Torque Characteristics of Pneumatic Muscle Actuator with Eccentric Pulley

Ján Piteľ, Mária Tóthová, Alena Vagaská, Dagmar Janáčová and Ondrej Líška

Abstract**—**The movement of the pneumatic actuator with artificial muscles in antagonistic connection is typically transmitted through the circular pulley rotating about its center. But torque of such actuator decreases with increasing rotation of the actuator arm due to the non-linear decrease of muscles forces according to their contraction. By application of the eccentric pulley instead of circular pulley a smaller torque decrease can be obtained. In the paper there are described torque characteristics of such pneumatic muscle actuator.

Keywords**—**torque characteristics, pneumatic artificial muscle, eccentric pulley

I. Introduction

PNEUMATIC actuator consisting of a pair of artificial muscles (AMs) in antagonistic configuration (Fig. 1) is suitable as nonconventional actuator for biomedical engineering applications [1]–[3] and also industrial robotic applications [4], [5]. It can be controlled by air pressure change only in one AM (active) in a particular half of the arm trajectory through the corresponding solenoid valve (inlet or outlet valve). The second antagonistic AM acts as a passive non-linear pneumatic spring (passive muscle) and it does not require any control. In the second half of the arm trajectory the actuator function is the same but muscle functions are mutually exchanged [6]–[8]. It simplifies the control of such antagonistic system [9], [10]. But muscle tensile forces (F_1, F_2) change non-linearly according to air pressure change in the muscle [11]–[17]. Each displacement of the shaft (due to a drop in the air volume of the related AM) is defined by equal torques between the AMs. Then such pneumatic actuator constitutes a non-linear system which dependence of arm position φ is non-linear centrally symmetric function of filling pressure (P_1, P_2) in the AMs [18]–[22]. Due to the constant radius r_{cp} of pulley the torque characteristics of such pneumatic muscle actuator (PMA) are also non-linear depending on the angle of the shaft rotation. A smaller decrease of torque on the actuator shaft can be achieved when a pulley with constant radius rotating around a point not located in its geometric center (along the longitudinal axis of the actuator), i.e. circular eccentric pulley is applied instead of the pulley with the constant radius rotating around its geometric center.

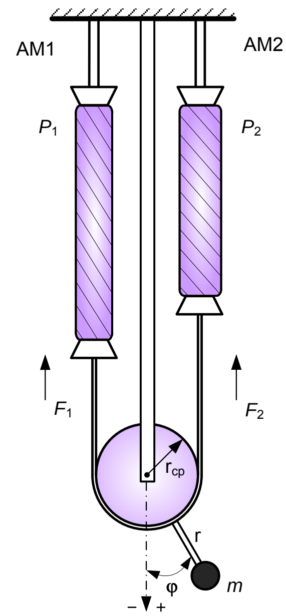

Fig. 1 Pneumatic actuator with AMs in the antagonistic configuration

II. Force Characteristics of AMs

The most common used type of AM is the McKibben pneumatic artificial muscle consisting of a flexible cylindrical isotropic rubber tube on the surface of which longitudinal nylon filaments forming netting are placed. When muscle is inflated, the tube extends causing a simultaneous extension and axial contraction of the length of netted nylon fibers. Thus the contraction of the whole muscle occurs and a tensile force of

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muscle thereby arises [15]. But muscle force depends on the muscle contraction in the range of high value at zero contraction to zero value at the maximum contraction [23]. Characteristics showing the dependence between the muscle force F of AM type MAS-20-250N and the muscle contraction κ under a constant muscle pressure P are shown in Fig. 2. These characteristics are specified by muscle manufacturer FESTO for seven values of the muscle pressure [24]. Numbers 1-4 indicate the borders applicability of AM which limit its work area with the given operating pressures.

Characteristics in Fig. 2 can be expressed as a function representing dependence between muscle tensile force, muscle contraction and pressure in the muscle. Method applied for approximation of this function was a polynomial approximation by means of Excel [25]. The basic form of approximated function was

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + ... \quad (1)$$

The force characteristic for working pressure 600 kPa was approximated. The result of approximation is in Fig. 3.

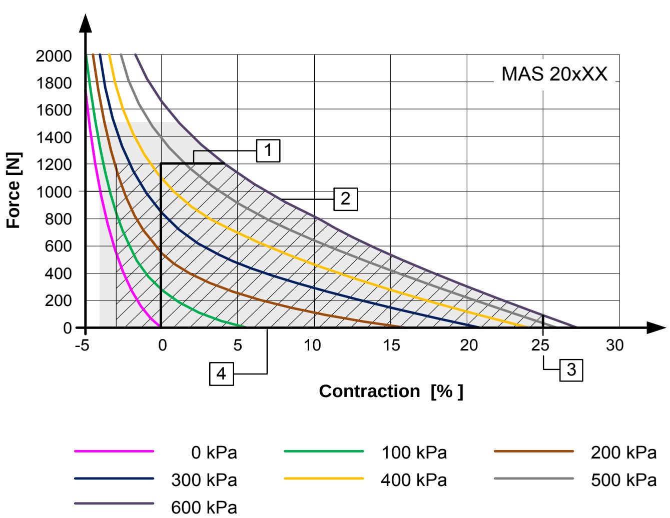

Fig. 2 Tensile force characteristics of the muscle MAS 20-200 [24]

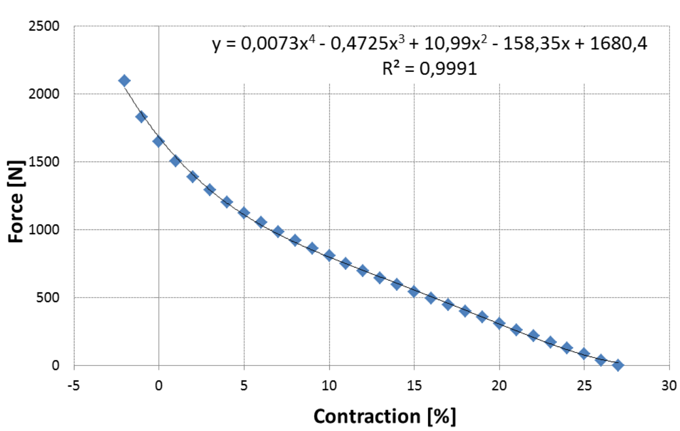

Fig. 3 The approximated tensile force characteristic for working pressure 600 kPa

After inserting calculated coefficient into the basic form of equation we get:

$$F = 1680{,}4 - 158{,}35 \cdot \kappa + 10{,}99 \cdot \kappa^2 - 0{,}4725 \cdot \kappa^3 + 0{,}0073 \cdot \kappa^4 . \quad (2)$$

III. Torque Characteristic of PMA

An antagonistic PMA consists of two AMs connected through holders to a base plate (Fig. 4). There are also two pillars mounted on a base plate with firmly attached bearing bushes. The actuator shaft supported by bearings is firmly connected with the circular pulley along which the flexible belt is passing through. Its ends are connected with AMs. There is also hub of the arm firmly slid onto the actuator shaft connected to the actuator arm with external load. Such actuator constitutes a relatively long and slender unit with satisfactory weight and dimensional characteristics.

A significant non-linear dependence there is in the PMA between change of the air pressure entering to the artificial muscles and the angle of rotating arm fixed to the shaft of the actuator. This is mainly due to non-linear decrease in muscle force depending on muscle contraction. It causes a decrease of the PMA torque with increasing value of the arm rotation angle. Then for circular pulley with constant radius r_{cp} the actuator torque M is determined by muscle force F. If parameters of the both AMs are the same, then $M = F \cdot r_{cp}$.

Torque characteristic of the actuator with AM in antagonistic connection is shown in Fig. 5. Both AMs have the same filling pressure at point Z, which corresponds to the value of the muscle contraction 12.5 %. At this point torque of actuator has maximum value.

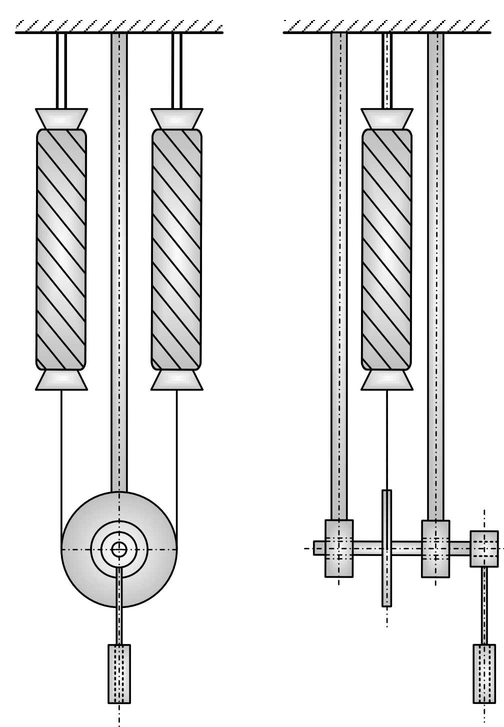

Fig. 4 PMA with circular pulley rotating about its center

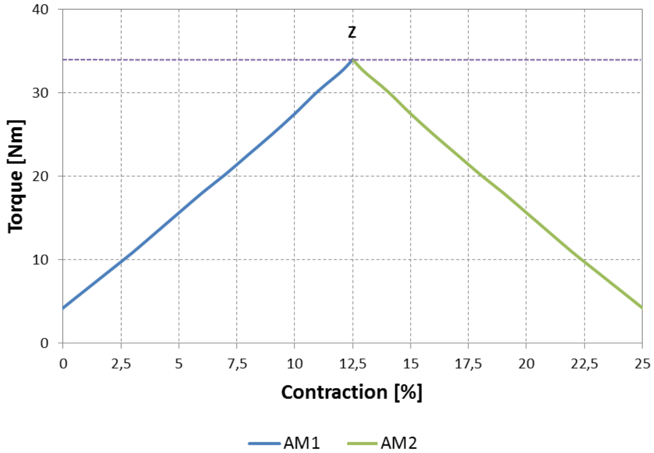

Fig. 5 Torque characteristic of the PMA with circular pulley rotating about its center

If pressure in the second AM decreases contraction of the first AM increases and torque of the actuator shaft decreases. Similarly, actuator torque decreases in the opposite direction of movement by deflation of the first AM.

IV. PMA with Eccentric Pulley

Torque decrease of the pneumatic actuator with two AMs in antagonistic connection can be reduced using an eccentric pulley, i.e. a pulley with also constant radius but rotating around a point not located in its geometric center (Fig. 6). Such actuator has a similar design as PMA with circular pulley in Fig. 4, the difference is only in using an eccentric pulley instead of classical circular pulley.

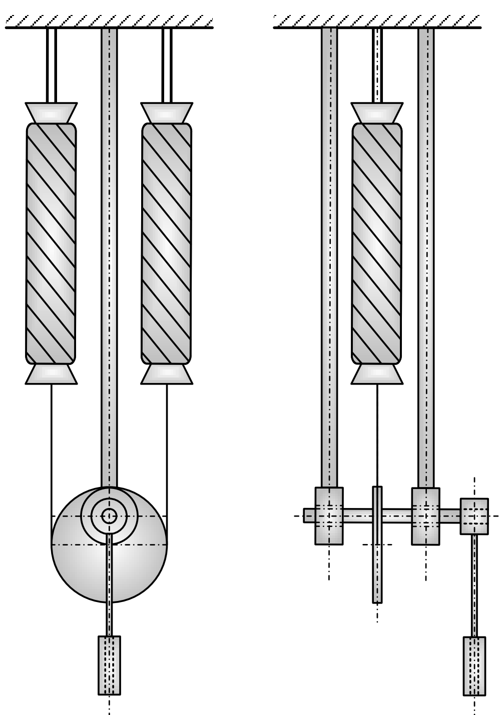

Fig. 6 PMA with eccentric pulley rotating around a point not located in its geometric center

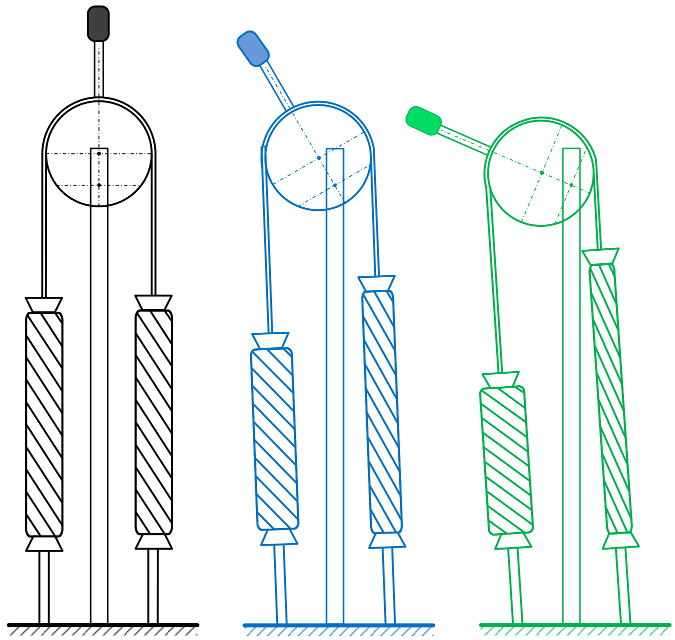

Fig. 7 The principle of movement of the PMA with eccentric pulley rotating around a point not located in its geometric center

The principle of the movement of PMA with eccentric pulley is shown in Fig. 7.

V. Torque Characteristics of PMA with Eccentric Pulley

For torque M of the PMA with axisymmetric eccentric pulley rotating around a point not located in its geometric center is valid:

$$M = F \cdot d^{*} = F \cdot r_{ep} \cdot \cos\gamma \,, \qquad (3)$$

where F is muscle tensile force, d^* is perpendicular distance of muscle force from the axis of the eccentric pulley, r_{ep} is length of the arm on which muscle force acts (i.e. the distance of the point of muscle force action from the axis of rotation of the eccentric pulley) and γ is angle between d^* and r_{ep}.

Basic parameters for geometric description of the PMA with eccentric pulley are radius r_{cp} of the pulley, the distance x of the axis of rotation of the eccentric pulley (i.e. the axis of rotation of the actuator arm) from the geometric center of the pulley and the height h_A of the PMA from a base plate to the axis of rotation of the eccentric pulley (Fig. 8).

The others important parameters in Fig. 8 can be expressed as a function dependent on the angle φ of the actuator arm rotation with constant parameters r_{cp}, x and h_A as follows:

$$r_{ep} = \sqrt{x^2 + r_{cp}^2 + 2x \cdot r_{cp} \cdot \sin\varphi} \,, \qquad (4)$$

$$\beta_1 = \arcsin\frac{x \cdot \cos\varphi}{r_{ep}} = \arcsin\frac{x \cdot \cos\varphi}{\sqrt{x^2 + r_{cp}^2 + 2x \cdot r_{cp} \cdot \sin\varphi}} \,. \qquad (5)$$

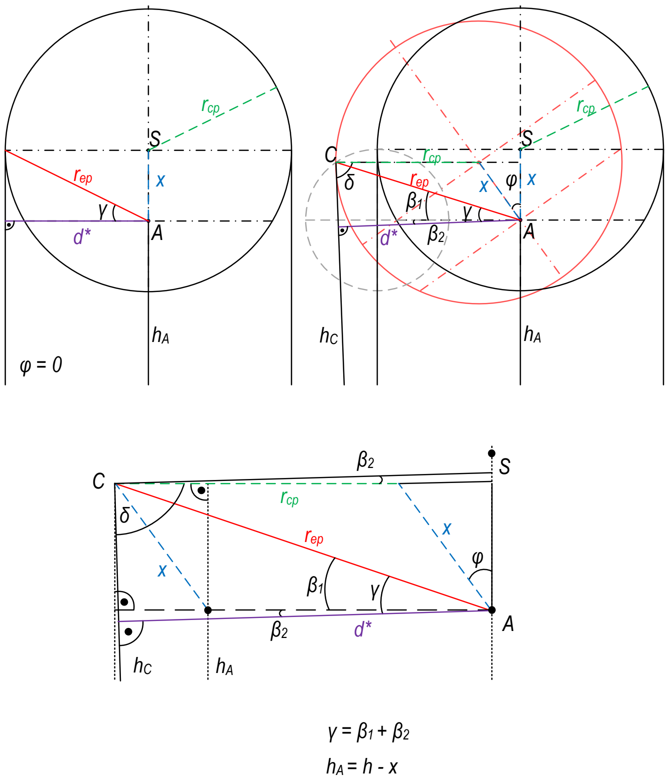

Fig. 8 Correlation between parameters of the eccentric pulley

Some parameters in Fig. 8 using the basic properties of the triangles must be expressed for calculation the angle γ in (3), as follows:

$$h_C = \sqrt{h_A^2 + x^2 + 2h_A x \cdot \cos\varphi}\,, \tag{6}$$

$$\delta = \arcsin\frac{h_A + x\cdot\cos\varphi}{h_C} = \arcsin\frac{h_A + x\cdot\cos\varphi}{\sqrt{h_A^2 + x^2 + 2h_A\cdot x\cdot\cos\varphi}}\,, \tag{7}$$

$$\beta_2 = \frac{\pi}{2} - \delta = \frac{\pi}{2} - \arcsin\frac{h_A + x\cdot\cos\varphi}{\sqrt{h_A^2 + x^2 + 2h_A\cdot x\cdot\cos\varphi}} \tag{8}$$

and

$$h_A = h - x\,, \tag{9}$$

where h is the length of the actuator.

Then the angle γ can be expressed using (5) and (8) as follows:

$$\gamma = \beta_1 + \beta_2 = \arcsin\frac{x\cdot\cos\varphi}{\sqrt{x^2 + r_{cp}^2 + 2x\cdot r_{cp}\cdot\sin\varphi}} + \frac{\pi}{2} - \arcsin\frac{h - x + x\cdot\cos\varphi}{\sqrt{(h-x)^2 + x^2 + 2(h-x)x\cdot\cos\varphi}}\,. \tag{10}$$

Then for torque M of the PMA with eccentric pulley rotating around a point not located in its geometric center can be written:

$$M = F\cdot\sqrt{x^2 + r_{cp}^2 + 2x\cdot r_{cp}\cdot\sin\varphi}\cdot \cdot\cos\left(\begin{array}{l}\arcsin\dfrac{x\cdot\cos\varphi}{\sqrt{x^2 + r_{cp}^2 + 2x\cdot r_{cp}\cdot\sin\varphi}} + \dfrac{\pi}{2} - \\ -\arcsin\dfrac{h - x + x\cdot\cos\varphi}{\sqrt{(h-x)^2 + x^2 + 2(h-x)x\cdot\cos\varphi}}\end{array}\right). \tag{11}$$

It follows from relation (11) that the torque of the PMA with eccentric pulley rotating around a point not located in its geometric center depends not only on the angle φ of the actuator arm rotation, but also on distance x of the axis of rotation of the eccentric pulley from the pulley center.

The torque characteristics of the actuator with AMs in antagonistic connection for different distances x of the axis of rotation of the eccentric pulley from the geometric center of the pulley which radius is constant 0.05 m are shown in Fig. 9. These characteristics are mutually oppositely oriented for both muscles and at point Z both AMs have the same maximum pressure.

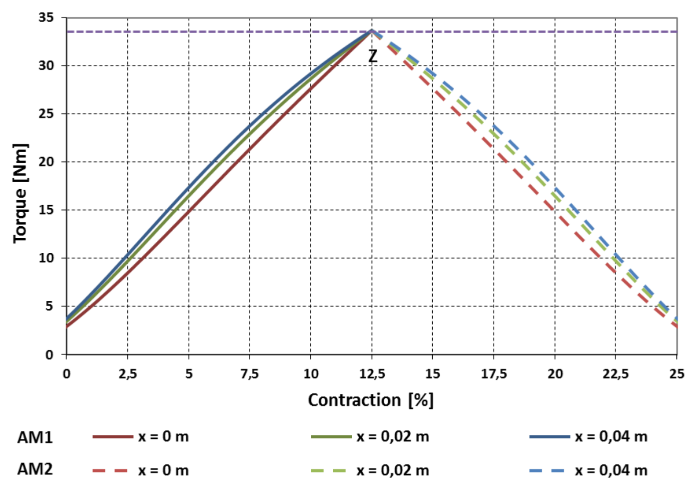

Fig. 9 Torque characteristics of the PMA with eccentric pulley

The angle φ of actuator arm rotation depends on the shortening of the muscle (muscle displacement s) and it is given by the length of the circular arc with a central angle:

$$s = \frac{2\pi\cdot(r_{cp} + x)}{360}\cdot\varphi\,. \tag{12}$$

For muscle modeling the muscle contraction κ is often used instead of muscle displacement s and then it can be expressed as:

$$\kappa = \kappa_0 + \frac{s}{l_0}\,, \tag{13}$$

where κ_0 is the initial muscle contraction and l_0 is the initial muscle length.

Substituting (13) to (12) the dependence of the angle φ of actuator arm rotation on the muscle contraction κ can be obtained:

$$\varphi = \frac{360}{2\pi} \cdot \frac{l_0(\kappa - \kappa_0)}{r_{cp} + x}. \tag{14}$$

The dependencies of the muscle contraction on the position of actuator arm derived from (14) for different distance x of eccentric pulley are shown in Fig. 10.

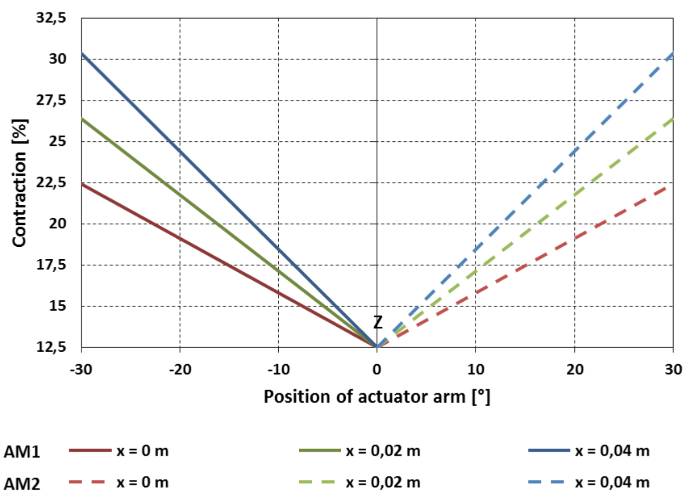

Fig. 10 The dependence of the muscle contraction on the position of actuator arm

VI. Conclusion

The torque characteristics in Fig. 5 and also in Fig. 9 show that the torque of the PMA with a circular pulley rotating about its center (displacement x of the axis of rotation of the actuator arm from the center of the pulley is zero) decreases depending only on the non-linearity of the muscle force. For the actuator with eccentric pulley (x different from zero) the torque decrease is smaller and it is given not only by non-linearity of the muscle, but also by the value of the distance x (Fig. 9). It is therefore possible to conclude that by using of the eccentric pulley rotating around a point not located in its geometric center it is possible to achieve even higher stiffness of the pneumatic actuator with AMs in antagonistic connection.

As it can be seen from Fig. 10 the disadvantage of using the eccentric pulley rotating around a point not located in its geometric center is the need to increase muscle contraction with increasing rotation angle of the actuator arm, which is limited by maximum contraction. Determination of the optimal distance of the axis of rotation of the actuator arm from the center of the pulley will be the subject of further research and on the basis of its results an experimental PMA with eccentric pulley will be realized.

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References

[1] O. Líška, M. More, D. Janáčová and H. Charvátová, "Design of rehabilitation robot based on pneumatic artificial muscles", *Mathematical Methods and Optimization Techniques in Engineering*, Antalya, October 8-10, 2013. Antalya: WSEAS Press, 2013. pp. 151-154.

[2] K. Židek, J. Piteľ, A Galajdová and M. Fodor, "Rehabilitation device construction based on artificial muscle actuators", *Proceedings of the Ninth IASTED International Conference: Biomedical Engineering BioMed 2012*, February 15-17, 2012, Innsbruck: ACTA Press, 2012, pp. 855-861.

[3] K. Židek and J. Šeminský "Automated rehabilitation device based on artificial muscles", *Annals of DAAAM for 2011*, Vienna: DAAAM International, 2011, pp. 1113–1114.

[4] A. Hošovský and M. Havran, "Dynamic modeling of one degree of freedom pneumatic muscle-based actuator for industrial applications", *Tehnički Vjesnik*, Vol.19, No.3, 2012, pp.673-681.

[5] I. Vojtko, M. Kočiško, M. Janák and V. Fečová, "The new design of robot arm", *Proceedings of the IEEE 11th International Symposium on Applied Machine Intelligence and Informatics (SAMI 2013)*, January 31 - February 2, 2013, Herl'any, Košice: IEEE, 2013, pp. 53 – 56.

[6] M. Balara, "The upgrade methods of the pneumatic actuator operation ability", *Applied Mechanics and Materials*, Vol. 308, pp 63-68, 2013.

[7] J. Piteľ and M. Tóthová, "Operating characteristics of antagonistic actuator with pneumatic artificial muscles", *Applied Mechanics and Materials*, Vol. 616, pp.101–109, 2014.

[8] M. Tóthová, J. Piteľ and J. Boržíková, "Operating modes of pneumatic artificial muscle actuator", *Applied Mechanics and Materials*, Vol. 308, pp. 39-44, 2013.

[9] M. Balara, "The linearised control system of the pneumatic actuator", *Annals of DAAAM for 2011*, 23-26th November 2011, Vienna: DAAAM International, pp. 1251-1252.

[10] M. Tóthová, J. Piteľ and J. Mižáková, "Electro-pneumatic robot actuator with artificial muscles and state feedback", *Applied Mechanics and Materials*, Vol. 460, pp. 23–31, 2014.

[11] Ch-P. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles", *Transaction on Robotics and Automation*, Vol. 12, No. 1 pp. 90-102, 1996.

[12] S. Hrehová and E. Fechová, "Gain knowledge of selected properties of artificial muscles using tools of Matlab", *Proceedings of the 2014 15th International Carpathian Control Conference (ICCC 2014)*. Velké Karlovice, May 28-30, 2014, Danvers: IEEE, 2014. pp. 164-167.

[13] W. Lepiarz, "The vision analysis of a McKibben pneumatic artificial muscle", *Proceedings of the 2014 15th International Carpathian Control Conference (ICCC 2014)*. Velké Karlovice, May 28-30, 2014, Danvers: IEEE, 2014. pp. 306-309.

[14] M. Mailah, H.M. Hooi, S. Kazi and H. Jahanabadi, "Practical active force control with iterative learning scheme applied to a pneumatic artificial muscle actuated robotic arm", *International Journal of Mechanics*, Vol. 6, Issue 1, pp. 88-96, 2012.

[15] J. Mižáková, J. Piteľ and M. Tóthová, "Pneumatic artificial muscle as actuator in mechatronic system", *Applied Mechanics and Materials*, Vol. 460, pp.81–90, 2014.

[16] J. Sárosi, "New approximation algorithm for the force of fluidic muscles", *Proceedings of 7th IEEE International Symposium on Applied Computational Intelligence and Informatics* (*SACI 2012*). Timisoara, May 24-26, 2012, Timisoara: IEEE, 2012. pp. 229-233.

[17] B. Tondu and P. Lopez, "Modeling and control of McKibben artificial muscle robot actuators", *Control Systems Magazine*, Vol. 20, No. 2, pp. 15-38, 2000.

[18] J. Boržíková, "The determination of analytic dependence of static characteristic of PAM-based antagonistic actuator", *Acta Mechanica Slovaca*. Vol. 12, No. 1-A, 2008. pp. 227-230.

[19] V.R. Dushin, V.F. Nikitin, J.C. Legros and M.V. Silnikov, „Mathematical Modeling of Flows in Porous Media“, *WSEAS Transactions on Fluid Mechanics*, Vol. 9, pp. 116-130, 2014.

[20] A. Hošovský and K. Židek, “Experimental validation of nominal model characteristics for pneumatic muscle actuator”, *Applied Mechanics and Materials*, Vol. 460, pp. 1-12, 2014.

[21] J. Piteľ and M. Tóthová, “Dynamics of pneumatic muscle actuator: measurement and modeling”, *Proceedings of the 2014 15th International Carpathian Control Conference* (*ICCC 2014*). Velké Karlovice, May 28-30, 2014, Danvers: IEEE, 2014. pp. 432-436.

[22] A. Vagaská, “Mathematical description and static characteristics of the spring actuator with pneumatic artificial muscle”, *Applied Mechanics and Materials*, Vol. 460, pp. 65-72, 2014.

[23] Ľ. Straka, “Operational reliability of mechatronic equipment based on pneumatic artificial muscle”, *Applied Mechanics and Materials*, Vol. 460, pp. 41-48, 2014.

[24] Fluid muscles DMSP / MAS [online] Actuators with special functions 2004/10 Available: https://www.festo.com/cat/sk_sk/data/doc_sk/PDF/SK/MAS_SK.PDF

[25] M. Zamani, ”A new, robust and applied model for approximation of huge data”, *WSEAS Transactions on Mathematics*, Vol. 12, Issue 6, pp. 727-735, 2013.

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