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PNEUMATIC MUSCLE – MEASUREMENT RESULTS AND SIMULATION MODELS

ABSTRACT *In the paper the advantages of pneumatic muscle are described. In the article are also presented:*

- Measurement stand for determine the static and dynamic characteristic pneumatic muscle MAS-10-88N (Festo manufacture).*
- Mathematical model of pneumatic muscle for static and dynamic simulations.*
- Results of the simulations for differents conditions pressures supply.*

Keywords: *pneumatic muscle, simulation models, biomechanics*

1. INTRODUCTION

Pneumatic (fluidic) muscle is a single-acting actuator. Fluid Muscle is a membrane construction system or, to put it more simply, a tube which constructs under pressure. The basic concept lies in the combination of an impervious, flexible hose and a covering of woven fibres as tensile material in a rhomboidal mesh. This results in a three-dimensional grid structure 2.

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Fig. 1. Fluidic muscle – general view

The medium flowing inwards changes the shape of the grid structure by expansion, thus generating a tensile force in the axial direction. The grid structure causes the muscle to shorten up to the neutral axis and as a internal pressure is increased. This corresponds to a stroke of approx. 25% of the initial unloaded length 2.

The advantage a pneumatic muscle are:

- resistant to dust and dirt,
- dynamic,
- powerful,
- judder-free.

2. STAND TO RESEARCH PNEUMATIC MUSCLE

In the article [3] the quick-release test rig is described. The muscle force is measured using a strain gauges by using strain gauges at the fixing muscle. The length muscle is detected by optical encoders on the deflector roll 4.

The test stand was described in the MSc work 1 and designed in the Inventor Program. The CAD model is presented in figure 2 (left side). Figure 2b (right side) presents Setup measures.



Fig. 2. Test stand: CAD model (left), view of real stand (right)

The diameter for pneumatic muscle (contraction and increase diameter) is measured by using the Clock detector which accuracy is 0,01 mm. Four different springs are responsible for load muscle.

3. RESULTS OF THE MEASUREMENT

First type a research: static characteristics.

The pressure values changes the pneumatic muscle shape. The universal dependence is: low values on the internal pressure fluid – minimal deformation (contraction and increase diameter), high value on the internal pressure fluid – maximal deformation (contraction and increase diameter).

The percentage contraction values are described by the relations:

$$k = \frac{l_0 - l}{l_0} \cdot 100\% , \quad (1)$$

where:

- l_0 – initial length muscle,
- l – length muscle.

A length pneumatic muscle depends on pressure values and load. The measurements for standstill muscle were realized.

The figure 3a showed results of measure increase diameter versus length muscle for different pressure: 1, 2, ...,6 bar. The muscel was not duty. Points in the figure – measurement values, curves – approximation function (polynominals 2 and 3 grade).

The figure 3b shows changes of contraction values on percentage during different loads. The loads was realized for springs in differents constant springs ($c_1 = 10$ N/mm; $c_2 = 18$ N/mm; $c_3 = 35,8$ N/mm and $c_4 = 66,22$ N/mm). The magenta curve – for not duty muscel.

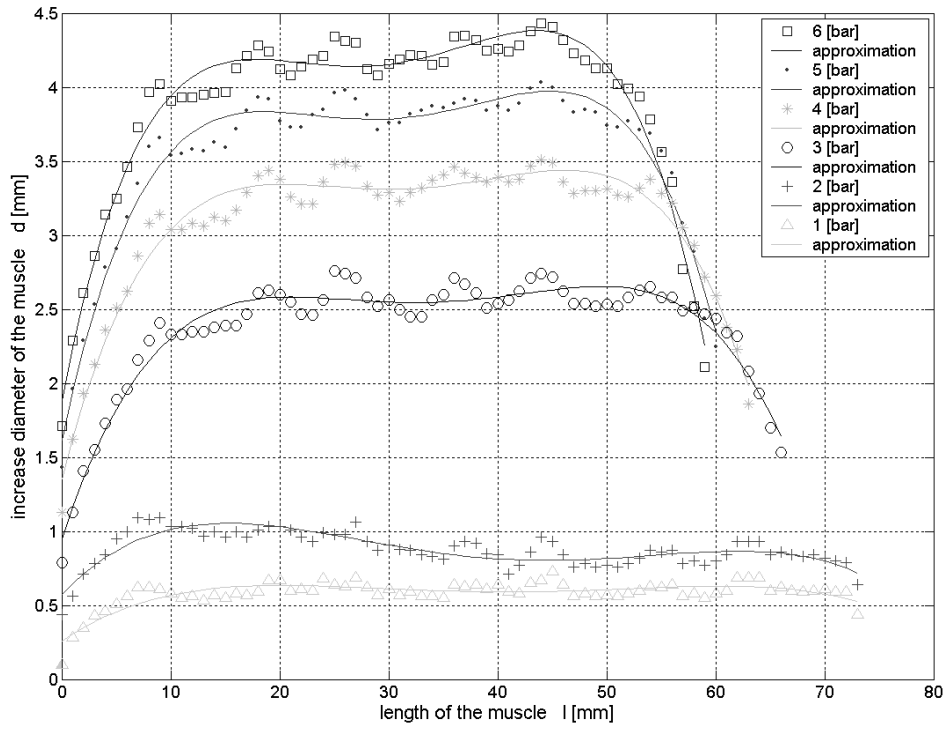


Fig. 3a. Increase diameter of the muscle for different pressure 1

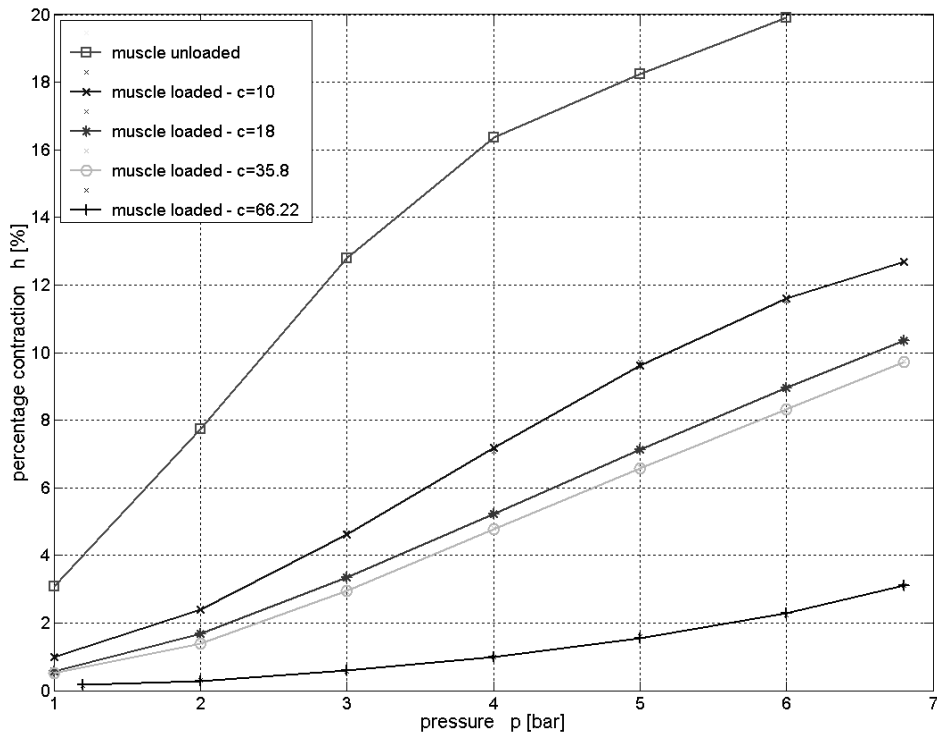


Fig. 3b. The percentage contraction versus different pressure for different loads 1

Second type a research: dynamic characteristics.

The dynamic change of time contractions is essential and has been taken into account during this researches. The laser displacement sensor (Keyence LK-G series) uses time dependent measure on the contraction.

For example the figure 4a shows the results contraction muscle (mm) measure versus time (ms). The muscle is not duty. Pressures supply 6 bar. Whole characteristic wi has divided for three ranges: A – the properly contraction, B – second contraction phase , C – phase of return to initial shape. Fig. 4b presents first range time dependent on the axial displacement free and of the muscle.

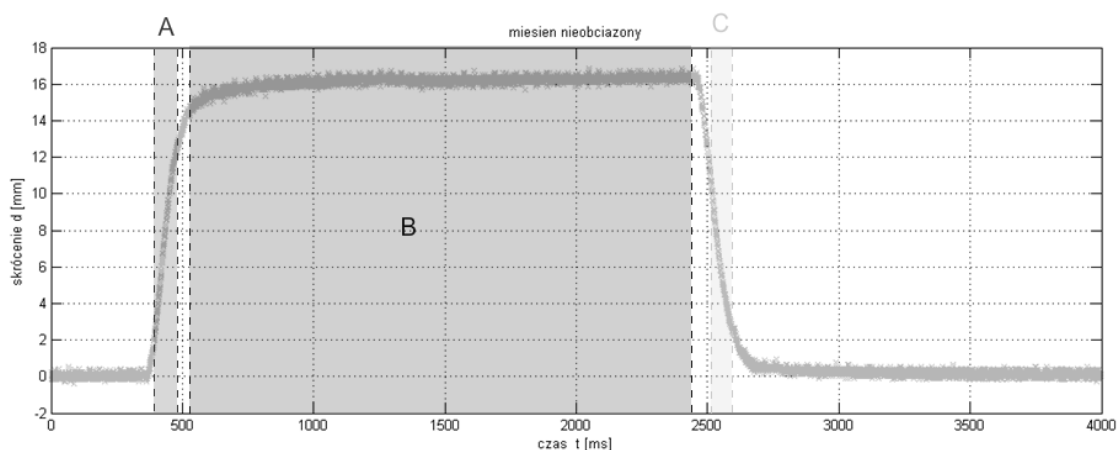


Fig. 4a. Contraction of the muscle versus time (muscel is not duty, pressure 6bar) 1

The linear equations for described change axial displacement free and of the muscle versus time using of Matlab functions (polyfit function) are determine. The example of range A (fig. 4b) the equation is determined: $k = 0,1339 \cdot t - 50,4387$. The velocity of the deformation is described by the equation:

$$v = \frac{dk}{dt}, \quad (2)$$

The velocity for the range A is $0,1339 \text{ mm/ms} = 133,9 \text{ mm/s}$.

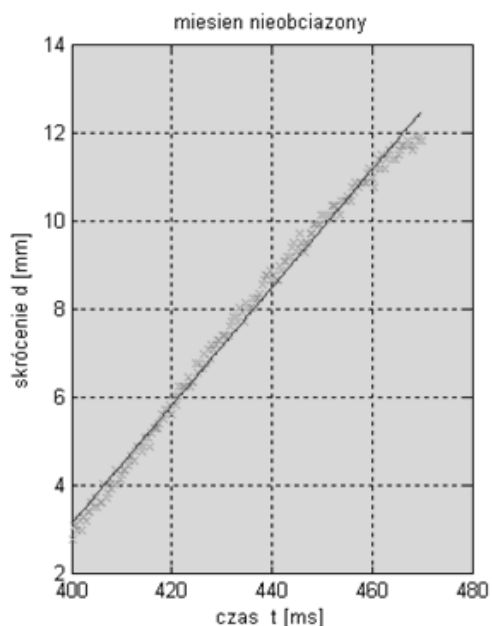


Fig. 4b. Range A of the fig. 4a 1

The table 1 presents values of velocity in range A, B and C for different values of pressures and loads.

load	Pressure [bar]	Velocity in range A [mm/s]	Velocity in range B [mm/s]	Velocity in range C [mm/s]
0	1	8,8	0,4	38,9
0	2	8,9	0,3	87,4
0	3	54,0	0,4	103,0
0	5	124,8	0,4	128,6
0	6	133,9	0,4	132,0
0	7	147,9	0,5	118,0
c = 35,8 [N/mm]	1	8,6	0,1	12,1
c = 35,8 [N/mm]	2	2,8	0,1	4,5
c = 35,8 [N/mm]	3	12,6	0,1	25,0
c = 35,8 [N/mm]	5	34,8	0,1	68,7
c = 35,8 [N/mm]	6	55,2	0,2	51,0
c = 35,8 [N/mm]	7	74,9	0,2	53,3

4. STATIC AND DYNAMIC SIMULATION MODELS

Static and dynamic characteristics from the measurements allows construct simulation models in Matlab/Simulink environment.

First type a simulation models: static models.

The results of the measures are basis for generating a calculate models.

First model base in values of pressures [bar] and different load. This values contractions [mm], pressures and loads for the matrix are notations. 3-dimensional relations presents figure 5a. Input in the model is realize with the help of the green blocks. This matrix is implanted in the simulation model (fig. 5b) in block Look-Up Table 2D. The row index input value is the constant in the spring. The column index input value is reserved for value of pressure. Output of the block is contraction value (mm). The muscle force is product values of contraction and constant spring.

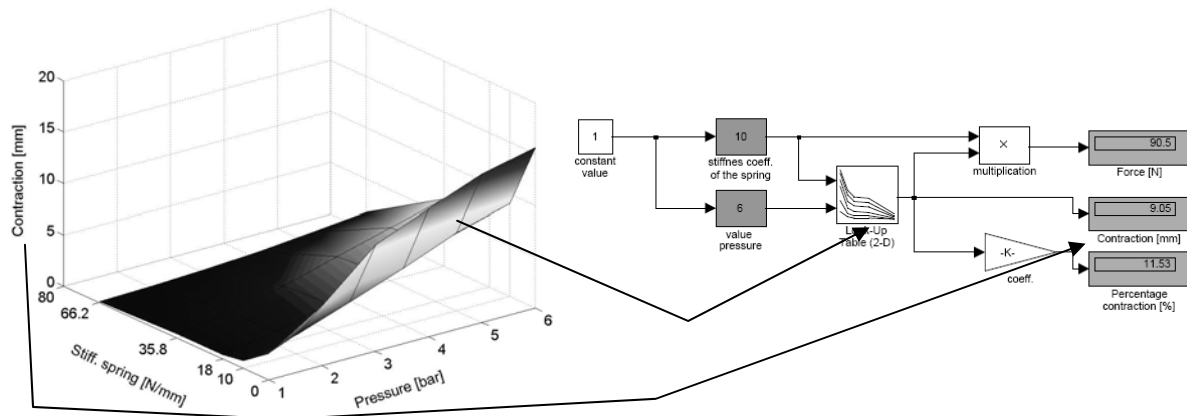


Fig. 5a. Muscle contraction [mm] versus pressure [bar] and loads [N/mm] 1

Fig. 5b. The model for computed the loaded by forces and contractions 1

The figure 6a presents the 3D isobaric characteristic for the muscle MAS-10-88N. Figure 6b shows that characteristic for 2D representation. The values for isobaric characteristics has been taken from the computer program Festo MuscleSim v.2.0.1.5 5.

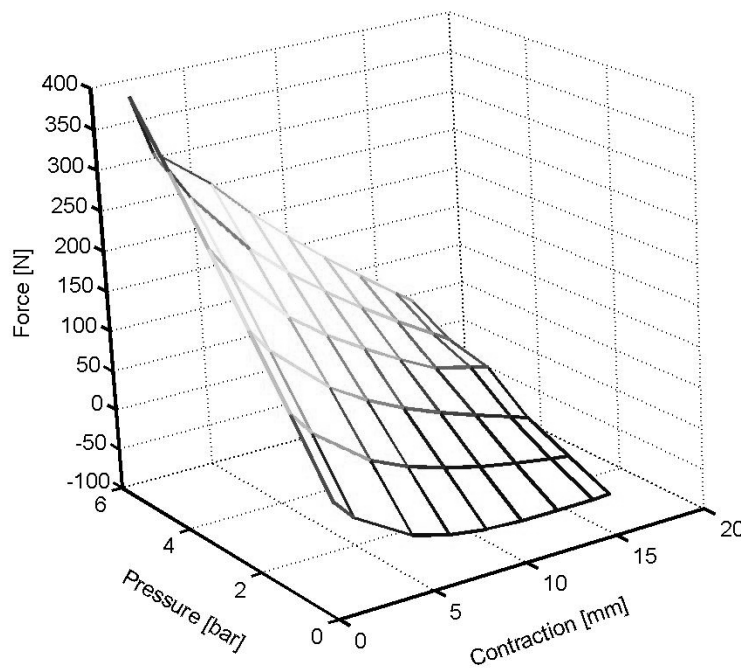


Fig. 6a. Force of a muscle [N] versus pressure [bar] and contraction [mm]

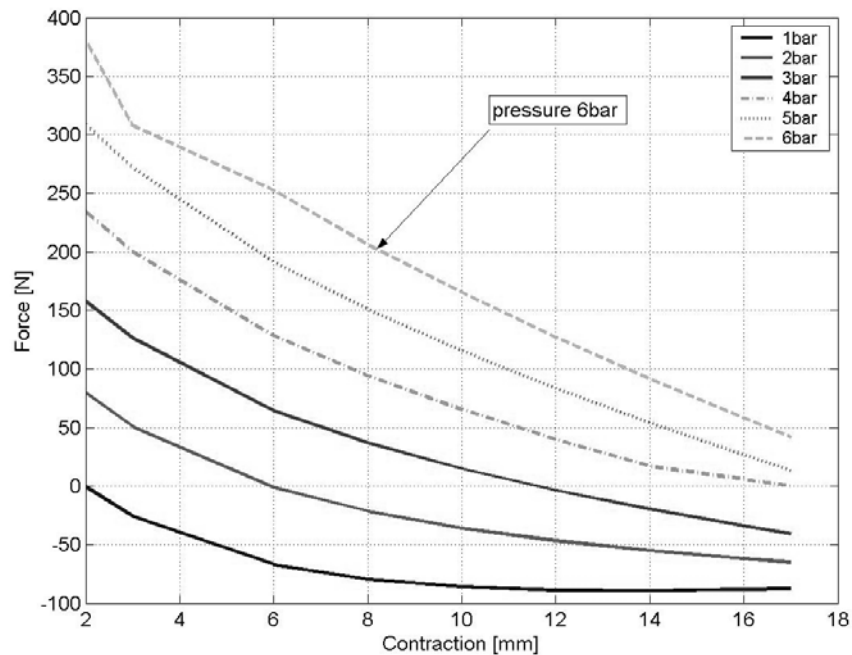


Fig. 6b. The isobaric characteristic for the muscel type MAS-10-88N

Second type a simulation models: dynamic model.

The dynamic model was build by the kinematic model which is presented below in the figure 7.

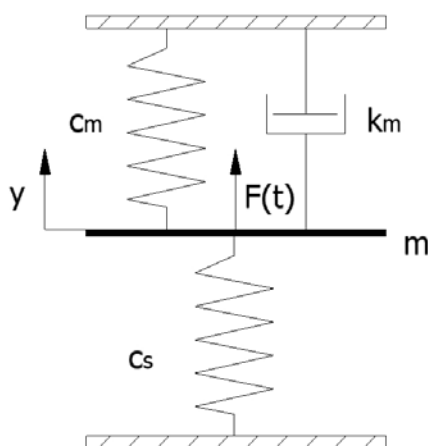


Fig. 7. The model for dynamic simulations

Where in the model:

- c_m – muscel stiffnes [N/mm],
- k_m – damping coefficient for the muscel [Ns/mm],
- c_s – stiffnes of loading spring [N/mm],
- m – mass in the end of the muscel [kg],
- $F(t)$ – external force [N].

The dynamic model was formulated by using the Lagrange'a formula:

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{q}} \right) - \frac{\partial E_k}{\partial q_i} = F_i - \frac{\partial E_p}{\partial q_i} - \frac{\partial D}{\partial \dot{q}_i} \quad i = 1, 2, \dots, n \quad (3)$$

where:

- E_k – kinetic energy,
- E_p – potential energy,
- D – dissipation energy,
- F – loading force;
- q – generalize displacement,
- $\dot{q} = dq/dt$ – generalize velocity.

The kinetic energy for model in figure 7 is described by equation:

$$E_k = \frac{1}{2} \sum_{i=1}^n m_i \dot{y}_i^2 = \frac{1}{2} m \dot{y}^2 \quad (4)$$

Derivative of the kinetic energy is described by equation:

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{y}_1} \right) = m \ddot{y} \quad (5)$$

The potential energy for model in figure 6 is described by equation (6):

$$E_p = -\frac{1}{2} c_m y^2 + \frac{1}{2} c_s y^2 + mgy \quad (6)$$

Derivatives of a potential energy are described by:

$$\frac{\partial E_p}{\partial y} = -c_m y + c_s y + mg \quad (7)$$

The dissipation energy for model in figure 6 is described by equation (8). The derivative from dissipation energy is relative to velocity. The equation (9) shows this relation:

$$D = \frac{1}{2} \sum_{i=1}^n k_{mi} \dot{y}_i^2 = \frac{1}{2} k_m \dot{y}^2 \quad (8)$$

$$\frac{\partial D}{\partial \dot{q}_i} = k_m \dot{y} \quad (9)$$

The final equation for the motion is described by equation:

$$m \cdot \dot{y} - c_m y + c_s y + mg = F(t) - k_m \cdot \dot{y} \quad (10)$$

where:

- y – displacement for mass m (free end the muscel) [mm],
 $\dot{y} = dy/dt$ – velocity for mass m (free end the muscel) [mm/s],

The model for dynamic simulations implemented in Matlab/Simulink presents figure 8.

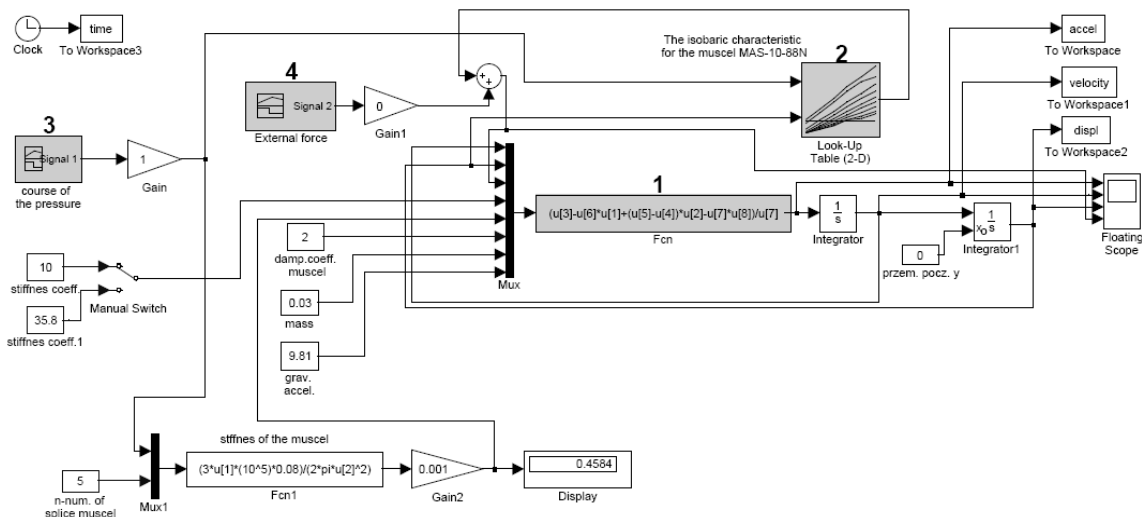


Fig. 8. The dynamic simulation model

This model was based on the equation (10). The equation (10) was written in Fcn block (number 1 in the figure 8). The isobaric characteristic for the muscle was implemented by block Look-Up Table 2D (number 2 in the model). In this model, block number 3 shows the course of pressure (example shows figure 9). Block number 4 presents the course of the external force $F(t)$.

The simulations for dynamic model was realized for two courses of the pressure. The change of the pressures was taken to consideration in figure 9.

The simulations was realized for assumptions:

- Changes of the pressure is linear (model not take into account nonlinear change of pressure inside muscel). First num. experiment – jump value of the pressure from 0bar to 6bar. Second num. experim. – increase from 0bar to 6bar in time 0,1s.
- Model based for isobaric characteristic from computer program (not from measurement).
- The damping coefficient of the muscle is not veryfying.

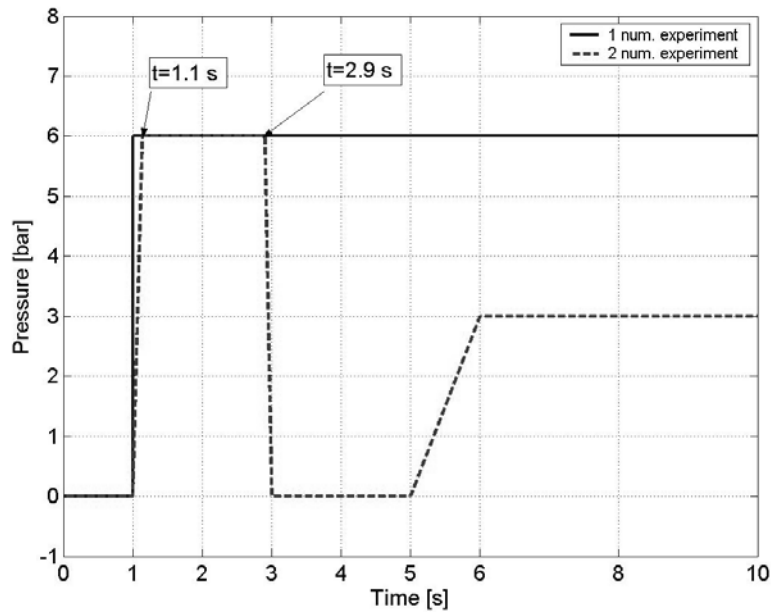


Fig. 9. Two courses of the pressure for dynamic simulations

The results of numeric experiments presents next figure (10). Figure 10a presents contractions for two courses of the pressure (figure 9). Figure 10b presents velocity (contraction speed) and 10c accelerations for two courses of the pressure (figure 9).

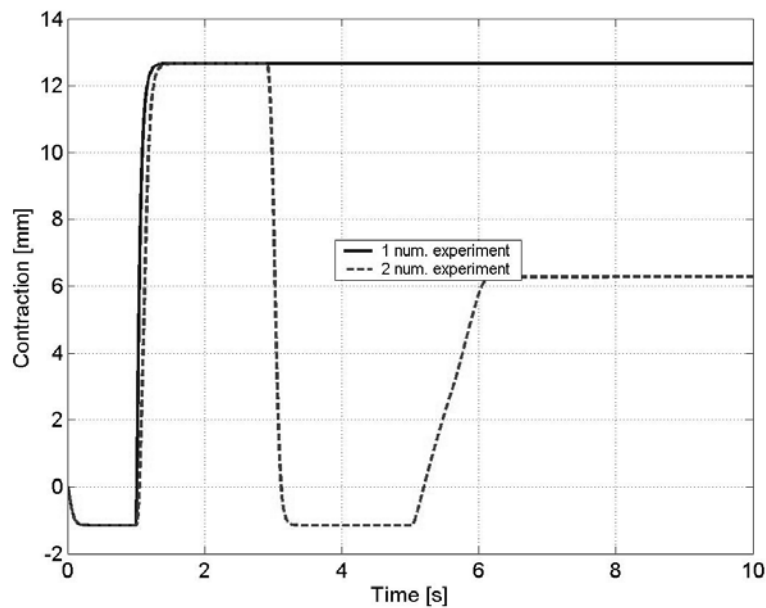


Fig. 10a. Contractions [mm] versus time [s] for two courses of pressure

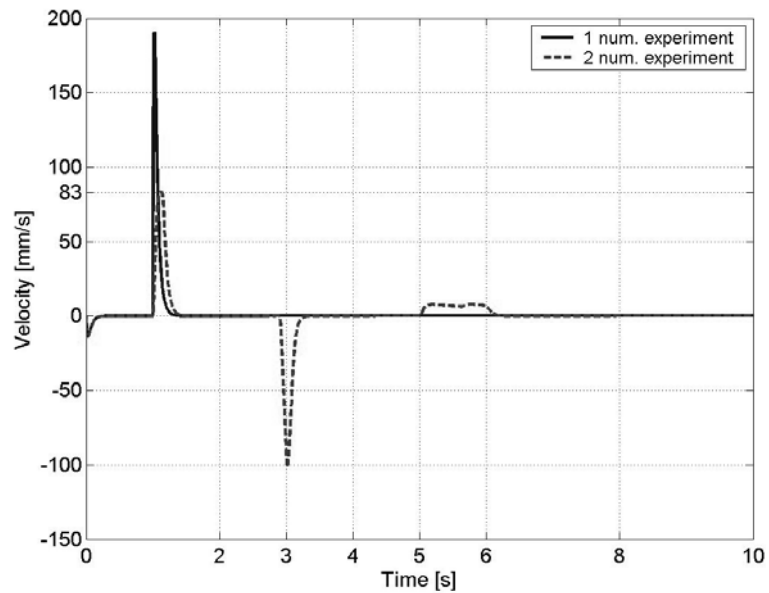


Fig. 10b. Velocity [mm/s] versus time [s] for two courses of pressure

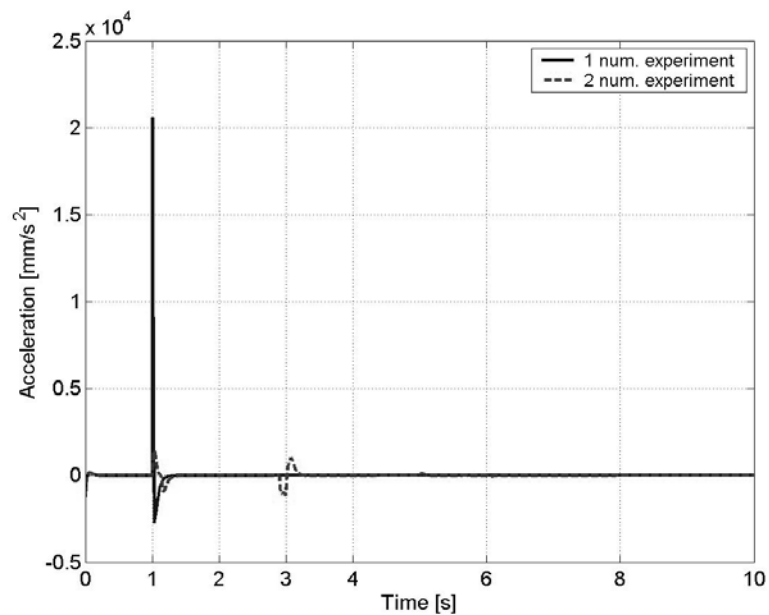


Fig. 10c. Acceleration [mm/s²] versus time [s] for two courses of pressure

5. SUMMARY

This article presents results of researches for pneumatic muscle MAS-10-88N.

The generally conclusions are:

- The pneumatic muscle have many advantages (resistant to dirt, dynamic, and powerful). This type of actuator is able to be interesting alternative for different applications.
- The fault of pneumatic muscle depends of the force not only from the pressure (this dependence is obligatory for classical pneumatics drives – standard cylinders) but from contraction (isobaric characteristics – fig. 6a and 6b) $F = f(p,k)$ as well.

The conclusions from those researches are:

- The test stand (fig. 2) is for static characteristics measured oriented. This stand enable the contraction and increase diameter measured.
- The model for dynamic simulations based in the equation of the Lagrange formula. This model enable simulations with different preconditions (courses of pressure and external forces).
- The results of simulations (velocity – fig. 10b and acceleration – fig. 10c) are very dependent of pressure increase. The simulation model should take into consideration the speed of the pressure values (second simulation model – the linear dependence between pressure value and the time).

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MIĘSIEŃ PNEUMATYCZNY – WYNIKI POMIARÓW ORAZ MODELE SYMULACYJNE

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STRESZCZENIE *W pracy przedstawiono wyniki pomiarów dla stanu statycznego i dynamicznego mięśnia pneumatycznego. Mięsień pneumatyczny zaliczany jest do klasy aktuatorów jednostronnego działania (tzn. o jednym ruchu roboczym). W rozdziale 1 omówiono krótko budowę mięśnia. W dużym uproszczeniu można powiedzieć, że jest to element o konstrukcji membranowej. Ściślej jest to giętki, podatny przewód opleciony podatnym, rozciągliwym materiałem o strukturze romboidalnej. W rezultacie daje o strukturę trójwymiarowej siatki.*

Elementy wykonawcze cechują się szeregiem zalet. Najważniejsze z nich to: odporność na zanieczyszczenia zewnętrzne i wewnętrzne (jakość zasilającego czynnika), duża dynamika odkształcenia, możliwość przenoszenia dużych obciążeń.

W rozdziale 2 przedstawiono zbudowane stanowisko pomiarowe, na którym przeprowadzono badania pomiarowe. Do pomiaru skrócenia mięśnia oraz zmiany jego średnicy wykorzystano czujniki zegarowe o dokładności pomiaru 0,01 mm. Jako obciążenie dla badanego mięśnia zastosowano sprężyny o różnych stałych ($c_1 = 10$ N/mm; $c_2 = 18$ N/mm; $c_3 = 35,8$ N/mm oraz $c_4 = 66,22$ N/mm). Stanowisko zaprojektowano w programie Inventor.

W rozdziale 3 przedstawiono i omówiono wyniki przeprowadzonych pomiarów. Pierwsza część dotyczy pomiarów statycznych. Na rys. 3a zamieszczono rodzinę charakterystyk (dla ciśnienia zasilania 1, 2, ..., 6 bar) przyrostu promienia zewnętrznego mięśnia w funkcji jego długości. Na rysunku widoczne są punkty pomiarowe oraz linią ciągłą oznaczone funkcje aproksymujące te wartości. Rysunek 3b przedstawia procentową kontrakcję - daną zależnością (1) - w funkcji różnych wartości ciśnienia zasilania mięśnia. Kolejne krzywe odnoszą się do różnych wartości obciążenia mięśnia.

Na podstawie przeprowadzonych badań pomiarowych oraz uzyskanych z nich wyników opracowano modele służące do wyznaczania charakterystycznych dla mięśnia pneumatycznego wielkości (wymiary – średnica, skrócenie oraz siła) w funkcji wielkości wejściowych (siła obciążenia, ciśnienie zasilania mięśnia).

Pierwszy z przedstawionych modeli (rys. 5b) to model pozwalający wyznaczyć skrócenie wyrażone w procentach oraz w milimetrach, wartość siły, z jaką działa mięsień. Wielkościami zadanymi jest ciśnienie powietrza oraz stała sprężyny.

W dalszej części przedstawiono model dynamiczny mięśnia pneumatycznego zaimplementowany w środowisku Matlab/Simulink bazujący na wyprowadzonym równaniu ruchu oraz charakterystyce izobarycznej mięśnia (model na rys. 8). W dalszej części przedstawiono wyniki symulacji – czasowe charakterystyki skrócenia, prędkości i przyspieszenia mięśnia. Artykuł podsumowano wnioskami w punkcie 5.