

TORQUE CHARACTERISTICS OF ROTARY PNEUMATIC MUSCLE ACTUATOR

MILAN BALARA, MARIA TOTHOVA

Technical University of Kosice, Faculty of Manufacturing Technologies with a seat in Presov, Slovak Republic

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e-mail: maria.tothova@tuke.sk

The control of the standard pneumatic muscle actuators is provided by increasing the air pressure in the one artificial muscle, while reducing the pressure in the second (antagonist) artificial muscle. The paper contains information about the control and basic properties of the rotary actuator based on pneumatic artificial muscles. It presents equations for the values of the actuator arm displacement depending on an input pressure; it shows the static characteristics of the actuator and the utilization of the muscle contraction. Pneumatic artificial muscles are connected in an antagonistic system through an oval centrally symmetric pulley. Due to the fact that with increasing rotating of actuator arm the torque decrease from the both artificial muscles; the stiffness of the actuator also decreasing in both directions. The proposed method of the present control in this paper has resulted in a small increase of torque of the rotary muscle actuator and thus adequate and symmetric stiffness of actuator.

KEYWORDS

pneumatic muscle actuator, artificial muscle, antagonistic connection, stiffness, torque characteristic

1 INTRODUCTION

Pneumatic position servo systems of the different equipment for automation and robotics are sometimes designed based on the use of pneumatic artificial muscles that constitutes their terminal part - an actuator. The rotary pneumatic muscle actuator is an equipment commonly used for lightweight, powerful and movable actuators [Tsagarakis 1999], [Zidek 2012]. The usual equipment for generating a rotary motion using pneumatic artificial muscles (Fig. 1) are designed as a mechanical systems with two pneumatic artificial muscles in antagonistic connection that are connected with their opposite ends by a flexible belt. This belt is mounted over the circuit of a circular pulley, which is inserted on the actuator shaft. It is embedded in bearings, whose are located at the ends of supporting pillars of the actuator. Such actuator constitutes the unit, in which the pillars are fixed on the supporting board and bearings, shaft and actuator arm with the external load are at the ends of the pillars [Zhang 2008], [Vagaska 2014], [Hosovsky 2012a].

Pneumatic artificial muscles are located along the pillars and their tensile forces (F_1 , F_2) act against each other. The resulting position of actuator arm is determined by the balance of tensile forces with various air pressures (p_1 , p_2) in individual muscles. The stiffness of such actuator corresponds to the forces generated in the individual muscles. In order to control each of the two pneumatic artificial muscles it is necessary to use two solenoid valves (SV1, SV2). Each pneumatic artificial muscle requires one valve for input and one valve for output, either a proportional or a two-position type, eventually a combination of these elements [Pitel 2011], [Hosovsky 2012b].

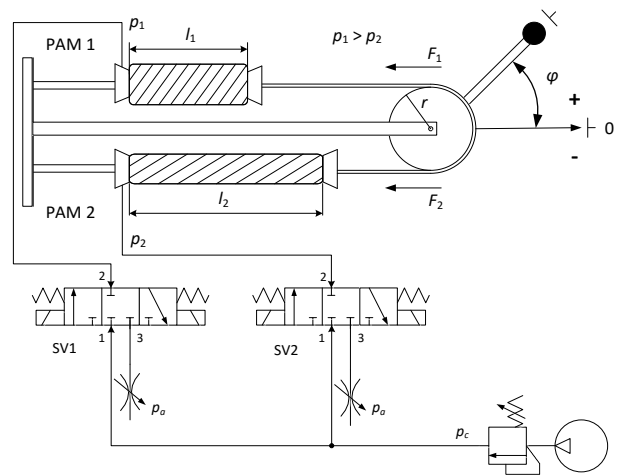


Figure 1. Diagram of the rotary pneumatic muscle actuator in antagonistic connection

The actuator represents a relatively long and slender equipment with satisfactory weight and dimensional characteristics. In case of application of two pneumatic artificial muscles, a non-linear proportion between the changing air pressure entering the artificial muscles and their contraction is significantly reflected [Macurová 2013], [Hosovsky 2014], [Pitel 2015a]. This is also expressed in the displacement angle φ of the actuator arm. This phenomenon is caused by the properties of the applied pneumatic artificial muscles mainly because the designers of the actuators try to fully use the range of the muscles contraction. This is also why the non-linear properties of pneumatic artificial muscles are fully and significantly occurring [Daerden 2001], [Borzikova 2008]. Such actuator has insufficient and asymmetric stiffness with the larger rotation of angles [Sarosi 2015]. A more precise position of control of such system is complicated and its possibilities of using are limited.

The control of currently used rotary pneumatic muscle actuators is provided by increasing the air pressure in one pneumatic artificial muscle and simultaneously decreasing the air pressure in the other (antagonistic) pneumatic artificial muscle. In such a case, the both pneumatic artificial muscle are active and they require a simultaneous control of the filling (or discharge) air pressure to the individual muscles [Caldwell 2002]. Such control method is difficult as in every moment in time it is necessary to comply with the condition of equality between the increase of pressure in one pneumatic artificial muscle and the pressure decrease in another one. Otherwise, non-uniformity of rotation of the actuator arm and variations of the stiffness values can occur [Havran 2012].

2 ISOBARIC CHARACTERISTICS OF THE PNEUMATIC ARTIFICIAL MUSCLE

Basic characteristics and principles of pneumatic artificial muscles can be easily explained using Fig. 2, during the experiment with a load suspended at one end of the artificial muscle, while the other muscle end is firmly anchored. If an artificial muscle is loaded with a constant weight m_z , length l of the muscle has maximal value and muscle contraction has zero value in the initial position at the zero pressure p in the muscle (Fig. 2). By gradually increasing the pressure in the muscle, the muscle will become shorter (contraction increases) generating a tensile force. This force causes lifting of load until the balance between muscle tension force and gravitational force of the weights occurs [Pitel 2008].

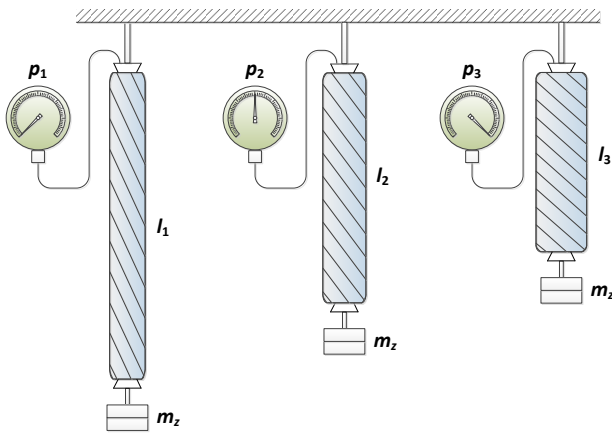


Figure 2. Pneumatic artificial muscle with constant load

Isobaric characteristics (Fig. 3) show the dependence of the force F of the pneumatic artificial muscle on the contraction κ , under the constant pressure p in the muscle [Chou 2002], [Vagaska 2014]. In case of the applied pneumatic artificial muscles type Festo MAS 20x250, the characteristics for 7 discrete values of the pressure are shown and they are specified by the manufacturer of pneumatic artificial muscles [Festo 2016]. These characteristics can be expressed by the function showing the dependence of the muscle force on the contraction and pressure or they can be expressed by using the measured of muscle characteristics.

The borders applicability of the pneumatic artificial muscle (number from 1 to 4) in Fig. 3 are indicated, which limit their work area with the given operating pressures. This muscle type Festo MAS 20xXX have the maximum contraction $\kappa_{max} = 25\%$ and the maximum force $F_{max} = 1200$ N.

The mathematical interpretation of isobaric static characteristics is of the general validity. This allows their integration into the overall mathematical model of the pneumatic artificial muscle.

These isobaric static characteristics (Fig. 3) of muscle were approximated by many authors [Kerscher 2006], [Sarosi 2010], [Joupilla 2014]. Four different approximations are described in [Pitel 2015b]:

- approximation using an analytical modelling of pneumatic artificial muscle,
- approximation deducted from the maximum force of pneumatic artificial muscle,
- approximation using an exponential function,
- approximation using a polynomial function.

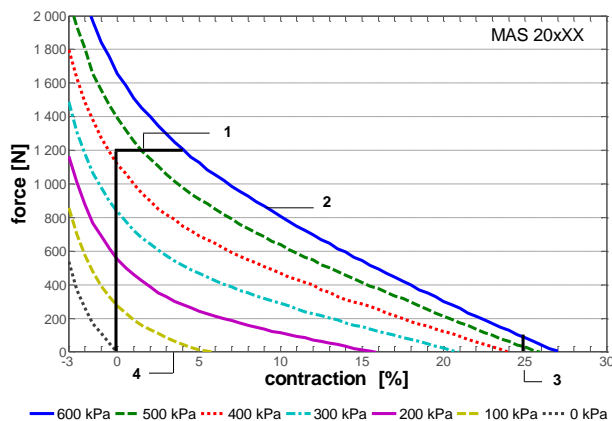


Figure 3. Isobaric characteristics of the pneumatic artificial muscle type Festo MAS 20xXX [Festo 2016]

According to [Sarosi 2010], a non-linear dependence of the muscle force F on its muscle contraction κ under the constant pressure p in the muscle can be approximated using an exponential function as follows:

$$F = f(p, \kappa, A) = (a_1 \cdot p + a_2) \cdot e^{a_3 \cdot \kappa} + a_4 \cdot \kappa \cdot p + a_5 \cdot p + a_6, \quad (1)$$

where p is pressure in the muscle, κ is muscle contraction, A is matrix of equation coefficients and the coefficients $a_i, i = 1..6$, are unknown coefficients which values were determined using Matlab Curve Fitting Toolbox. The obtained values of these coefficients are presented in Tab. 1. Tab. 2 shows the fit results [Tothova 2015] and approximated surface in Matlab is shown in Fig. 4 [Pitel 2015b].

Table 1. The values of coefficients (1) for the approximation using an exponential function

Coefficients	Values
a_1	0.11210
a_2	263.70000
a_3	-0.35150
a_4	-0.08619
a_5	2.62400
a_6	-245.60000

Table 2. Fit results for the approximation using an exponential function [Tothova 2015]

SSE	1.842E+07
R-square	0.9996
adj. R-square	0.9996
RMSE	209.2000

For muscle description the muscle length l is often used instead of muscle contraction κ and then it can be expressed as:

$$l = l_0(1 - \kappa), \quad (2)$$

where l_0 is the initial length of the muscle.

Then the function $f(p, l, A)$ can be expressed as:

$$F = f(p, l, A) = (a_1 \cdot p + a_2) \cdot e^{\frac{a_3 \cdot (l_0 - l)}{l_0}} + \frac{a_4 \cdot p}{l_0} \cdot (l_0 - l) + a_5 \cdot p + a_6. \quad (3)$$

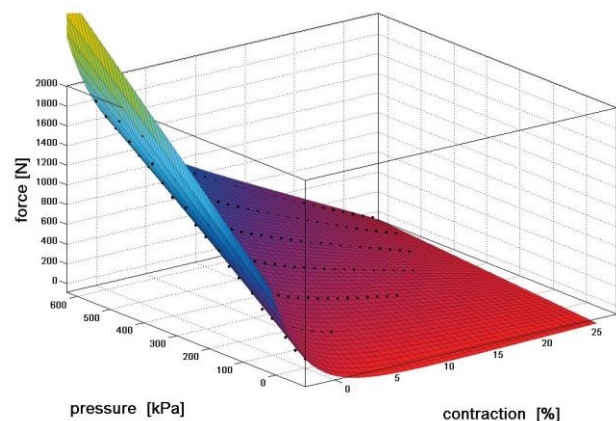


Figure 4. Force-contraction-pressure relations approximated using an exponential function

3 ISOBARIC CHARACTERISTICS OF THE ROTARY PNEUMATIC MUSCLE ACTUATOR

The another control method of the rotary pneumatic muscle actuator is based on the identical mechanical configuration such as present antagonistic actuators (Fig. 1), but the acting of muscles are different. One of the pneumatic artificial muscle (passive) in a particular half of the trajectory of the actuator arm acts as a passive non-linear pneumatic spring and it does not require any control intervention. The movement of the second antagonistic pneumatic artificial muscle (active) is controlled and its position is adjusted by the regulation of the air pressure through the corresponding valve (inlet or outlet solenoid valve). In the second half of the actuator arm trajectory, the actuator control is the same, the pneumatic artificial muscles are mutually exchanged. The presented solution simplifies the control of such system. When controlling the arm movement and position, there is only one of the solenoid valves active.

The actuator arm initial position is set up after both pneumatic artificial muscles are filled to a certain (maximum) pressure p_{max} . The both pneumatic artificial muscles due to the equal muscle contraction indicate the position of the actuator arm in the reference (initial) position (parallel to the longitudinal axis of the actuator). Due to the discharge of one of the pneumatic artificial muscles, the pressure in the muscle decreases and this muscle extends. At the same time, contraction of the second pneumatic artificial muscle (which is under maximum initial pressure) occur. This action causes displacement of the flexible belt and also rotating pulleys on the shaft. Due to the air filling into one of the pneumatic artificial muscles, the pressure in the muscle increases and this muscle shortens. Actuator arm returns to its initial position after a sufficient opening the corresponding outlet solenoid valve.

Fig. 5 shows the isobaric characteristics of the rotary actuator with pneumatic artificial muscles (PAM 1 and PAM 2) type Festo MAS 20x250 in the antagonistic connection [Mizakova 2012]. Static characteristics of these muscles are mutually oppositely oriented. The pneumatic artificial muscle 1 (PAM 1) has a constant pressure (600 kPa) but its contraction is changed according to the changing of the force of the second pneumatic artificial muscle 2 (PAM 2). PAM 1 acts as a pneumatic spring with a nonlinear characteristic (passive muscle), and therefore Fig. 5 shows only one characteristic of this muscle at corresponding initial pressure p_{max} . This characteristics show the opposing force which act in both artificial muscles [Hosovsky 2008].

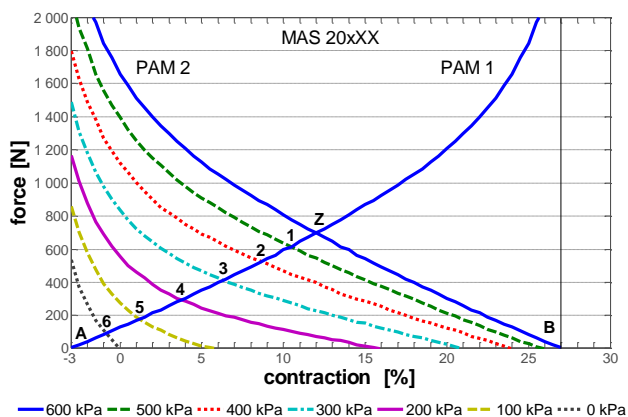


Figure 5. Isobaric characteristics of the rotary actuator with pneumatic artificial muscles type Festo MAS 20XX in antagonistic connection

The intersection points of characteristics in section A-Z corresponding process of increase the muscle contraction in PAM 1 in progressively decrease of pressure in active muscle PAM 2. In this way any negative value of muscle contraction κ can be achieved. The point B on the characteristic PAM 2 in Fig. 5 is a point of maximum muscle contraction in which a tension force is already zero. For PAM 1 it is point A. The pressure in PAM 2 is gradually reduced (from the point Z to the point A). The contraction κ has the axis oriented towards as PAM 2. At the point 5, the value of the contraction of PAM 2 will be cca. zero; the the rotation of the actuator arm will be within one of the accepted limit values (φ_{max}). Applying the same process, the actuator arm achieves the opposite the deflection ($-\varphi_{max}$).

A stable position of the actuator arm corresponds with the equal forces of both artificial muscles and for each pressure in the active muscle is different.

Provided that the used pneumatic artificial muscles are identical (identical matrix A):

$$F_{PAM1} = F_{PAM2} = f_1(p_1, l_1, A) = f_2(p_2, l_2, A) = f_{\kappa_1}(p_1, \kappa_1, A) = f_{\kappa_2}(p_2, \kappa_2, A) \quad (4)$$

For the pressure p in the muscle apply, that $p_1 = \text{const.}$ and $p_2 = f(t)$ and vice versa. The variables l_1, l_2 are the actual lengths of the muscles and κ_1, κ_2 are the actual muscle contractions. The total operating pressure p of the medium (a pressure difference) can by expressed as:

$$p = p_1 - p_2 \quad (5)$$

For the muscle contraction κ and its length l , these dependences apply:

$$\kappa = l_{max} - l \quad (6)$$

$$\kappa_{max} = l_{max} - l_{min} \quad (7)$$

where κ_{max} is the maximum muscle contraction, l_{max} is the maximum length of the muscle, l_{min} is the minimum length of the muscle and l is the actual length of the muscle.

4 TORQUE CHARACTERISTICS OF THE ROTARY PNEUMATIC MUSCLE ACTUATOR AT THE MAXIMUM INITIAL PRESSURE

A significant non-linear dependence is in the rotary pneumatic muscle actuator between change of the air pressure entering to the pneumatic artificial muscles and the angle of rotating arm fixed to the shaft of the actuator. This is mainly due to the non-linear decrease of the muscle force according to their muscle contraction. The character of this non-linearity causes decrease of the actuator torque with the increasing value of the actuator arm position (rotation angle φ). The torque M of the actuator shaft is determined by the force F of the muscle in the given actuator arm position φ (eventually κ or l) and the pulley radius r and it is valid [Balara 2013]:

$$M = F_1 \cdot r = F_2 \cdot r = f_1(p_1, l_1, r, A) = f_2(p_2, l_2, r, A) = f_{\kappa_1}(p_1, \kappa_1, r, A) = f_{\kappa_2}(p_2, \kappa_2, r, A) \quad (8)$$

Fig. 6 shows the torque characteristics of the rotary pneumatic muscle actuator in the antagonistic connection where the circular pulley has radius $r = 0.05$ m.

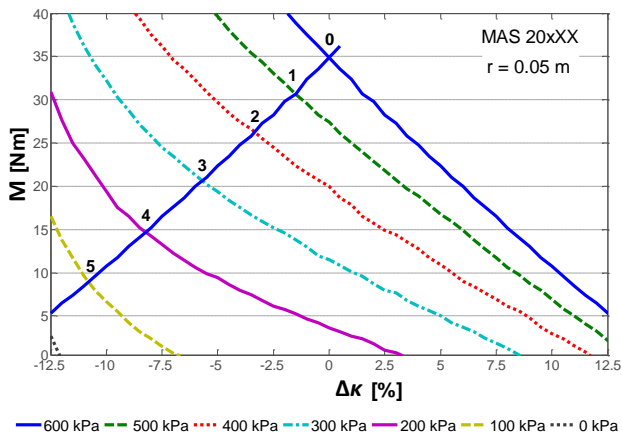


Figure 6. The torque characteristics of the rotary pneumatic muscle actuator in antagonistic connection

For initial change of the muscle contraction $\Delta\kappa$ in Fig. 6 apply:

$$\Delta\kappa = \kappa - \frac{\kappa_{max}}{2} \quad (9)$$

where κ is the actual muscle contraction and κ_{max} is the maximum muscle contraction.

Pneumatic artificial muscles have equal filling pressures (600 kPa) in the muscles at the point 0, initial change of the muscle contraction is 0%, muscle torque and stiffness have maximal value. If pressure in pneumatic artificial muscle 2 (active) decreases, contraction of pneumatic artificial muscle 1 (pasive) is changes (points from 0 to 6, muscle contraction from 0 % to -12.5 %) and the torque on the actuator shaft decreases. The torque also decreases for arm rotation in the opposite direction (point 0 to contraction 12.5 %) when pressure in pneumatic artificial muscle 1 (active) decreases.

Provided that the parameters of both pneumatic artificial muscles are equal apply:

$$M = F \cdot r = f(p, l, r, A) = f_{\kappa}(p, \kappa, r, A) \quad (10)$$

Due to the fact that torques from both pneumatic artificial muscles are decreasing with the changes of the muscle contraction κ (rotation angle φ), the stiffness of the rotary actuator in both directions ($\Delta\kappa = \pm 12.5\%$) is also decreasing. Such rotary pneumatic muscle actuator with larger rotation angle has insufficient and asymmetric stiffness. The control of the position of such a system is complicated and its possibilities of using are limited.

5 TORQUE CHARACTERISTICS OF THE STIFF ROTARY PNEUMATIC MUSCLE ACTUATOR

The torque characteristics (black) of the stiff rotary pneumatic muscle actuator in the antagonistic connection are shown in Fig. 7, where circular pulley has radius $r = 0.05$ m.

The another control method of the stiff rotary pneumatic muscle actuator is based on the identical control such as present control of rotary actuator, but the initial conditions are different. Pneumatic artificial muscles have equal filling pressures in the muscles at the initial point SU (Set Up) and the initial change of the muscle contraction is 0%. The values of these pressures in the muscles are the same, and given the scale of the used pressures are relatively low (e.g. 200 kPa, while $p_{max} = 600$ kPa).

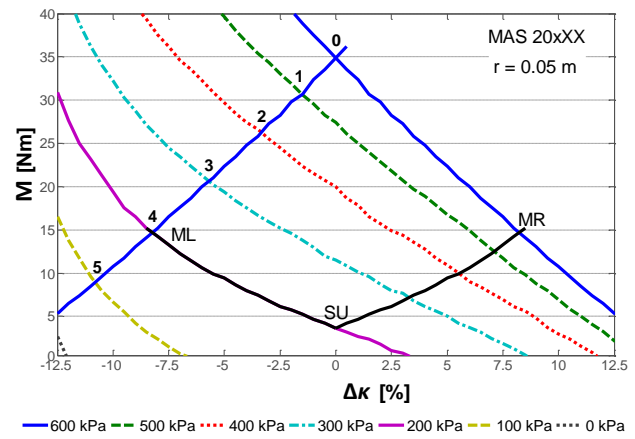


Figure 7. The torque characteristic (black) of the stiff rotary pneumatic muscle actuator in antagonistic connection

By increasing the air pressure in the active pneumatic artificial muscle (point SU to ML or point SU to MR), muscle contraction (rotation angle φ of the actuator shaft) is changed, while the force of this muscle and thus the torque and stiffness of actuator increases. Due to the fact that the torques of the both artificial muscles increase with increasing of the muscle contraction κ (rotation angle φ) of the active pneumatic artificial muscle, the stiffness of actuator in both directions ($\Delta\kappa = \pm 12.5\%$) also increases. This actuator has a sufficient and increasing symmetric stiffness at the higher rotation. Position control of this system is not complicated but its possibilities of using are limited in the range of achieved contraction. The desired range of use by appropriate choice of length of used muscles can be achieved.

6 CONCLUSION

In the paper three methods of control of rotary actuator with pneumatic artificial muscles in antagonistic connection are showed. In the initial position (at a given air pressure in the pneumatic artificial muscle), actuator have a certain stiffness, while the highest stiffness has at a maximum pressure in the both pneumatic artificial muscles. Under unequal pressures in the pneumatic artificial muscles, actuator arm stabilizes at a position corresponding equal tensile forces of both muscles. Angle rotation of the actuator arm (on which the external load of a certain weight) depends on radius of the pulley and the size of changes the lengths of pneumatic artificial muscles (dilatation, contraction) and pressures (muscle volume) in the different muscles. For arm rotation apply, that the length of each muscles was changed by the same value, while the shortening (contraction) of one muscle has increased and of second muscle decreased. Stiffness of such a mechanism can be varied according to the specified requirements. The arm position is proportional to the pressure difference in the muscles, while the stiffness is proportional to the sum of the pressures in the muscles. The same pressure difference can be achieved for different values of their sum, which means that it is possible to achieve the same rotation of the arms with the different stiffness.

The control method of rotary pneumatic muscle actuator (according to the proposed solution) may be used for short and longer application of the functional units in which are used pneumatic or the other artificial muscle in an individual, antagonistic or the other connection. The proposed method of control can be used in the area of automation, robotics and mechatronics, where are usually used lightweight and powerful actuators.

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CONTACTS:

doc. Ing. Milan Balara, PhD.

Ing. Maria Tothova, PhD.

Technical University of Kosice, Faculty of Manufacturing Technologies, Department of Mathematics, Informatics and Cybernetics

Bayerova 1, 080 01 Presov, Slovak Republic

Tel.: +421 055 602 6420

e-mail: milan.balara@tuke.sk, maria.tothova@tuke.sk,

<http://www.fvt.tuke.sk>