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Experimental Validation of Change of Volume in Pneumatic Artificial Muscle during Excitation

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Abstract

The majority of pneumatic artificial muscles (PAMs) models for calculating generated force with virtual work are good approximations. These models usually do nottake into account the edge deformations of the muscle orthe elastic deformations of the muscle bladder as a function of different internal pressure of the muscle, but only the contraction of the muscle. This paper presents the method that enables us to accurately measure the change in pneumatic muscle volume. Experimental results are compared with the standard Chou model. Also, further improvement of the PAM model is suggested.

Key words: *pneumatic artificial muscle, machine vision, volume calculation, camera calibration.*

1. INTRODUCTION

PAM actuator is a mechanical actuator that contracts when air pressure is applied. As the pressure in the bladder increases through the valve air supply the muscle contracts (Figure 1) [1].

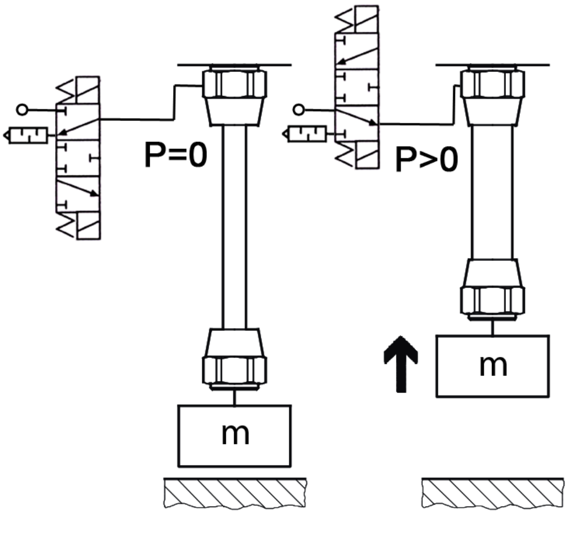

Figure 1. PAM generating force and contraction with an increase of internal pressure p [1]

PAM consists of a rubber bladder and reinforcement fibres. The reinforcement fibres act as a leverage to generate as much contractile force as possible. The fibres must be correctly oriented in respect to PAM's main axis. The combination of changing air pressure in both the muscle and the rubber bladder during operation makes PAM's characteristics highly nonlinear.The dynamic spring and dumping coefficients are constantly changing and therefore the control algorithms must have very fast control loops. To achieve a fast control loop the pneumatic valves must have as fast response as possible.

Therefore, special attention has to be paid to the choice of the most suitable valves and especially to the choice of actuators, which enable a high dynamic operation of the valve [2]. It is also very important to choose the best valve configuration regarding metering edges and to check the system response and suitability of the valve choice through the modelling and simulation of the whole system [3].

First step in making a new and improved mathematical model of PAM's generated force is to measure the volume in the different states of contraction under different pressure and load.

2. VOLUME OF A PNEUMATIC ARTIFICIAL MUSCLE

To calculate the generated force using a mathematical model most researchers use the Chou and Hannaford model [4], which is based on virtual work, where input work Win in PAM is expressed as (Eq. 1):

$$dW_{in}\int_{Si}(P-P_o)dl_i ds_i = P' dV \tag{1}$$

The *P* is absolute PAM's pressure, P_0– ambient pressure, dl_i – inner surface displacement,ds_i – area vector, *P'*–relative pressure and *dV*–change in volume. To calculate generated force the output work $W_{out}$is equalled with the input work (Eq. 2) and the result is a generated force *F* as a function of change of volume that depends on the axial displacement *dL*(Eq. 3).

$$dW_{out} = -FdL \tag{2}$$

$$F = -p\frac{dV}{dL} \tag{3}$$

The Chou model then suggests, that the fibre length does not change and the generated force is calculated as a function of change in fibre angle (Eq. 4)

$$F = \frac{\pi D_0^2 \overset{'}{P}}{4}(3\cos^2 - 1) \tag{4}$$

This widely used model does not take into account that fibres can extendand therefore the volume changes. Tsagarakiset. al.[5] and Tondu et.al. [6]have made some attempts to improve this model byincluding friction loss in bladder. . In this paper we show an experiment that enabled us to measure the internal volume in the muscle and to compare it to the mathematical model.

2. EXPERIMENTAL SETUP

To measure the volume of the muscle the machine vision was applied (Figure 2). The machine vision applications are widely used in industry for fault detection, measurement and data extraction [7]. The pneumatic muscle was fixed horizontally on linear guides with clamping mechanism. The contraction of the muscle was fixed in different positions while the internal pressure was increased from 1 to 6 bar. During the incremental pressure raise the pictures of PAM were taken for further analysis. The pressure inside the muscle was controlled by two fast switching valves, the pressure sensor and an embedded PCX controller (Figure 2).

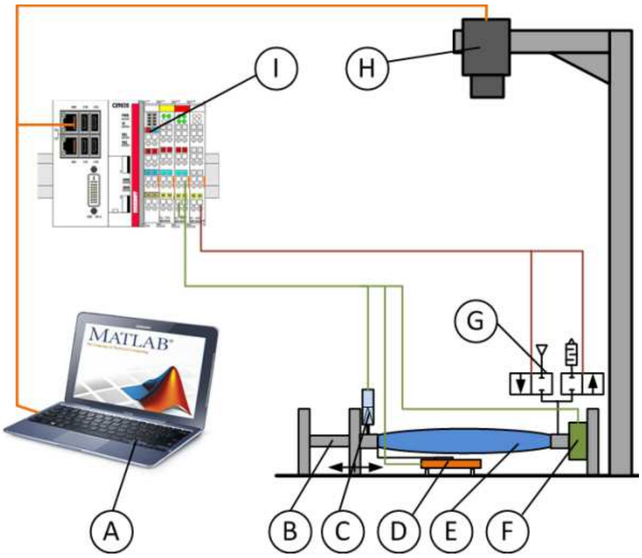

Figure 2. Experimental setup for the image acquisition of PAM's volume. A – PC with Matlab, B – linear guides with clamping device, C – pressure sensor, D – displacement sensor, F – force sensor, G - fast switching valves, H – high resolution industrial camera and I – PCX controller

To achieve best possible accuracy the camera had to be calibrated. The calibration was used for correction of radial and axial distortion, due to camera lens deformation. Figure 3 presents the experimental setup during the camera calibration using the algorithm, which is described in detail in [8].

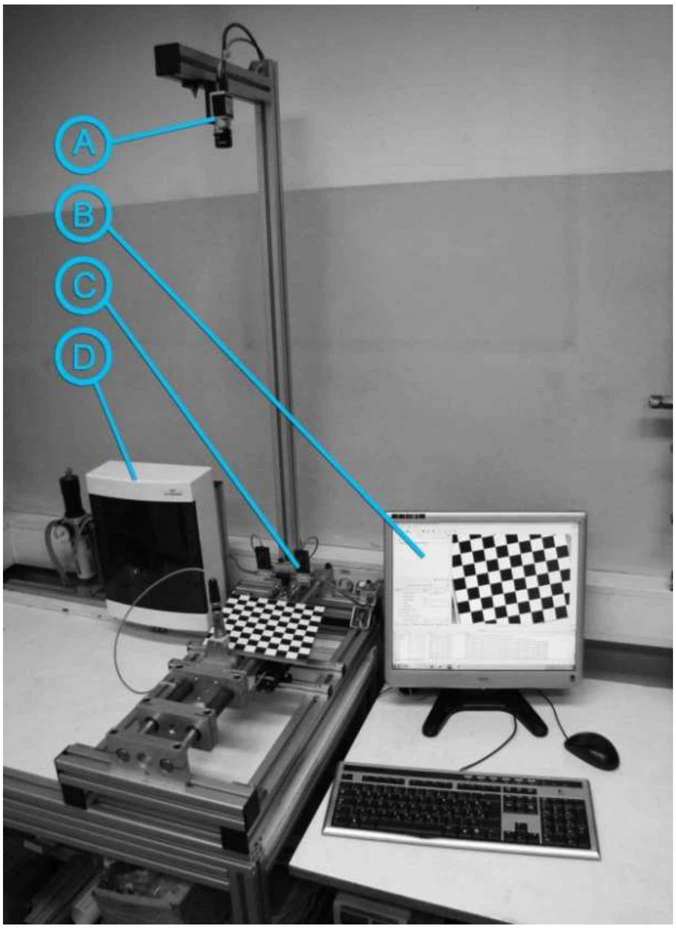

Figure 3. Camera calibration using chess board. A – CCD camera, B – PC, C – chess board and D – PCX controller

After calibratingthe camera the relative width of the camera pixels has to be calculated. This can be done with the use of the calibration blocks.

3. THE EXPERIMENT

For the experiment we chose the combination of pressures from 1 to 6 bar and contractions from 0 mm to maximum PAM's contraction. The combinations of the measured parameters are shown in table 1.

The contraction was made in 2.5 mm steps from 0 to maximum contraction. Maximum contraction depends on the pressure in the muscle and increases to maximum of 25% of total PAM's length at 6 bar.

Table 1. Combinations of the measured parameters

	Pressure [bar]					
	1	*2*	*3*	*4*	*5*	*6*
Cont. [mm]	*0* -5	*0* -23	*0* - 35	0 - 40	*0*- 45	*0* -50

4. CALCULATION OF PAM'S VOLUME

After the acquisition of all states of PAM, the images had to be prepared for analysis. This was done in 3 steps:

A) Defining a region of interest and cropping the picture;
B) Converting the cropped picture from RGB to binary form and reducing noise and mask PAM's logo;
C) Inverting picture for blob analysis.

All three steps are shown in figure 4.

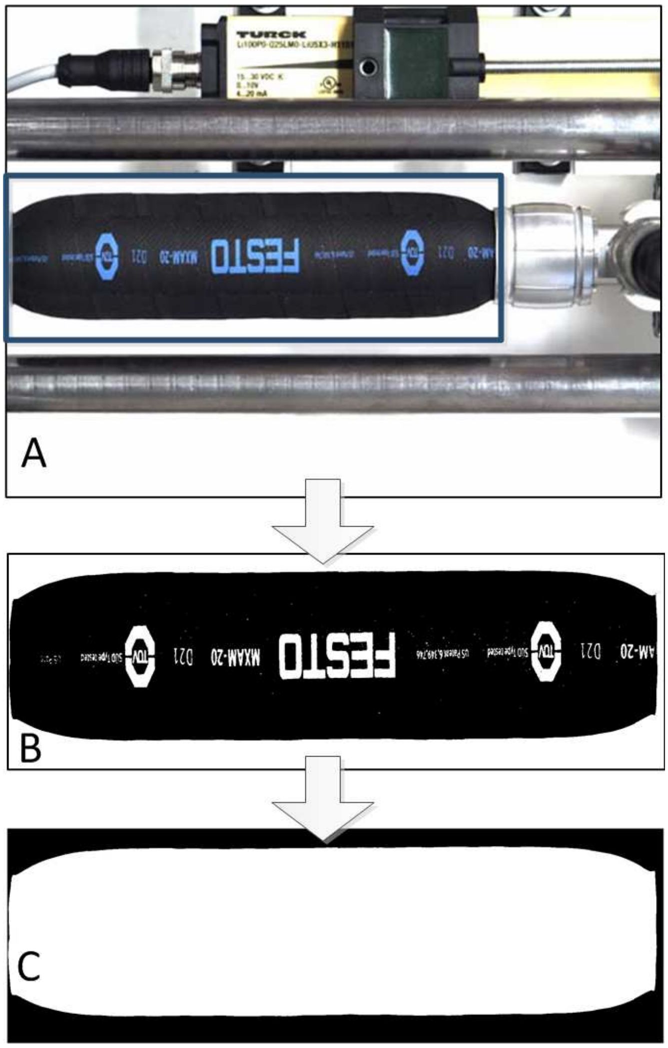

Figure 4. Image preparation for analysis

After the image preparation, the volume of the pneumatic muscle was determined with the use of blob analysis in Matlab [9] and the use of Guldin's rule [10] for calculation of volume for rotated area.

Guldin's rule states that the volume of the solid, which can be created by rotating a 2D shape around an external axis, is equal to the product of the area of the rotated shape and the distance travelled by the shape's geometric centroid, as shown on figure 5.

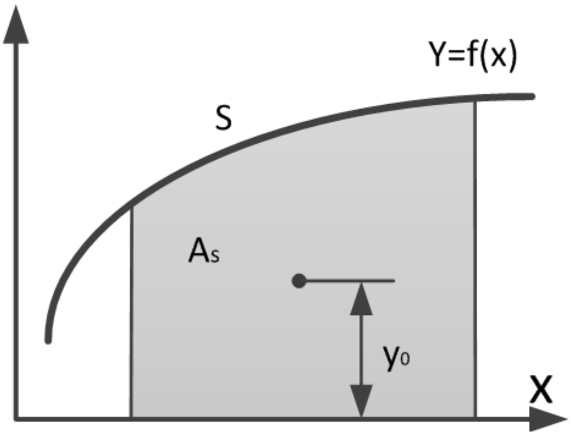

Figure 5. Calculation of volume using Guldin's rule.A_S – area under the curve, y_0 – distance from rotational axis to the centre of gravity of the area, y – function of the curve and S – length of the curve

The volume is therefore calculated as shown in equation (5).

$$V=2\pi y_0 A_s \tag{5}$$

We used the blob analysisto calculate the y_0 and A_S. The blob analysis was done in the following steps:

A) Loading binary image to memory;
B) Findingblob;
C) Determining the centre, minor axis, major axis and angle of the blob;
D) Rotating the blob and making two identical parts;
E) Makingblob analysis of upper and lower parts, calculating their area and distance to rotation axis;
F) Calculating the average value of upper and lower area and centre of gravity.

Figure 6 shows two detected blobs with calculated area and centre of gravity.

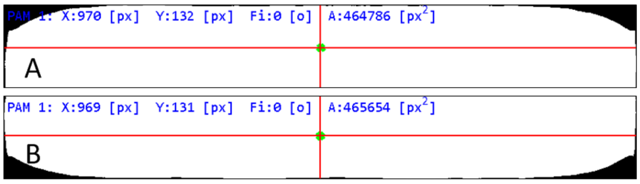

Figure 6. Calculated area and centre of gravity for upper and lower part of PAM for calculation of y_0 and A_S

However, the calculated volume presented the entire volume of the muscle and not only the inside volume of the air. Therefore, in this paper we must subtract the calculated volume with the volume of the bladder.

The bladder is made from rubber and is known to be incompressible [11], therefore, we must calculate the volume and make it constant. The volume is calculated by taking one PAM apart and by measuring the inner and outer diameter.

Table 2. Measurement results for PAM

Length [mm]	Inner diameter [mm]	Bladder thickness [mm]	Volume V_p [mm^3]
200	20	2,05	28401

Figure 7. shows a cut out part of PAM used for measurement of dimensions and determination of the angle of fibres in the bladder.

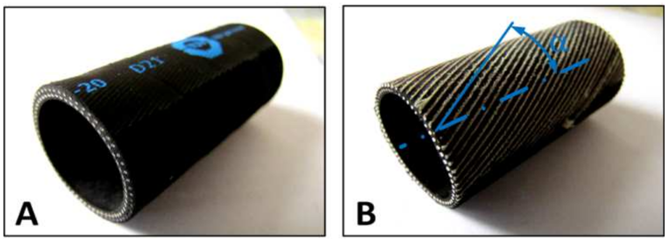

Figure 7. Cut out part of PAM for measurement of bladder dimensions (A) and fibre angle α (B).

The PAM fibres are positioned in the bladder in two layers one over another as shown in figure 8.

Figure 8. Two layers of PAM fibres(A – PAM bladder, B – first layer of fibres, C – second layer of fibres)

The angles of fibres of the upper and lower layers are opposite to each other to prevent the PAM from twisting under contraction so that only axial force is generated. The angle of reinforcement fibres angle α is 25° and is shown in image 9.

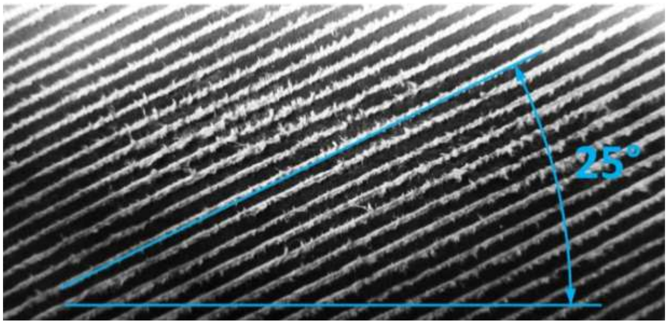

Image 9. Angle α of the upper reinforcement fibre layer.

The results of the measurement are presented in table 2.

After calculatingthebladder volume, we were able to calculate the volume of PAM in different states and compare it to the standard Chou model.

5. EXPERIMENTAL RESULTS AND COMPARISON TO CHOU MODEL

The experimentally acquired data clearly show that the internal volume of the muscle increases with the increase of pressure while the level of contraction stays constant. This is not included in Chou's model. In figure 10 the graph of measured volume of PAM is shown at different contractions and pressures.

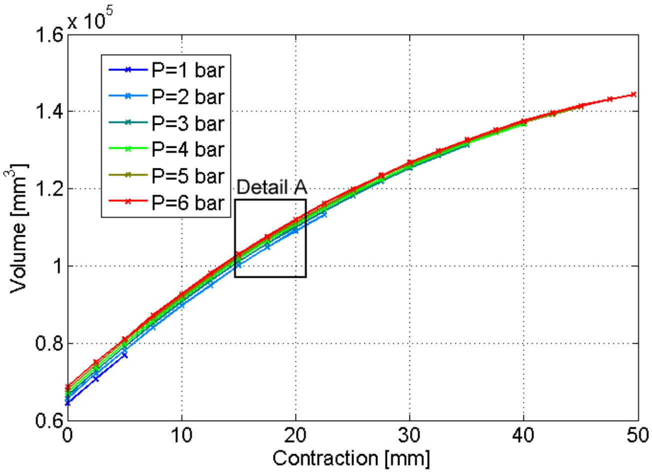

Figure 10. Change of PAM's internal volume as a function of contraction and pressure

Closer look of the data (see Figure 11) shows that at the same contractions of the PAM and at different pressures the volume changes nonlinearly. Figure 11 displays only the acquired data of PAM's volume at contractions between 15 and 17.5 mm.

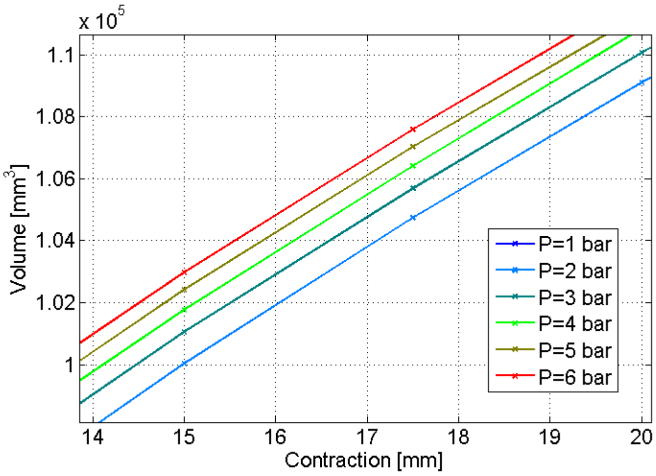

Figure 11. Detail A - Change of volume for contraction between 15 and 17.5 mm

We can conclude from the observations that the difference in volume at all contractions is always only a function of the pressure. Figure 12 contains a graph representing the relation between the calculated volume, difference of the muscle and the incremental pressure change from 1 to 6 bar.

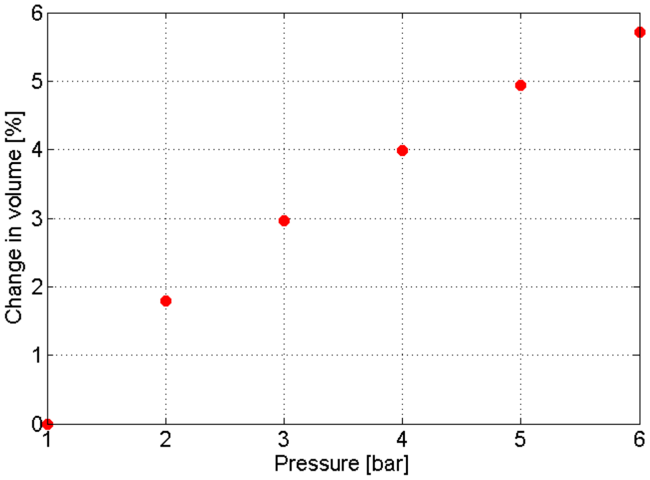

Figure 12. Change of volume in % depending on muscle pressure

A comparison between the experimental data and the Chou model (see Figure 13) shows that in general the Chou model corresponds with the experimental results of the volume change only at the PAM pressure of *P = 1 bar*. But at the PAM pressure of *P = 1* bar the muscle can contract only approximately 3 %. Therefore, at the PAM pressure of *P = 6 bar*, when the muscle contraction can reach full 25% of PAM's length, the difference in the volume comparingthe measured data and the Chou model is the greatest.

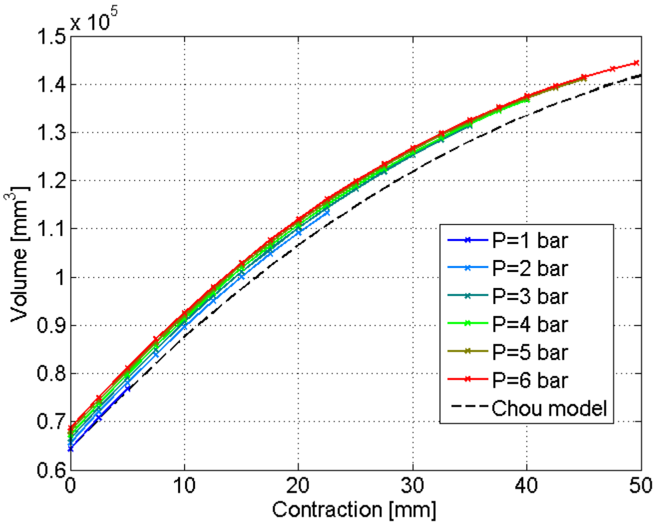

Figure 13. The comparison of the Chou model and the gathered experimental data.

The Chou model can therefore be improved by a simple function, which takes into account the stretching of the bladder under different pressures and then uses this new model to calculate generated force.

The difference between experimental data for the muscle volume at the pressure of *p = 6 bar* and the Chou model is shown in mm^3 in figure 14.

It is obvious that the deviation between the Chou model and the experimental results is nonlinear and depends on the PAM's contraction.

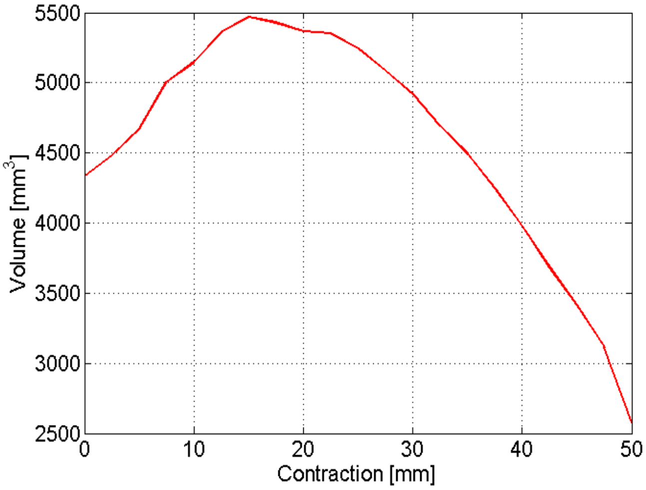

Figure 14. Calculated difference between the Chou model and the experimental data for PAM at 6 bar and contraction from 0 to 50 mm

6. DISCUSSION AND CONCLUSION

The aim of the experimental research, **presented** in this paper was to measure the change of the PAM's volume at different contractions and pressures and to compare the results with the Chou model. The standard and the most used Chou model assumes that fibres in PAM bladder do notextend under pressure and therefore the volume does notchange. In this paper we proved that there is a significant change in the volume of the PAM in comparison to the Chou model.

The volume was measured with the use of high resolution machine vision camera for acquiring images of the pneumatic muscle at different states. For the purpose of this experimental approach the camera had to be calibrated to compensate for lens distortion and relative pixel dimension for accurate PAM image acquisition. The algorithm using the blobanalysis and Guldin's rule for volume calculation was used.

From the experimental results, it is clear that the volume change is not only the function of the contraction but it depends also on the pressure change. Therefore, the Chou model can be modified with the suggested correction as the function of pressure and contraction. As a result, we could get more accurate generated force with the use of virtual work.

Also, for further experiments, the losses in PAM's should be measured and included in the calculation. Thiswould enable us to make an accurate model of force generated by PAMs in different states.

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Eksperimentalna Provera Promene Zapremine Pneumatskog Veštačkog Mišića Usled Pobude

Miha Pipan

Primljen (14.07.2014.); Recenziran (16.02.2015); Prihvaćen (02.03.2015)

Rezime

Većina modela pneumatskog veštačkog mišića (PAM) za izračunavanjenje proizvedene sile koje proizilaze iz virtualnog rada su samo približne. Ovi modeli ne uzimaju u obzir deformacije na ivici mišića i elastične deformacije mehura mišića zbog promene pritiska već samo kontrakcije mišića. Ovaj članak predstavlja metodu koja nam omogućava precizno merenje promena zapremine u pneumatskom mišiću. Eksperimentalni rezultati su zatim upoređivani sa standardnim Chou modelom. Takođe se predlaže buduće unapređenje PAM modela.

Ključne reči: pneumatski veštački mišić, mašinski vid, računanje zapremine, kalibracija kamere