Analytical Modeling of Pneumatic Muscle Actuator Torque Characteristics

Mária Tóthová and Ján Piteľ

***Abstract*—**Rotational motion of actuator with pneumatic artificial muscles in antagonistic connection is typically generated using a circular pulley. But torque and stiffness of such actuator decrease with increasing rotation of the actuator arm. This is due to the non-linear decrease of artificial muscles forces according to their contraction. By application of the eccentric pulley a smaller decrease in torque and thus the greater and symmetrical stiffness of the actuator can be obtained.

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

I. Introduction

ACTUATOR consisting of a pair of pneumatic artificial muscles (PAMs) in antagonistic connection is suitable as nonconventional actuator for industrial robotic applications [1] and also biomedical engineering applications [2]–[4]. It can be controlled by air pressure change only in one artificial muscle (active muscle) in a particular half of the arm trajectory through the corresponding solenoid valve (filling or discharge valve). The second antagonistic muscle 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 the muscle functions are mutually exchanged [5]–[8]. The presented solution simplifies the control of such system. But muscle contraction and size of muscle tensile force is changed non-linearly according to air pressure change in the muscle [9]–[12]. Each displacement of the shaft (due to a drop in the air volume of the related artificial muscle) is defined by equal torques between the PAMs. Then such actuator constitutes a non-linear system which dependence of arm position is non-linear centrally symmetric function of filling pressure in the muscles [13]–[15]. Due to the constant radius of pulley the torque characteristics of such pneumatic muscle actuator (PMA) are also non-linear depending on the angle of the shaft rotation [16], [17]. Elimination or at least reduction of this phenomenon is possible 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. As a result, a smaller decrease of torque on the actuator shaft can be achieved when compared to the initial one and it has also higher stiffness of an actuator.

This work was supported by the Project of the Structural Funds of the EU, Operational Programme Research and Development, Measure 2.2 Transfer of knowledge and technology from research and development into practice.

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II. Characteristics of PAMs

The most common used type of PAM is the McKibben artificial muscle based on a flexible cylindrical isotropic rubber tube. When muscle is inflated, the tube extends causing a simultaneous extension and axial contraction of the length of netted nylon fibers on its surface. Thus the contraction of the whole muscle occurs and a tensile force of muscle thereby arises [7]. But muscle force depends on the muscle contraction in the range of extremely high value at zero contraction to zero value at the maximum contraction [18]. Characteristics showing the dependence between the muscle force F of PAM type FESTO MAS-20-250N and the muscle contraction κ under a constant muscle pressure P are shown in Fig. 1. These characteristics are specified by the manufacturer of PAM for seven values of the muscle pressure [19].

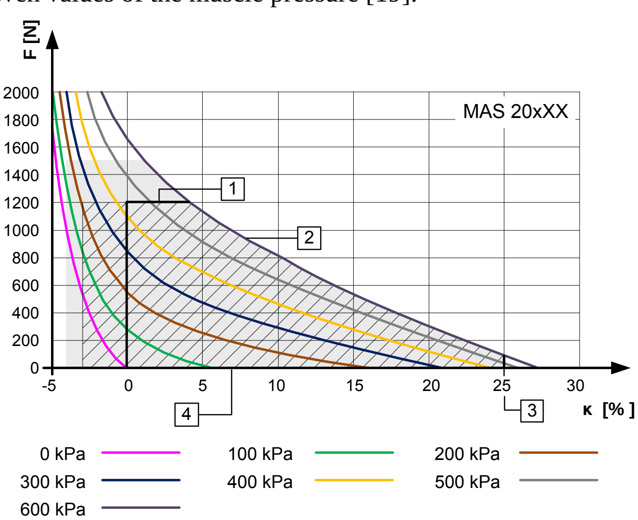

Fig. 1 Tensile force of the muscle FESTO MAS 20-200 depending on the muscle contraction [19]

Characteristics in Fig. 1 can be expressed as a function representing dependence between muscle tensile force, muscle contraction and pressure in the muscle. Numbers 1-4 indicate the borders applicability of PAMs which limit their work area with the given operating pressures. The maximal operating muscle force is 1200 N and maximal contraction is 25 % for this type of PAM.

III. Torque Characteristic of PMA

An antagonistic pneumatic muscle actuator consists of two PAMs connected through holders to a base plate. 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 PAMs. 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 (Fig. 2).

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 PAMs are the same, then $M = F \cdot r_{cp}$.

Torque characteristic of the actuator with PAM in antagonistic connection is shown in Fig. 3. Both PAMs 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 and its stiffness have maximum values. If pressure in the second muscle decreases contraction of the first muscle increases and torque of the actuator shaft decreases. Similarly, actuator torque decreases in the opposite direction of movement by deflation of the first muscle.

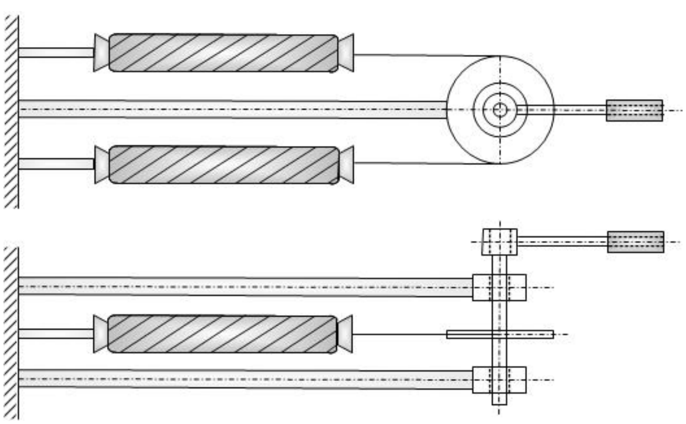

Fig. 2 PMA with circular pulley

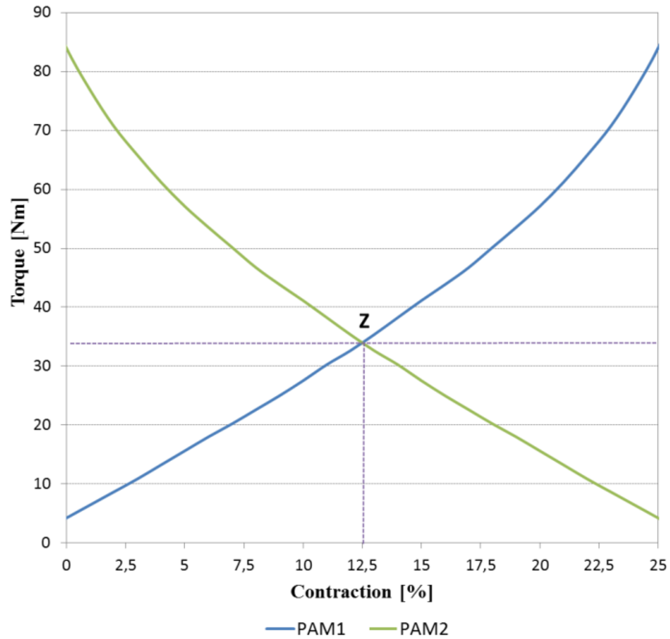

Fig. 3 Torque characteristic of the PMA with circular pulley

Due to the fact that torques from both PAMs decrease with increasing muscle contraction the actuator stiffness in both directions also decreases. PMA with such torque characteristic has therefore insufficient and asymmetric stiffness for larger angle rotations.

IV. PMA with Eccentric Pulley

Torque decrease of the pneumatic actuator with two PAMs 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. 4). Such actuator has a similar design as PMA with circular pulley in Fig. 2; the difference is only in using an eccentric pulley instead of classical circular pulley. The principle of the movement of PMA with eccentric pulley is shown in Fig. 5 [20].

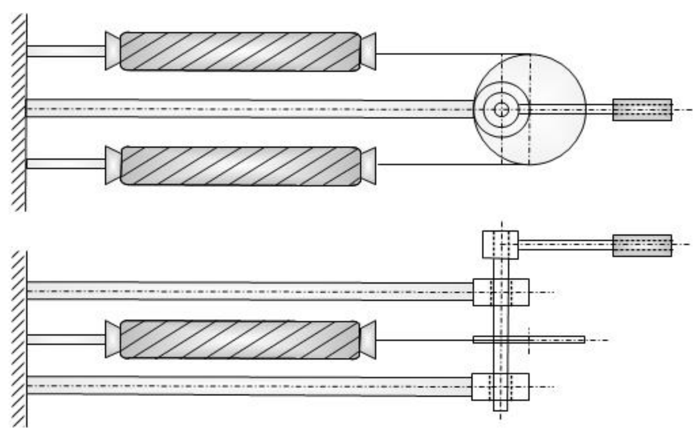

Fig. 4 PMA with eccentric pulley

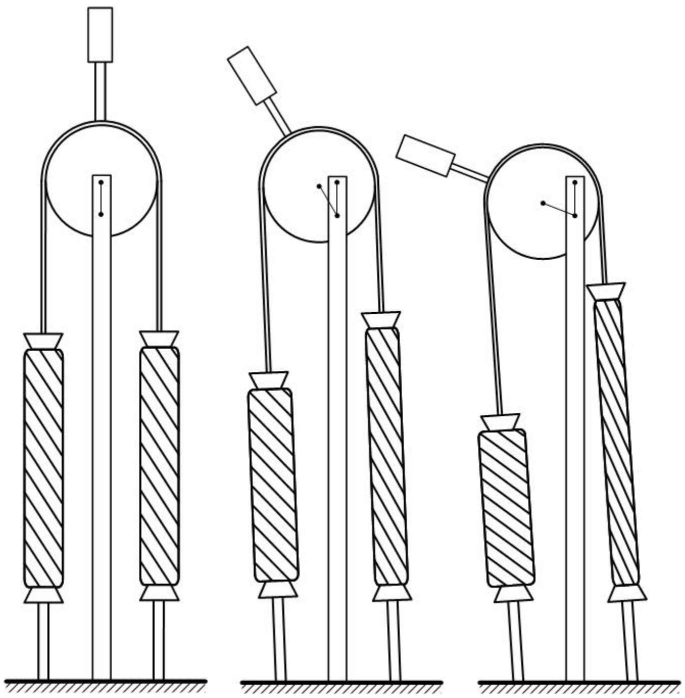

Fig. 5 The principle of movement of the PMA with eccentric pulley

V. Torque Characteristics of PMA with Eccentric Pulley

For torque M of PMA with axisymmetric eccentric pulley is valid:

$$M = F \cdot r = F \cdot d \cdot \cos\alpha, \tag{1}$$

where F is muscle tensile force, r is perpendicular distance of muscle force vector from the axis of the eccentric pulley, d 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 α is angle between vectors r and d. 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. 6).

The others important parameters in Fig. 6 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:

$$d = \sqrt{x^2 + r_{ep}^2 + 2x \cdot r_{ep} \cdot \sin\varphi}\,, \tag{2}$$

$$\beta_1 = \arcsin\frac{x \cdot \cos\varphi}{\sqrt{x^2 + r_{ep}^2 + 2x \cdot r_{ep} \cdot \sin\varphi}}\,, \tag{3}$$

$$\beta_2 = \frac{\pi}{2} - \arcsin\frac{h_A + x \cdot \cos\varphi}{\sqrt{h_A^2 + x^2 + 2h_A \cdot x \cdot \cos\varphi}}\,. \tag{4}$$

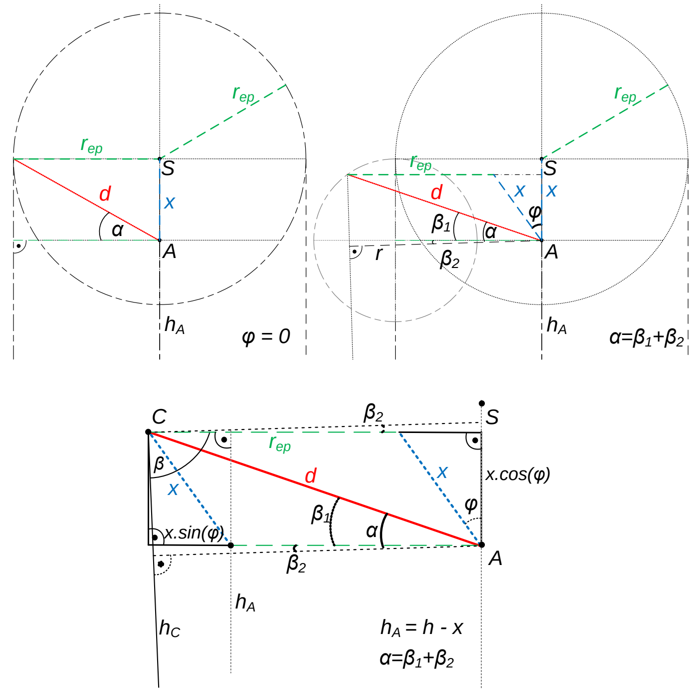

Fig. 6 Correlation between parameters of the eccentric pulley

Then for torque M using (2) can be written:

$$M = F \cdot \sqrt{x^2 + r_{ep}^2 + 2x \cdot r_{ep} \cdot \sin\varphi} \cdot \cos(\alpha), \tag{5}$$

where

$$\alpha = \beta_1 + \beta_2, \tag{6}$$

$$\alpha = \arcsin\frac{x \cdot \cos\varphi}{\sqrt{x^2 + r_{ep}^2 + 2x \cdot r_{ep} \cdot \sin\varphi}} + \frac{\pi}{2} - \arcsin\frac{h_A + x \cdot \cos\varphi}{\sqrt{h_A^2 + x^2 + 2h_A \cdot x \cdot \cos\varphi}}\,. \tag{7}$$

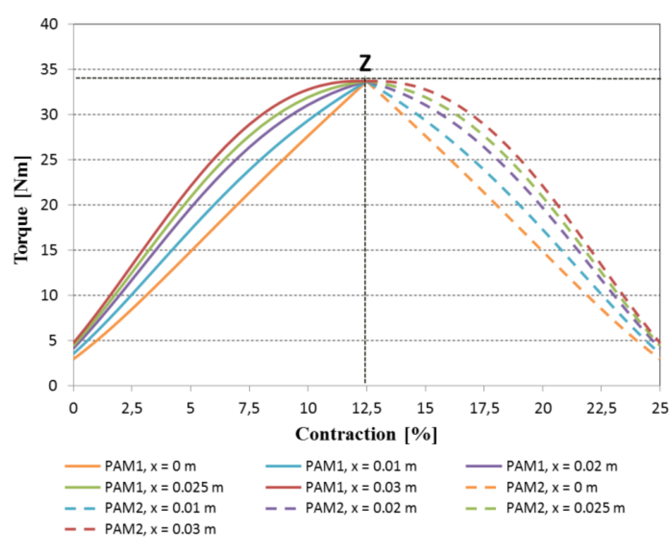

Fig. 7 Torque characteristics of the PMA with eccentric pulley

It follows from relations (5) and (7) that the torque of the PMA with eccentric pulley 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 PAMs 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. 7. These characteristics are mutually oppositely oriented for both muscles and at point Z both PAMs have the same maximum pressure.

VI. Conclusion

The torque characteristics in Fig. 2 and also in Fig. 6 show that the torque of the PMA with a circular pulley which the axis of rotation in the geometric middle of the pulley (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 artificial muscle, but also by the value of the distance x (Fig. 6). It is therefore possible to conclude that by using of the eccentric pulley it is possible to achieve even higher stiffness of the pneumatic actuator with artificial muscles in antagonistic connection. 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.

Acknowledgment

The research work is supported by the Project of the Structural Funds of the EU, title of the project: Research and development of intelligent nonconventional actuators based on artificial muscles, ITMS code: 26220220103.

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