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Pneumatic Muscle-Based Actuator for Industrial Robotic Applications

Ján Piteľ [1+], Ondrej Líška [2] and Dagmar Janáčová [3]

[1] Technical University of Kosice, Faculty of Manufacturing Technologies, Department of Industrial Engineering and Informatics, Bayerova 1, 080 01 Prešov, Slovakia

[2] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Automation, Control and Human-Machine Interaction, Letná 9, 042 00 Košice, Slovakia

[3] Tomas Bata University in Zlin, Faculty of Applied Informatics, Department of Automation and Control Engineering, Nad Stráněmi 4511, 760 05 Zlín, Czech republic

Abstract. The outstanding feature of the pneumatic artificial muscle is its high power to weight ratio vastly outperforming both pneumatic cylinder and DC motor. This feature is very important for using of pneumatic muscle-based actuators in industrial robotic systems where high forces and stiffness of mechanism are often required. The most common so far produced and used type of pneumatic artificial muscle is McKibben muscle and it is now made commercially available by different companies (e.g. Festo). In the paper there are described some of its characteristics and principles of control important for using as actuator for industrial robotic applications.

Keywords: industrial robotics, pneumatic actuator; artificial muscle, fuzzy adaptive control

1. Introduction

The pneumatic artificial muscles (PAMs) belong to progressive nonconventional actuators powered by compressed air, which is able to perform mechanical work. PAMs can be classified into the groups [1-3], namely:

- braided muscles - McKibben muscle, sleeved bladder muscle,
- netted muscles - Yarlott muscle, ROMAC, Kukolj muscle,
- embedded muscles - Morin muscle, Baldwin muscle, under-pressure muscle, Kleinwachter torsion device, Paynter knitted muscle, Paynter hyperboloid muscle,
- pleated muscles - PPAM muscle,
- special muscles - rotary muscle, 3-DOF muscle, single-action elastic tube.

The type of PAM most frequently used is the McKibben muscle. It is a cylindrical braided muscle and it has tube and sleeving connected at both ends to fittings that not only transfer tensile force but also serves as air closure. The principle of this PAM is described for example in [4-7].

Some important advantages of PAMs for using in industrial robotic applications [8-12]:

- extremely high ratio of force and power to weight and volume,
- tensile force per unit of muscle cross-sectional can reach up to 300 N/cm2,
- can be produced in different sizes and thus in different power ranges,
- absent stick-slip effect resulting from the movement of the piston in the pneumatic cylinder,
- exact and smooth movement between the limit positions of the muscle working stroke,
- ability operate in antagonistic configuration enables to control the stiffness of mechanism,
- safe to use in an explosive environment,

[+] Corresponding author..
E-mail address: jan.pitel@tuke.sk.

- low cost and maintenance,
- high reliability and environmentally friendly.

2. Pneumatic Artificial Muscles in Antagonistic Configuration

PAMs are contractile devices and can therefore only generate motion in one direction. Just like skeletal muscles, two muscles need to be coupled in order to generate bidirectional motion. The Fig. 1 shows a pair of two PAMs in antagonistic configuration in order to generate a retraction force or rotary movement [13].

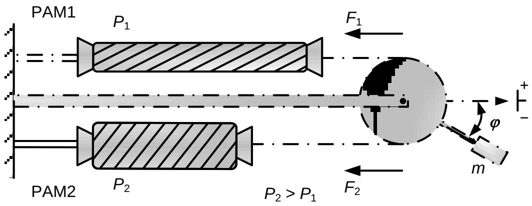

Fig. 1: PAMs in antagonistic configuration.

Tensile force F_1 of PAM1 is transmitted by gear to PAM2, which acts by its tensile force F_2. If the filling air pressures in both PAMs are equal, their tensile forces are also equal under the same values of their contractions [13]. System is stabilized in reference position and it is considered as initial zero position of the actuator. In this case the gravity force of mass load *m* does not have the influence to force relations between PAMs. If the filling air pressures in PAMs are different (Fig. 1), arm of the actuator is stabilized in position φ corresponding to balance of both PAM forces. If pressure in PAM1 decreases, its contraction κ and tensile force F_1 also decreases. It involves rotary movement of load mass *m* on the actuator arm. This sense of motion is considered as negative (minus) in relation to the initial position.

Relation between tensile force *F* and contraction κ is expressed by characteristics shown in Fig. 2, where dependence of the muscle force on the contraction at isobaric conditions is shown [14,15]. It is clear from these characteristics that PAM evolves maximum force in minimum contraction and this force with the increasing contraction decreases nonlinearly (especially at lower contractions) [16,17]. In Fig. 2 there is shown on the *x* axis contraction in percentage of the muscle nominal length and on the *y* axis is the force, whereas each of PAM2 characteristics corresponds to constant pressure in the working range 0-600 kPa. Working area of this muscle is marked with hatching. PAM1 has the constant working pressure 600 kPa.

The torque characteristic of the actuator with PAMs in antagonistic configuration is shown in Fig. 3. The maximum value of the actuator torque is when both PAMs have maximum filling pressure (initial zero position $\varphi = 0$ of the actuator according to Fig. 1) and then the muscle contraction at this point is 12.5 %. But torque and stiffness of the actuator decrease with increasing actuator arm rotation from initial zero position. This is due to the nonlinear decrease in force of the artificial muscles according to their contraction (Fig. 2).

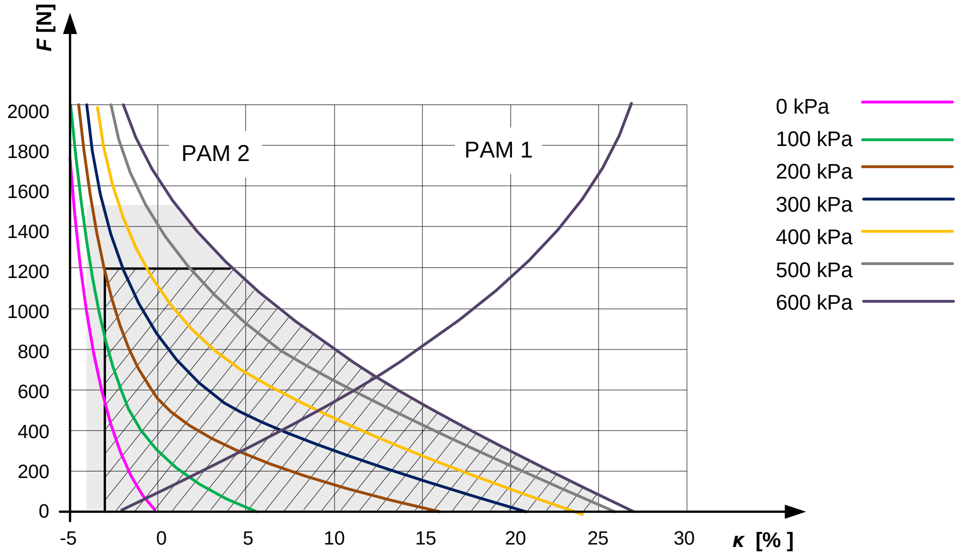

Fig. 2: Force characteristics of two PAMs in antagonistic configuration.

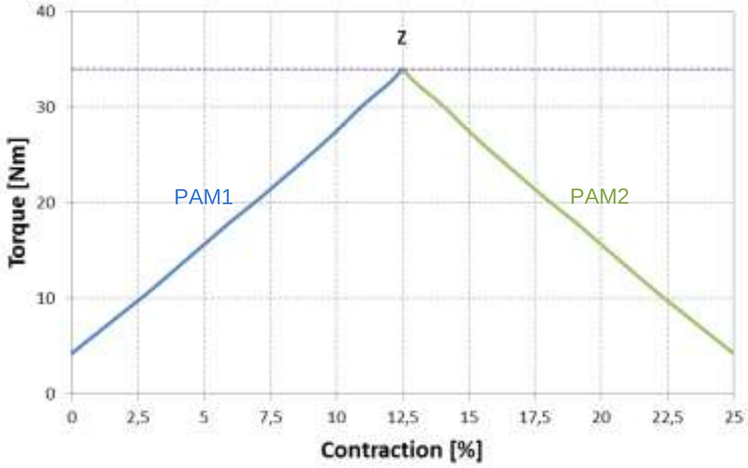

Fig. 3: The dependence of the actuator torque on the muscle contraction.

3. Pneumatic Muscle-Based Actuator with Eccentric Pulley

Pneumatic actuator with PAMs in antagonistic configuration is typically solved that generation of rotary motion is through the circular pulley rotating about its center (Fig. 1). The flexible strip is togged on this circular pulley and the ends of the strip are connected to the muscles. A torque of such actuator decreases with increasing contraction of one of the muscles (Fig. 3). A smaller torque decrease can be obtained by application of the eccentric pulley instead of circular pulley (Fig. 4).

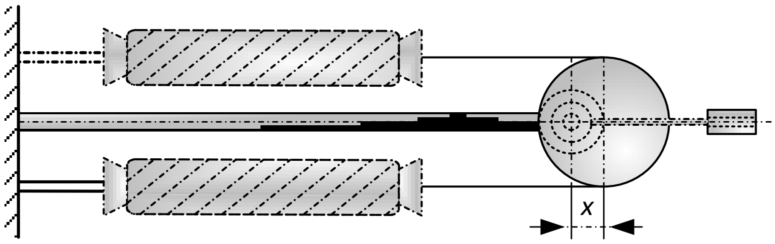

Fig. 4: Pneumatic actuator with PAMs in antagonistic configuration and eccentric pulley.

The principle of the movement of this pneumatic muscle-based actuator with eccentric pulley is described in detail for example in [18,19] and its mathematical description can be found in [20]. The torque characteristics of the actuator with PAMs for different distances *x* of the axis of rotation of the eccentric pulley from the geometric center of the pulley are shown in Fig. 5.

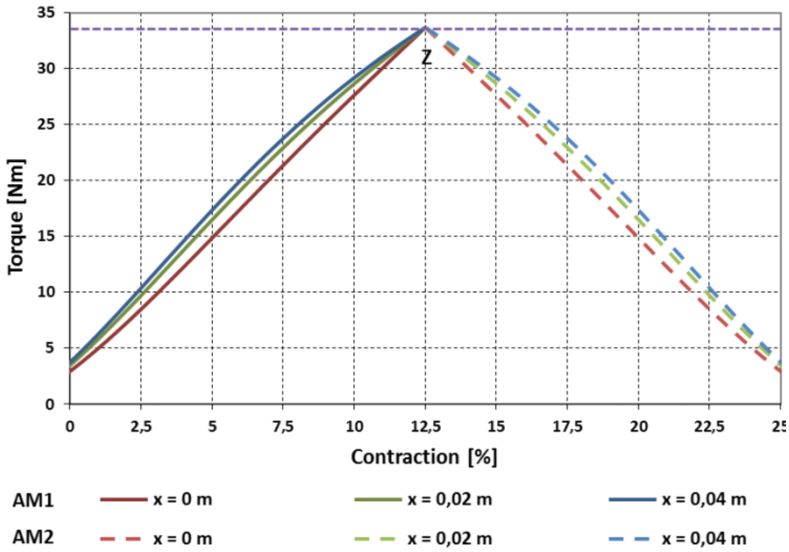

Fig. 5: The dependence of the actuator torque on the muscle contraction for pneumatic muscle actuator with eccentric pulley.

4. Control of the Pneumatic Muscle-Based Actuator

Two twin-spool ON/OFF solenoid valves (SV1, SV2) are needed to operate (inlet part of valve for muscle inflation and outlet part for muscle deflation) of a pneumatic actuator with PAMs in antagonistic configuration (Fig. 6). Control of such actuator is based on simultaneous pressure change only in one PAM. The other PAM has constant maximal pressure and subserves as nonlinear pneumatic spring toward to deflated and controlled PAM. Than this conception was designed for actuator arm position control for using in industrial applications [21,22]:

- The stiffness of the arm position should be maximally achievable and self-aligning – it assumes using of maximal air pressure allowed for used type of PAM.
- The main and sometimes the only one controlled variable will be actuator arm position.
- The manipulated variables will be in the form of discrete impulse signals on the controller output for the input to coils of solenoid valves.
- One of the PAM will be always filled to maximal pressure and will subserve as non-linear pneumatic spring toward to another PAM.
- The resultant stiffness of the actuator won't be constant within the whole actuator operating range. It will be different at different actuator arm positions.

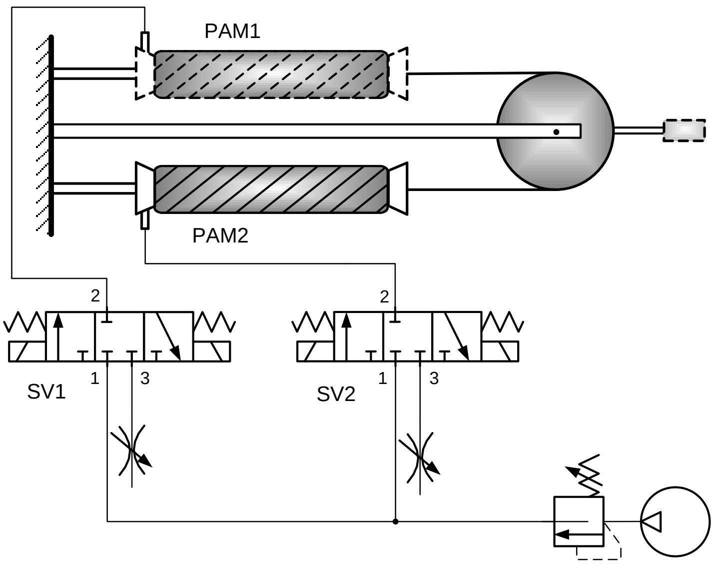

Fig. 6: Pneumatic diagram of the actuator with PAMs in antagonistic configuration.

From point of view of control the pneumatic muscle-based actuator is highly non-linear system with time delay, dead zone and non-linear static characteristic with saturation due to air compressibility, hysteresis and non-linear characteristics of PAMs and solenoid valves [23,24]. That is why difficult to control such actuator using only a linear controller with fixed gains which is inadequate for meeting the possible performance specifications within the whole actuator operating range [25]. Sophisticated control methods based on computational intelligence can solve this problem as for example fuzzy adaptive control with reference model (Fig. 7) [26,27].

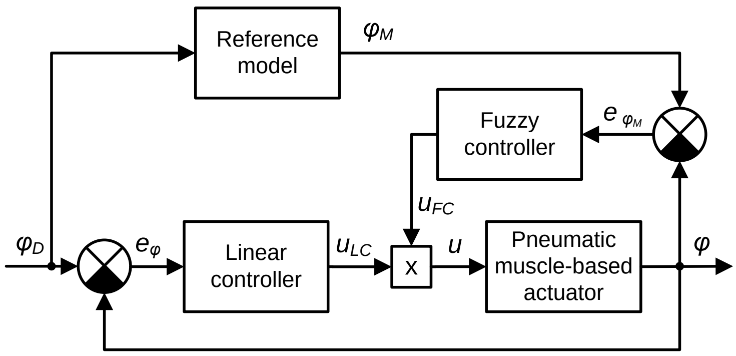

Fig. 7: Fuzzy adaptive control scheme with reference model.

The task of the fuzzy controller in the adaptation branch is to force the system to follow the reference model's trajectory φ_M using the compensation signal u_{FC} which is multiplied with the control signal u_{LC} of the linear controller in the feed-forward branch.

5. Conclusion

The pneumatic muscle-based actuators have an advantageous power-to-weight ratio as higher as 400:1, vastly outperforming both pneumatic cylinders and DC motors that can attain a ratio of only about 16:1. Besides it these actuators are characterized by several other appealing characteristics such as tightness against dirt and dust, cleanness, structural simplicity. Especially their high stiffness and power to weight ratio are interesting for industrial robotic applications. But there are also their deficiencies such as high nonlinear character and torque decrease with increasing rotation of the actuator arm. This problem can be partially solved by application of the eccentric pulley instead of the circular pulley. Thus the higher stiffness of the pneumatic muscle-based actuator can be obtained which is often important in industrial robotic systems.

The simple ON/OFF solenoid valves can be used for control of such actuator with simultaneous pressure change only in one muscle for low cost industrial applications. But advanced control algorithms are needed to achieve acceptable results in position control of this pneumatic muscle-based actuator.

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