kappa + d \tag{1}$$

Where (a, b, c, d) are unknown parameters.

The next step is to make some parameters of the core function pressure dependent resulting in a general function called transfer function. One of the main benefits in using a simple function instead of an algorithm is the ability to invert it. The inverse form of the transfer function can be used as an open-looped positioning system [13]. For this step the following criteria should be satisfied:

- The transfer function must fit well the whole permissible operating range.
- In order to make the parameters pressure dependent, only a limited number of new parameters should be added to the core function to preserve simplicity.
- The general function should be invertible to express the required pressure for a desired contraction and force.

The general form of the core function in equation (2) is using only six unknown parameters .

$$F_y\left(p,\kappa\right) = \left(ap+b\right)\exp^{\left(\frac{1}{\kappa+c}\right)} + \left(d\kappa+e\right)p + f \tag{2}$$

Where (a, b, c, d, e, f) are unknown parameters.

From equation (2) the variable (p) can be expressed by equation (3) as an inverse function.

$$F_p\left(\kappa, y\right) = -\frac{b\exp^{\left(\frac{1}{\kappa+c}\right)} + f - y}{a\exp^{\left(\frac{1}{\kappa+c}\right)} + d\kappa + e} \tag{3}$$

Where (a, b, c, d, e, f) are the same parameters from equation (2).

Note that equation (2) can be given as a more realistic formula expressing the permissible operating range. For instance, in equation (4) the force limiting property was added.

$$F\left(p,\kappa\right) = \begin{cases} F_y\left(p,\kappa\right), & if \quad 0 \leqq F_y\left(p,\kappa\right) \leqq y_{max} \\ y_{max}, & if \quad y_{max} < F_y\left(p,\kappa\right) \\ 0, & if \quad 0 > F_y\left(p,\kappa\right) \end{cases} \tag{4}$$

Where $y_{max}$is the highest force in the operating range, or the force compensation limit in the force limited muscle. The limits for κ can be added similarly with trivial modification of equation (2).

III. Experimental setup

All measurements were conducted on an experimental setup capable of measuring the pressure, contraction and the force generated by the PAM actuator at the same time. Main components of the test-bed are the followings:

- Motorola MPX5999D pressure sensor
- LINIMIK MSA 320 type linear incremental encoder
- MOM 7923 type strain gauge force sensor
- FESTO VPPM-6L-L-1-G18-0L6H-V1N-S1-C1 proportional valve
- Lab PC 1200 National Instruments multi-IO card

The assembled test-bed is depicted in figure 2. The working principle of the setup is simple. One end of the PAM actuator is attached to the force sensor (left side on the photo), while the other end is linked to a movable cart with an adjustable length rod (middle and right side on the photo). The movable cart is also attached to the linear encoder (bottom on the photo) and all other main components including the valves are in the background. The encoder can only measure the distance relative to a reference point which is programmable. In order to make valid and accurate data series, all measurements have to be done using the same initial reference point.

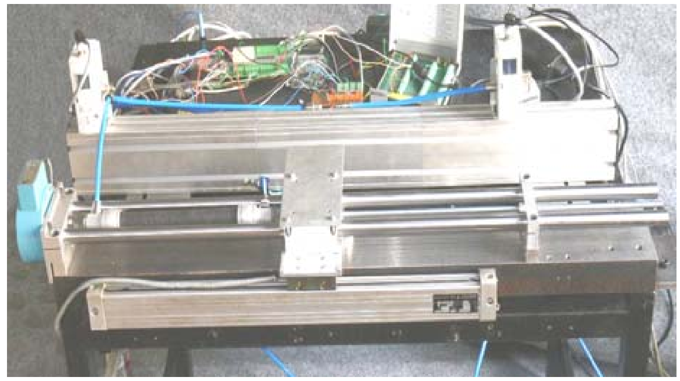

Figure 2. Photo of the test setup [14]

Also note that, in order to make the transfer function generally valid, the contraction of the PAM has to be considered as relative contraction instead of absolute change of displacement. This relative contraction can be calculated as the signed change of displacement in percentage of the total length, where a negative value means the actuator is expanded further than at rest condition. The inner pressure of the actuator can be adjusted with the proportional valve while the inner pressure and force can be recorded together with the calculated relative contraction. For detailed description of the setup see reference [14].

For experimental validation the FESTO DMSP-20-400 type of artificial muscle was used with the test-bed to obtain the reference data series that consist of 340 measurements. Thirty measurements were recorded for each fixed pressure value in the working range from 0 to 5.5Bar pressure with 0.5Bar steps. Each isobaric data series were recorded equidistantly starting from the relaxed contraction state up to -3% contraction. Finally, data points were removed due to permissible operating range limits, that means only smaller than 1500N forces and smaller than 25% contractions were used as suggested by the FESTO catalog [12].

IV. Results and Discussions

A. Model prediction capabilities

For fair comparison the function first published in 2009 was used, see reference [15] for more details. That study suggested the use of function (5) with eight parameters as a transfer function.

$$F_{prev}(p,\kappa) = \left(ap+b\right)\exp^{\left(c\kappa+d\right)} + \left(ep+f\right)\kappa + gp + h \tag{5}$$

Where (a, b, c, d, e, f, g, h) are unknown parameters.

To compare the prediction capability of function (5) with function (2), identical circumstances were created for the search of the unknown parameters. The goal of this search was to find those parameters that give the best estimation of the cleaned dataset described above. For finding those parameters genetic search was used with the following properties:

- Fitness function: root-mean-square error (RMSE) of the predicted values for the cleaned dataset.
- Population size: 40.
- Generations: 10000.

Table (I) shows the best RMSE values after the genetical algorithm search.

Table I
BEST RMSE VALUES FOR THE PREDICTED FORCES

	$F_{prev}(p,\kappa)$ function (5)	$F(p,\kappa)$ function (2)
RMSE value [N]	6.93N	6.44N

The presented function gives approximately 7.1% smaller RMSE value. Note that, the previous function is more likely to fall in local minimum during the search due to the higher number of parameters or as known as the curse of dimensionality, while the presented function tends to be more stable. The prediction capability of the presented function can be seen in figure 3 with the whole dataset. The data points are depicted for the working range from 0 to 5.5Bar pressure with 0.5Bar step, where the lowest series represents the 0Bar and the highest series the 5.5Bar measurements.

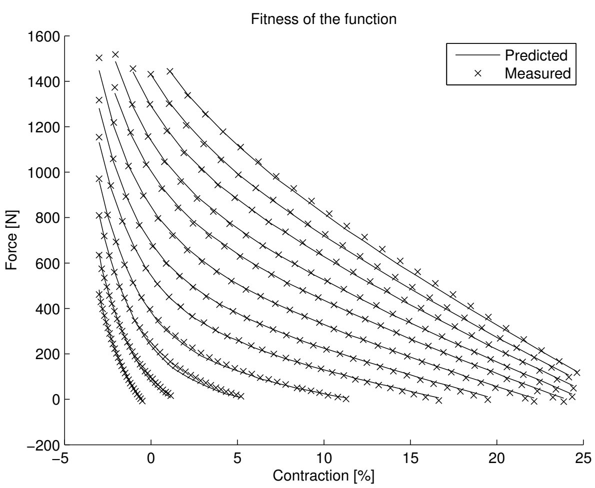

Figure 3. Comparison of measured and predicted data

In order to further compare the prediction capability of the presented model (2) with the previously described model (5), the error function was obtained from the difference of the measured and predicted forces. The error functions shown in figure 4 and figure 5 consist of three data series for fixed 0, 2.5 and 5.5Bar pressure respectively.

The theoretical optimum for the error function would be constant zero for all cases, meaning that the model fits perfectly for all the measured data points. As seen in figure 4, the error of the previous model is significantly higher at low pressure (0Bar) and high contraction ($> 20\%$) compared to the presented model. Furthermore, the error function of

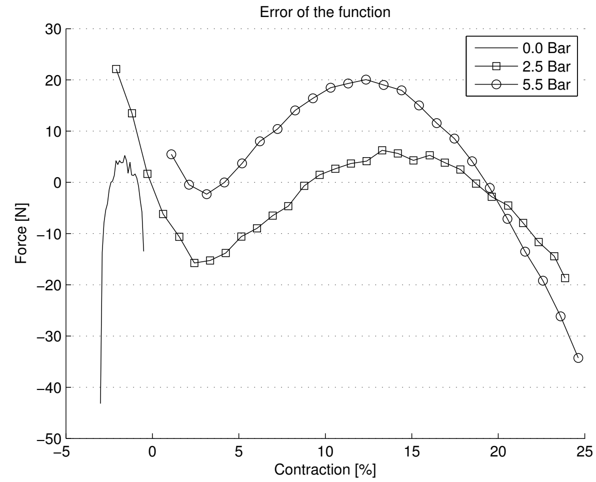

Figure 4. Error function for the previous model (5)

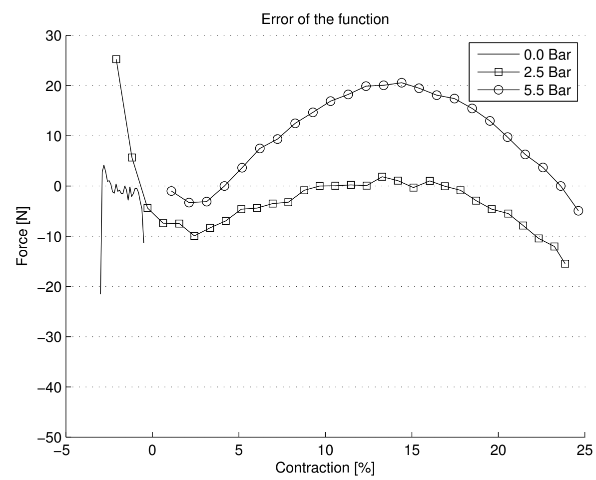

Figure 5. Error function for the presented model (2)

the presented model tends to be near zero for many cases especially at the usual working range (2.5Bar) as shown in figure 5.

B. Calibration procedure

The basic component of the FESTO PAM actuator is an inflatable elastic rubber tube. In a typical application using this type of actuator, the inner pressure is continually changing, thus the elastic material will become harder and the performance will deteriorate. To compensate this behavior of the PAM actuator, regular calibration is required after installing the system. This means that the parameters must be regularly readjusted when using the proposed function as part of the controller.

To calibrate the system, measuring several hundreds of different state can be quite time consuming, instead of that only a few specific measurements should be taken. To lower the required number of measurements, three different pressure with three different contraction ratio were chosen as a total of nine representative data points for the whole operating range. These points were at low (0Bar), medium (2.5Bar) and high (5.5Bar) pressure with the lowest, medium and the highest contraction respectively as seen in figure 6.

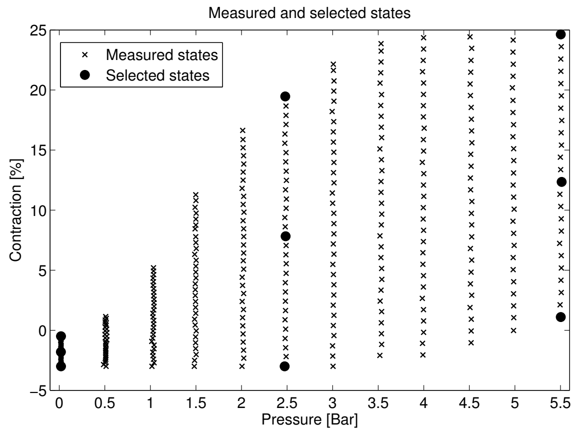

Figure 6. For calibration, nine states were selected from the whole operating range.

As a result the following figure 7 shows the function (2) that was fitted on the nine selected states. It is remarkable to note when using only nine states for calibration the resulting function is more precise at the extreme working range. However, the average fitness is slightly less accurate compared to the case when using all 340 states for model fitting.

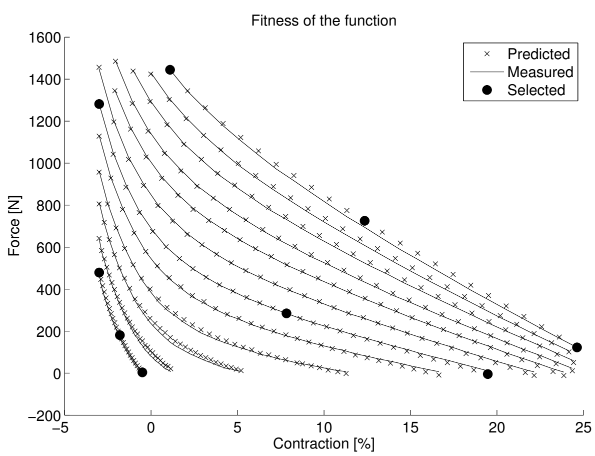

Figure 7. Comparison of all the measured data with the predicted based on the selected states

To compare the prediction capability of function (5) with function (2), identical circumstances were created for the search of the unknown parameters including fitness function, population size and number of generations as detailed in the previous subsection. Table (II) shows the best RMSE values after the genetical algorithm search. As a result, 9.37N RMSE was achieved with function (2) when trained on the nine selected and evaluated to the total 340 measured data points. In contrary, the function (5) gives 11.53N RMSE that is approximately 18.7% worse when compared to the predicting capability of function (2).

Table II
RMSE VALUES FOR THE PREDICTED FORCES TRAINED WITH THE SELECTED DATA POINTS

	$F_{prev}(p, \kappa)$ function (5)	$F(p, \kappa)$ function (2)
RMSE value [N]	11.53N	9.37N

V. CONCLUSION

The transfer function of PAM actuator describes the correlation between the muscle contraction, the relative pressure in the muscle and the generated force. The precision and simplicity are the main aspects that must be considered when creating these functions. Numeral studies aimed to describe simple transfer functions where the number of the unknown parameters are relatively low (< 10) [16], [17], [15]. For instance Kerscher et al. [17] introduced a function with five unknown parameters only, but the model error is higher at lower pressure range. In contrary, Hosovsky et al. [18] showed a highly accurate model, although as many as 189 unknown parameters were required to be determined. In 2009 [15], a relatively compact yet accurate model was presented using eight parameters capable of modeling the static characteristics of PAM actuators. The aim of this paper was to further improve the compactness and precision, therefore a new simple force function was presented and compared with the model introduced in reference [15].

The benefit in using this function is the lower error of it, especially in the usual working range. It uses only six unknown parameters resulting in faster and reliable parameter search. Furthermore, its inverse function is capable to express the pressure required to maintain a given contraction with a given force. This property of the function is necessary in an open-looped controlled system or generally, when it is not possible to take direct measurements for all three parameters but one of them can be expressed from the others. The compactness of the function results in high evaluation speed necessary for fast controllers and for modeling complex systems equipped with PAM actuator. In case of recalibration, only a limited number of measurements required to refit the model with remarkable precision. This capability can be used to develop real-time calibration system that has longer operating time in between regular maintenances.

ACKNOWLEDGMENT

The author would like to thank the colleagues of the Department of Technical and Process Engineering, Faculty of Engineering, University of Szeged for providing accession of the experimental setup.

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