

Dynamic Simulation Model of Pneumatic Actuator with Artificial Muscle

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Abstract—Antagonistic actuator with pneumatic artificial muscles (PAMs) is a kinematic structure that consists of two pneumatic muscles acting in opposition to each other, connected through the chain gear. The resulting position of the actuator can be determined by the angle of arm of the load attached to a shaft. Stiffness position of shaft in the given direction is determined by size of pressure of the relevant pneumatic muscle, which is loaded in tension and rotation (position) of shaft is proportional to pressure difference in individual muscle. The main drawback of this actuator is that its dynamic behavior is highly nonlinear. Due to this knowledge of the muscle properties it is necessary to use the model of the muscle. This muscle model of the system is based on modified Hill's basic model which consists of a variable damper and a variable spring connected in parallel. All the work on dynamic model was created in Matlab/Simulink environment.

I. INTRODUCTION

Pneumatic artificial muscles (PAMs) are progressive non-conventional actuators with an excellent power to weight ratio comparable to human muscle. There are a lot of advantages for PAMs like e.g. the passive damping, ability to interconnect the muscles into complex manipulating equipment, different sizes and lengths, exact and smooth operation between the extreme positions and usage in rough environments [1]. But there are major problems with their control due to highly non-linear characteristics of the muscle and it should be remembered that there are necessary two antagonistic muscles at each joint. To use the muscles as an adjustable spring-damper-system, it is necessary to have a model of these actuators which describes the whole dynamics for using in advanced control algorithms [2], [3], [4], [5]. For that reason there are many research groups of artificial muscles and their models studied [6], [7], [8], [9].

Experimental set-up which is used to control variables of the actuator is shown on Fig. 1. The main part of the system is formed by two FESTO MAS-20 fluidic muscles fitted with the force compensator. The muscles are connected in configuration called the antagonistic system through the chain gear and drive the shaft to which an arm with screwed weight is attached (not shown) [10]. Resultant position of the arm is given by equilibrium of tensile forces of PAM through the chain to the roller according to different pressures in artificial muscles [11]. Inflation and deflation of the muscle with compressed air is controlled by two ON/OFF twin-solenoid valves. The compressed air is supplied into the muscles in a form of pressure impulses.

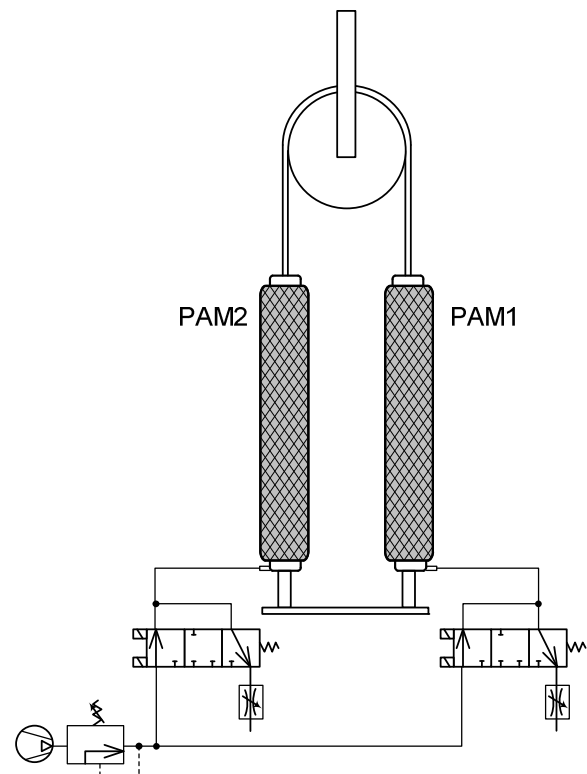


Figure 1. Pneumatic diagram of actuator with artificial muscle

II. MODELING OF PNEUMATIC ACTUATOR WITH ARTIFICIAL MUSCLE

The main aim of modeling of pneumatic actuator with artificial muscle is to build its dynamic simulation model using Matlab/Simulink environment. This model is intended as a model capturing of system dynamic that could be used for the control system design using simulation. This model can simulate various time dependent control signals of the inlet (outlet) solenoid valves and different muscle parameters.

Several basic models of pneumatic artificial muscles were designed before this date and a modified Hill's basic model with variable valve is used here because of it uses an engineering approach to muscle modeling [12]. Modified Hill's basic model does not include internal structure and function of muscle and consists of a variable damper and a variable spring connected in parallel. Mechanical model of system was obtained by joining two antagonistic muscles as shown on Fig. 2 [10].

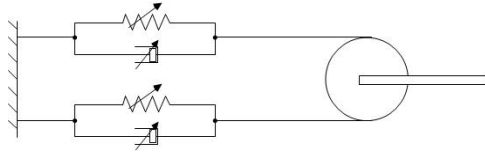


Figure 2. Mechanical model of PAMs antagonistic connection using modified Hill's model

Block diagram of pneumatic actuator with artificial muscles (Fig. 3) was designed after studying the available information about the principle functions of the actuator, Hill's model and experimental measurements [13].

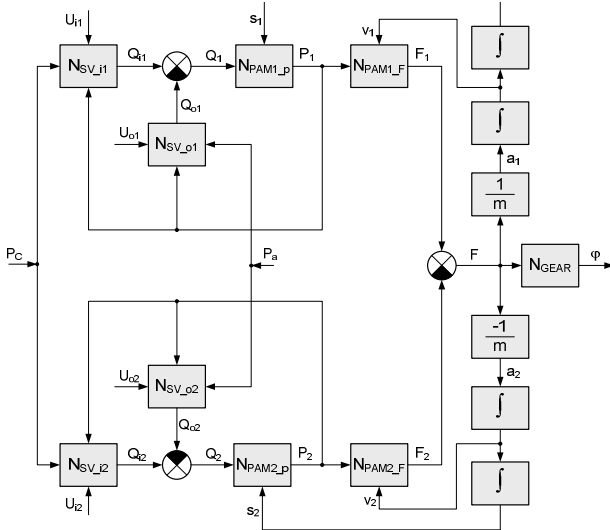


Figure 3. Block diagram of pneumatic actuator with artificial muscle

The variables and blocks in the block diagram (Fig. 3): ϕ is actuator arm position, F is resultant force of the actuator, P is the pressure in the muscle, P_C is the compressor pressure, P_a is the atmospheric pressure, a is acceleration, v is the speed of muscle contraction, s is displacement, m is weight load fixed on the end of the arm, U_i (U_o) is control voltage inlet (outlet) solenoid valve, Q_i (Q_o) is the air flow rate through inlet (outlet) solenoid valve, Q is the air flow rate in supply line to the muscle, N_{SV-i} (N_{SV-o}) is nonlinearity of the inlet (outlet) solenoid valve, N_{PAM-P} is nonlinearity of the muscle when output is total pressure in the muscle, N_{PAM-F} is nonlinearity of the muscle when output is muscle force, N_{GEAR} is nonlinearity of the gear, index number 1 pass for the first pneumatic artificial muscle – PAM1, index number 2 pass for the second pneumatic artificial muscle – PAM2.

For proper functioning of the system it should be presumed that all the variables in the initial state are zero (except for the pressure of compressor). Compressed air coming from the compressor through a pressure reducing valve to the inlet valve N_{SV-i} , thus increases the air pressure in the pneumatic muscle and leads to the artificial muscle contraction. This occurs after applying the control voltage U_i and on its output will be the air flow rate Q_i after a time delay T_d in the air supply line [14]. According to the nonlinearity N_{PAM-P} and N_{PAM-F} , the pressure and force in pneumatic muscles will be changed. Pressure changes in the muscle are expressed as the differential pressure between the inlet and outlet of the solenoid valve. Position ϕ of the actuator arm will depend of the difference forces

in muscles. Load torque in this model can also be taken into account.

A. Nonlinearity of the inlet (outlet) solenoid valve

Volume flow rate of compressed air through the valve can be easily mathematically described using of models with two ON/OFF twin-solenoid valves. This flow rate depends only on the pressure in the muscle at a constant pressure of compressor or atmospheric pressure and it is therefore necessary to take into account the state filling and discharge of pneumatic muscles. For modeling of the flow characteristics several models can be applied. There are application depends (among other things) also on valve parameters designated by the manufacturer. The article [15] presents relations for mass flow rate modeling, which have become the standard by ISO 6358. These terms have been adjusted for volume flow rate and are shown as [16]:

$$\dot{V}_a = \begin{cases} P_1 \cdot C \sqrt{\frac{T_0}{T_1}} \sqrt{1 - \left(\frac{P_2 - b}{P_1 - b} \right)^2}, & \text{if } \frac{P_2}{P_1} > b \\ P_1 \cdot C \sqrt{\frac{T_0}{T_1}}, & \text{if } \frac{P_2}{P_1} \leq b \end{cases}, \quad (1)$$

where \dot{V}_a is volume flow rate, P_1 is absolute upstream pressure, P_2 is absolute downstream pressure, C is sonic conductance, T_0 is ambient air temperature at reference conditions, T_1 is upstream temperature and b is critical ratio.

B. Nonlinearity of the muscle

Block nonlinearity of the muscle is divided into two parts: the first concerns relation of pressure change in the muscle and the second calculates the force of a single muscle [17].

One of the basic state variables of actuator based PAMs is the pressure in the muscle, whose time dependence of the changes is necessary to know for build the model. Differential equation for the pressure in the muscle can be derived using the Boyle-Mariotte law, which describes the relation between the pressure in the muscle and the muscle volume of air in a closed system at constant temperature:

$$P_a \cdot V_a = P \cdot V, \quad (2)$$

where P_a is absolute atmospheric pressure, P is absolute muscle air pressure, V_a is volume of air in the muscle and V is muscle volume.

Time derivative of the air pressure in the muscle (2) is in form

$$\dot{P} = \frac{d}{dt} \left(\frac{P_a \cdot V_a}{V} \right) = \frac{1}{V} (P_a \cdot \dot{V}_a - P \cdot \dot{V}), \quad (3)$$

where \dot{V} is time derivative of muscle volume, \dot{V}_a is time derivative of air volume in the muscle.

The pressure in pneumatic muscle is defined by (3), therefore it is necessary to express the volume of the muscle and its time derivative. In the simplest case, the artificial muscle can be regarded as a cylinder whose volume depends on the geometric parameters of the muscle. Because muscle is terminated with metal endings, it leads to its deformation, which can be modeled by combining cylinder and two cut hemispheres [16]. The resulting relation is relatively complex but it can be approximated with good accuracy using a third degree polynomial in the form:

$$V = a \cdot \kappa^3 + b \cdot \kappa^2 + c \cdot \kappa + d, \quad (4)$$

where V is volume of the muscle; κ is muscle contraction and a, b, c, d are polynomial coefficients.

Time derivative of the muscle volume (4) is in form:

$$\dot{V} = 3a \cdot \kappa^2 \cdot \dot{\kappa} + 2b \cdot \kappa \cdot \dot{\kappa} + c \cdot \dot{\kappa}, \quad (5)$$

where $\dot{\kappa}$ is muscle velocity, κ is muscle contraction and a, b, c are polynomial coefficients.

To describe the dynamics of the PAM system, a modified Hill's model of the muscle is used. It consists of series-parallel combination of standard mechanical components. It can be described by the following nonlinear differential equation based on the Newton's second law [18]:

$$\ddot{y} = \frac{1}{m} [F_E - F_s(\kappa, P) - F_D(\dot{\kappa}, P)], \quad (6)$$

where m is moving mass, y is muscle displacement, $F_s(\kappa, P)$ is nonlinear term representing a variable spring force, $F_D(\dot{\kappa}, P)$ is nonlinear term representing a damper force, F_E is external force, P is absolute muscle pressure and κ is muscle contraction (defined as $\kappa = \kappa_0 + y/l_0$ where κ_0 is initial contraction and l_0 is initial muscle length).

PAM generates two types of forces, active and passive, which together form a resultant force of the muscle. The load contractile element in Hill's model is an active source of power utilized to drive. The force contractile element F_{CE} is a nonlinear function of two variables, pressure and contraction of the muscle. This dependence was approximated by a polynomial of the fifth degree with 21 coefficients:

$$\begin{aligned} F_{CE} = & a_{00} + a_{10} \cdot \kappa + a_{01} \cdot P + a_{20} \cdot \kappa^2 + a_{11} \cdot \kappa \cdot P + \\ & + a_{02} \cdot P^2 + a_{30} \cdot \kappa^3 + a_{21} \cdot \kappa^2 \cdot P + a_{12} \cdot \kappa \cdot P^2 + \\ & + a_{03} \cdot P^3 + a_{40} \cdot \kappa^4 + a_{31} \cdot \kappa^3 \cdot P + a_{22} \cdot \kappa^2 \cdot P^2 + \\ & + a_{13} \cdot \kappa \cdot P^3 + a_{04} \cdot P^4 + a_{50} \cdot \kappa^5 + a_{41} \cdot \kappa^4 \cdot P + \\ & + a_{32} \cdot \kappa^3 \cdot P^2 + a_{23} \cdot \kappa^2 \cdot P^3 + a_{14} \cdot \kappa \cdot P^4 + a_{05} \cdot P^5. \end{aligned} \quad (7)$$

Damper and spring represent passive elements in Hill's model, the forces of which are nonlinear functions of velocity and displacement of the muscle. Nonlinear term representing a variable damper force F_D is proportional to the speed of movement of the muscle and is expressed by

the coefficient of damper, pressure in the muscle and velocity contraction:

$$F_D = R \cdot P \cdot \dot{\kappa}, \quad (8)$$

where R is damping coefficient, P is absolute muscle pressure and $\dot{\kappa}$ is muscle velocity.

Passive power in the model consists of two non-linear springs, one in series with the contractile elements and one connected in parallel. These springs create reversible forces that tend to the muscle of the original length. The force nonlinear springs connected in parallel to the contractile elements is the force necessary to push the tube in contraction and lowers the value of active force developed by the contractile elements [18].

External force F_E represents all forces to which a muscle is subjected. It can be the gravitational force of a load, frictional force and in case of two pneumatic muscles in antagonistic connection; it is the force of the other muscle.

III. SIMULATION MODEL OF PNEUMATIC ACTUATOR WITH ARTIFICIAL MUSCLE

Dynamic simulation model of PAM using modified Hill's model was realized in Matlab/Simulink environment (Fig. 8). Design model consists of four main subsystems:

- nonlinearity of the inlet (outlet) solenoid valve (Fig. 4) based on (1),
- transfer the resulting forces on the actuator arm angle (Fig. 5).
- nonlinearity of the pressure changes in the muscle (Fig. 6) based on (3), (4) and (5),
- nonlinearity of the force changes in the muscle (Fig. 7) which includes contractile element based on (7), damper force based on (8),

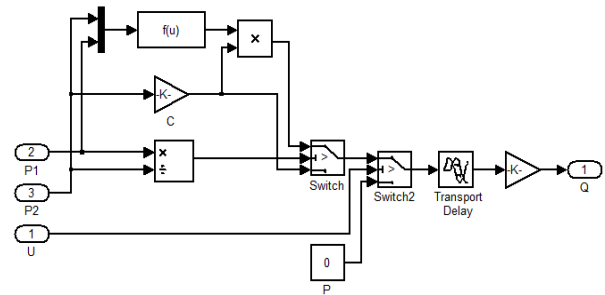


Figure 4. Subsystem of inlet (outlet) solenoid valve

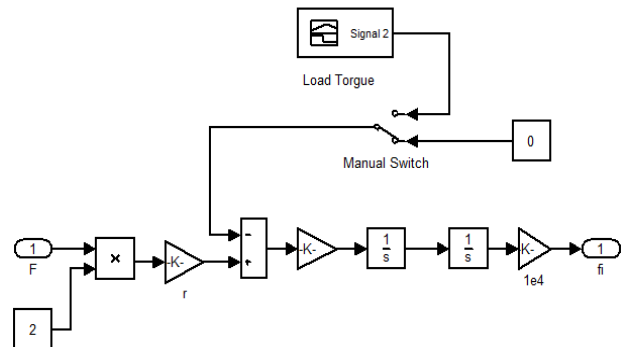


Figure 5. Subsystem of gear nonlinearity

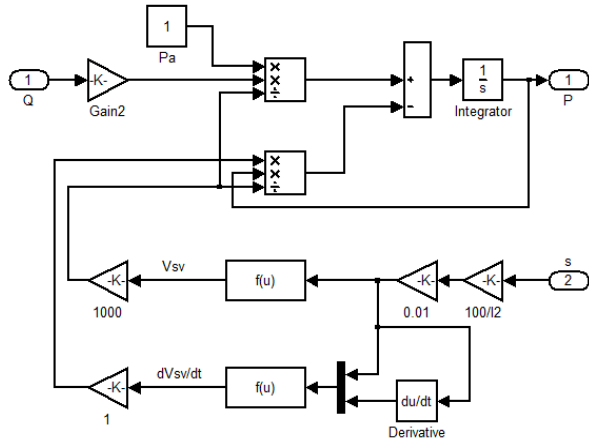


Figure 6. Subsystem of muscle nonlinearity when output is total pressure in the muscle

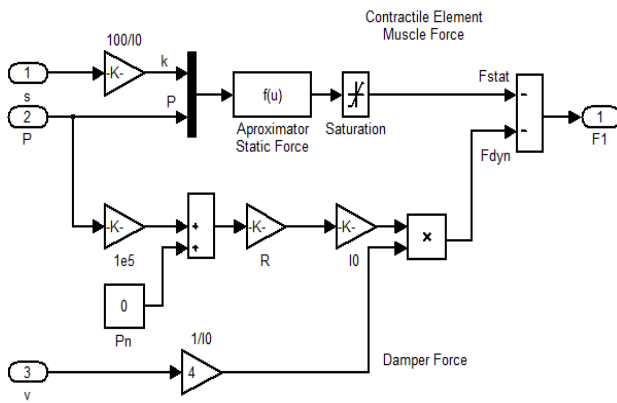


Figure 7. Subsystem of muscle nonlinearity when output is muscle force

CONCLUSION

The basic part of dynamic model of pneumatic actuator with artificial muscles is a subsystem describing the muscle nonlinearities. It is dependence between pressure in the muscle and air flow rate into or from the muscle. It includes dependence of pressure in the muscle on muscle volume, dependence of muscle volume on muscle contraction, dependence of force contractile element on muscle pressure and muscle contraction, dependence of damper force on muscle pressure and velocity contraction. Two subsystems were designed for understanding muscle nonlinearity: subsystem of muscle nonlinearity when output is total pressure in the muscle and subsystem of muscle nonlinearity when output is muscle force.

Another part of model is subsystem of inlet (outlet) solenoid valve. It is dependence between air flow rate, upstream pressure and downstream pressure in front of the valve and behind the valve.

Subsystem of gear nonlinearity is finally part of model, whose output is the angle of actuator arm.

Limitations of the method have appeared when the results obtained were examined. Higher modeling errors are created due to the simplification of modeling. There is a space for further refinement of the model in order to decrease the modeling errors so that the reliance on robustness of the control technique might be somewhat diminished.

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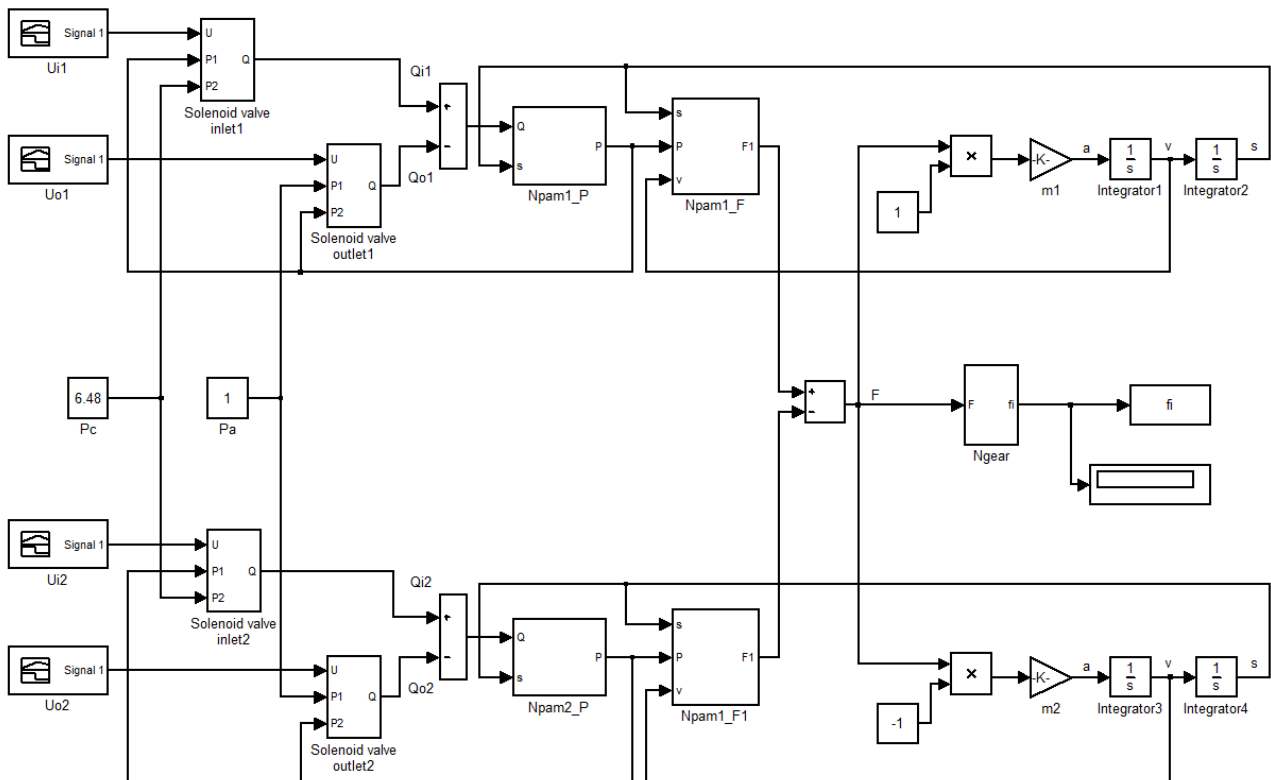


Figure 8. Dynamic simulation model of pneumatic actuator with artificial muscles using modified Hill's model

REFERENCES

- [1] J. Piteľ and M. Balara, "Pneumatic artificial muscle – perspective component of mechatronics (2)", *AT&P Journal*, 2009, vol. XVI., no 1, pp. 50-51.
- [2] J. Piteľ, M. Balara and J. Boržíková, "Control of the actuator with pneumatic artificial muscles in antagonistic connection", *TRANSACTIONS of the VŠB – Technical University of Ostrava*, 2007, LIII, Nr. 2/2007. pp. 101-106.
- [3] M. Balara, "Rotary actuators with pneumatic artificial muscles", *Proceedings of SEKEL 2007 and PRINCIPIA CYBERNETICA 2007*, 3–5th September 2007, Prague: Czech Technical University, 12 p.
- [4] G.K. Klute "Artificial Muscles: Actuators for Biorobotic Systems", Dissertation Work, Washington: University of Washington, 1999, 84 p.
- [5] K. Židek, O. Liška and V. Maxim "Advanced rehabilitation device based on artificial muscle actuators with neural network implementation", *Journal of automation, mobile robotics & intelligent systems*, vol.6, no.3, 2012, p.30-32. ISSN 1897-8649.
- [6] T. Kerscher, et al. "Evaluation of the dynamic model of fluidic muscles using quick-release", *Proceedings of the 2006 IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics BioRob 2006*, Pisa, 2006, p. 637-642.
- [7] M. Balara, "The linearized control system of the pneumatic actuator", *Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium: 23-26th November 2011*, Vienna: DAAAM International, 2011, pp. 1251-1252.
- [8] N. Saga, J. Nagase, and T. Saikawa, "Pneumatic artificial muscles based on biomechanical characteristics of human muscles", *Applied Bionics and Biomechanics*, 2011, vol. 3, Issue 3, pp. 191-197.
- [9] J. Sárosi, "New model for the force of fluidic muscles", *Proceedings of Factory Automation 2012*, 21-22nd May 2012, Veszprém: University of Pannonia, pp. 102-107.
- [10] A. Hošovský, J.N. Marcinčin, J. Piteľ, J. Boržíková and K. Židek, "Model-based evolution of a fast hybrid fuzzy adaptive controller for a pneumatic muscle actuator", *International Journal of Advanced Robotic Systems*, 2012, vol. 9 (56), 2012, p. 1-11.
- [11] J. Piteľ, R. Neydorf and J. Boržíková, "Arm position simulation of PAM based actuator", In: *Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium*, 23-26th November 2011, Vienna: DAAAM International, pp. 0145-0146.
- [12] J. Rosen, M.B. Fuchs and M. Arcan "Performances of Hill-type and neural network muscle models – toward a myosignal-based exoskeleton", *Computers and Biomedical Research*, vol. 32, Issue 5, 1999, pp. 415–439.
- [13] J. Piteľ and M. Balara "Model of the actuator with pneumatic artificial muscles", *Proceedings of the 7th International Scientific - Technical Conference PROCESS CONTROL 2006*, 13 – 16th June 2006, Pardubice: University of Pardubice, pp. R140b-1-4.
- [14] J. Boržíková, J. Piteľ, M. Tóthová and B. Šulc, "Dynamic simulation model of PAM based antagonistic actuator", *Proceedings of the 2011 12th International Carpathian Control Conference (ICCC)*, 25–28th May 2011, Ostrava: VŠB-TU, pp. 32–35.
- [15] P. Beater, "Pneumatic Drives: System Design, Modeling and Control", New York: Springer, 2007.
- [16] A. Hošovský and M. Havran "Dynamic modeling of one degree of freedom pneumatic muscle-based actuator for industrial applications", *Tehnicki Vjesnik*, 2012, vol. 19, no. 3, pp. 673-681.
- [17] J. Boržíková and J. Piteľ, "Nonlinearity of static characteristics of the antagonistic system", *Proceedings of XXI International Scientific Conference „Mathematical Methods in Technics and Technologies MMTT-21“*, 27-30th May 2008, Saratov: SG TU, pp. 196–197.
- [18] M. Havran, "Computer Support Control of Nonconventional Drive of Manipulator", Dissertation work, Prešov: FVT TUKE, 2012, 136 p.