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The properties of the Actuators with Pneumatic Artificial Muscles

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Abstract

The article concerns the actuator with one pneumatic artificial muscle and spring which is acting again the direction of pull force of the pneumatic artificial muscle. This solution needs only one inlet and one outlet of the electromechanical pneumatic valve. The article concerns also the actuator with two McKibben´s type pneumatic artifical muscles in the antagonistic configuration. They are acting again the force of the other artificial muscle. The actuator is realized by using of two artifical muscles of Shadow Air Muscle type. This solution needs two inlets and two outlets of the electromechanical proportional or on – off pneumatic valves. At last cause it is suitable for the solving of low cost bioservosystems. The paper contents the mathematic descriptions, static characteristics of the parts of actuator and characteristics of the all mechanism.

Key words: *Pneumatic artificial muscle, pneumatic actuator, antagonistic system, McKibben´s artificial muscle, Shadow Air Muscle*

1 Introduction

Pneumatic position servosystems of various devices are sometimes solved with the use of pneumatic artificial muscles. If requirements of precision, stiffness and dynamic of the system are lower, it is possible to use antagonistic servosystem with one pneumatic artificial muscle and spring, which acts against the tensile force of artificial muscle. Such solution requires only one inlet and one outlet valve, what significantly contributes to decreasing the costs of such device.

Configuration with two artificial muscles is antagonistic system. Pneumatic artificial muscles (PM) act each against other by their forces and resulting position is determined by balance of tensile forces in various air pressures in individual muscles. Tensile forces of PM are transmitted through tackle fall of roller. It is necessary to use two electropneumatic valves for controlling each one of two pneumatic artificial muscles. Each artificial muscle requires one inlet and one outlet valve, either proportional or on-off, eventually combination of them.

2 Static load characteristics of pneumatic artificial muscle

2. 1 Characteristic of PM in constant pressure

Length (contraction) of pneumatic artificial muscle in constant air pressure depends on force, which acts to muscle and which is equal to its tensile force. Length is increased and the value of contraction decreased with increasing force. Consequently the contraction of artificial muscle decreases with increasing force of active load. It is property corresponding to the properties of human muscle. Tensile force of artificial muscle in constant pressure is a function of artificial muscle length (contraction). This characteristic is nonlinear. It is shown in Figure 1.

Operating point O marked on static characteristic of PM AM2 is shown in Figure 1, in which the length of PM is $l_0 = l_{min} + \Delta\, l_{max}/2$, where $\Delta\, l_{max}/2 = l_{dmax}$, in constant air pressure p_m.

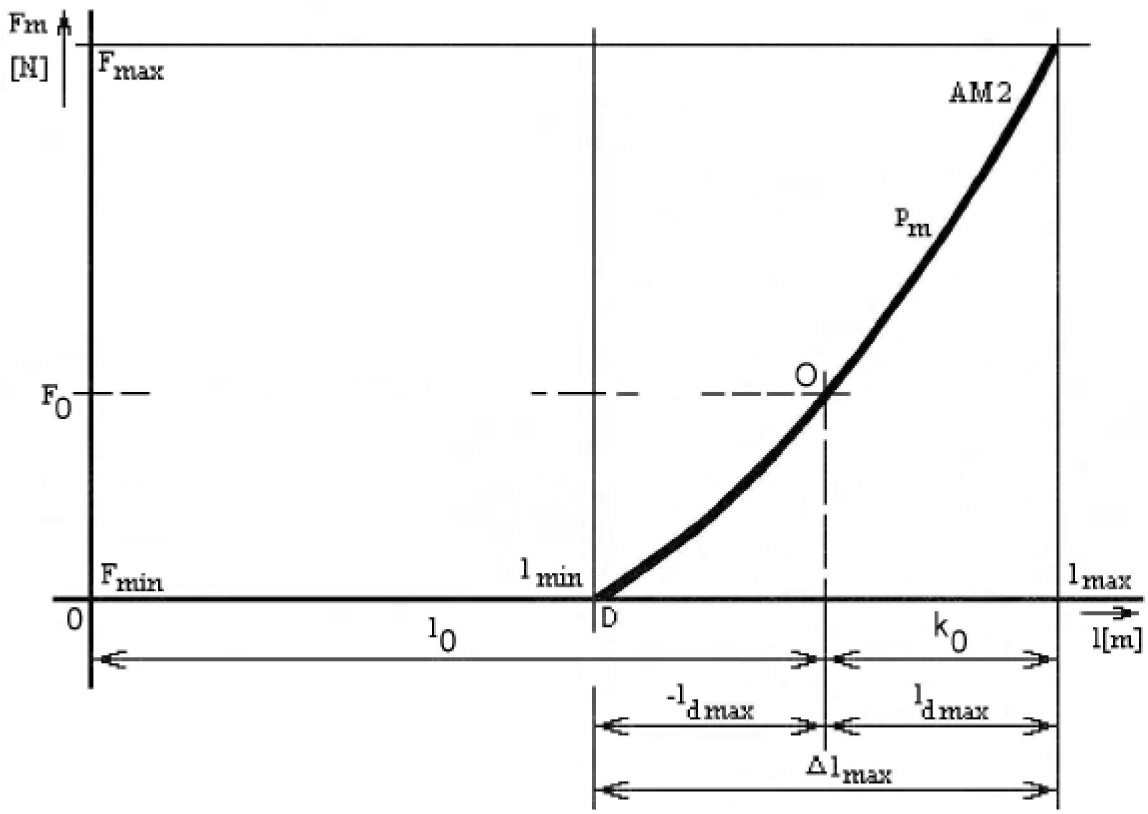

Figure 1 Static characteristic of pneumatic artificial muscle in constant filling pressure

PM acts by force F_0 with contraction k_0 in this operating point. Value l_d is displacement against position l_0 of PM. Tensile force F_m of pneumatic artificial muscle in constant pressure p of filling medium has nonlinear characteristic:

$$F_m = g_N(l) \tag{2.1}$$

$$F_m = g_{NK}(k) \tag{2.2}$$

where g_N is nonlinear function of PM force in dependency on its length in constant filling air pressure and g_{NK} is nonlinear function of PM force in dependency on its contraction in constant filling air pressure.

2. 2 Characteristics of PM in nonconstant pressure

Length (contraction) of pneumatic artificial muscle in nonconstant air pressure depends on force, which acts to muscle and moreover on the value of air pressure. Tensile force of artificial muscle is in nonconstant pressure a function of artificial muscle length (contraction) and moreover of air pressure. This characteristics is similarly to previous case nonlinear, various values of air pressure are reason for description of properties of pneumatic artificial muscle by meshed characteristics.

Figure 2 depicts nonlinear characteristics of PM AM2, where length of muscle l (contraction of PM k) is dependent on filling air pressure p. Characteristics of PM create the mesh of characteristics dependent on load force F, and on length of PM l, in various values of pressure p in range from 0 to maximal pressure $p_{max}=p_m$. This figure shows characteristics for individual pressures, where: $p_m > p_4 > \ldots\ldots\ldots > p_2 > p_1$. Figure shows positions of points O and 1, to which correspond relevant lengths of PM and forces accordingly to characteristics, in various pressures.

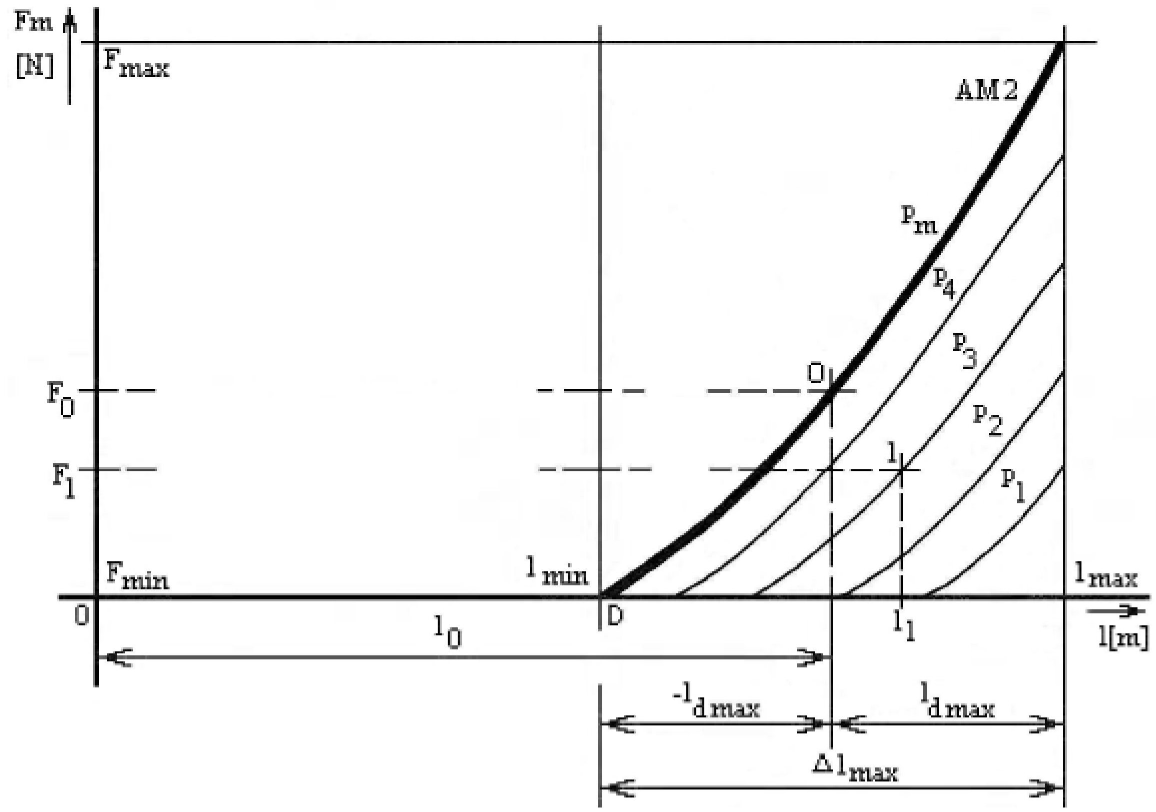

Figure 2 Characteristics of pneumatic artificial muscle in variable filling pressure

Relation between the length of pneumatic muscle l and its contraction are dependencies 3.9 and 3.10, where l varies in range (l_{min}, l_{max}). Tensile force F_m of pneumatic artificial muscle in nonconstant (variable) pressure p of filling medium has nonlinear characteristics:

$$F_m = g_M(l,p) \tag{2.3}$$

$$F_m = g_{MK}(k,p) \tag{2.4}$$

where g_M is nonlinear function of two variables, length of PM l and air pressure in PM p and g_{MK} is nonlinear function of contraction of PM k and air pressure in PM p. Figure 2 shows point of characteristics O in state, when PM with tensile force F_0 and filling pressure p_m has length l_0. Analogical is point 1, when PM AM2 has lower air filling pressure p_3. Point D is point of PM maximal contraction (l_{min}, k_{max}), its tensile force is minimal (zero).

3 Pneumatic actuator with artificial muscle and return spring

Servomotor with corresponding load is a regulated system in proportional position servosystems. In case of pneumatic bioservosystems with artificial muscles, it is own artificial muscle (PM) with corresponding mass load m. Actuating variable that inputs into PM is compressed air, which comes from proportional electropneumatic valve, which is actuating unit. In case of use only one PM, the function of second PM is performed by return spring. This configuration is shown in Figure 3.

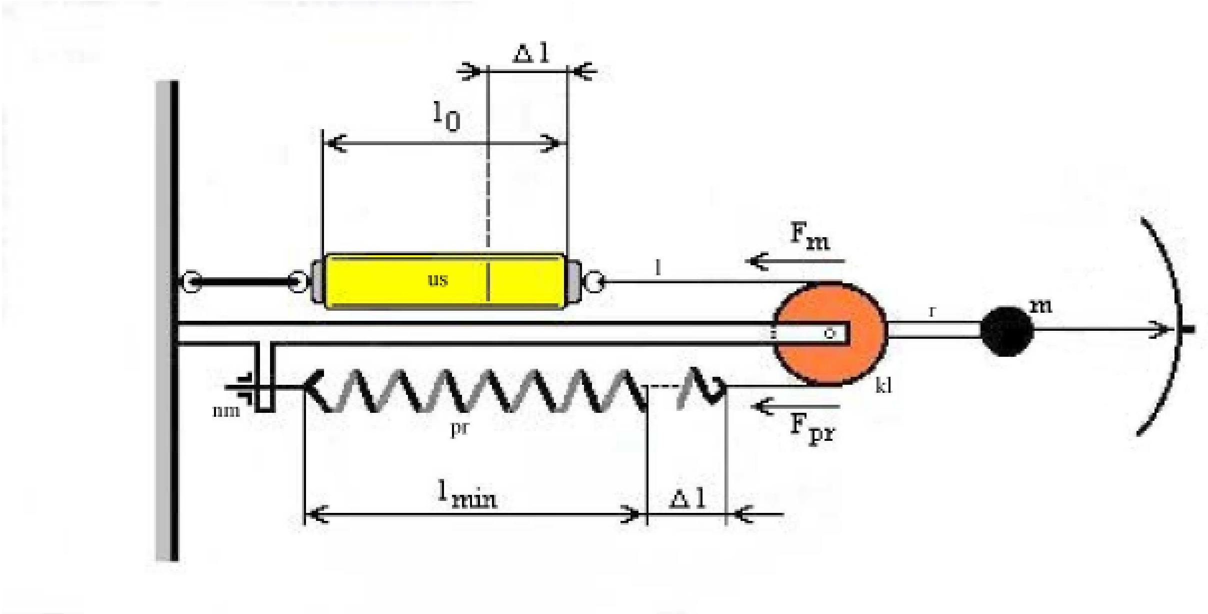

Figure 3 Spring actuator with pneumatic artificial muscle

Figure shows pneumatic artificial muscle PM of maximal length $l = l_0$, which is shortened about length $\Delta\ l$ after its filling by compressed air. Tensile force of artificial muscle F_m is transmitted by tackle fall *ln* through roller *kl* to spring *pr*. Spring, which has length l_{min} in prestrained state is extended about $\Delta\ l$ during muscle contraction *k* and acts against the artificial muscle by force F_{pr}. This force is dependent from value of contraction and its initial value F_1 is set by tension gear *nm*. The change of air pressure in muscle causes also the change of its contraction what results in performing rotary motion of load mass *m* on arm *r* mounted to axis of roller. Gravity force of mass load *m* is perpendicular to plane of Figure 2 and thus does not have the influence to force situation between spring and muscle. Object of next research are not dynamic states of actuator, only steady static states will be described. Therefore, forces dependent from derivations of length *l* or angular position β are not considered. Friction moments of roller *kl* bearings are also not considered. We will consider translational values as final output in following sections due to the fact, that producers of springs and artificial muscles provide all characteristics in form of translational motion. Angular position β of arm *r* depends on radius of roller *kl* in same length changes of muscle and spring. Following characteristics valid between these values also characterizes limits of the value, since contraction of artificial muscle and thus also $\Delta\ l$ has limited value:

$$\beta = \Delta\ l\,/r \tag{3.1}$$
$$\beta_0 = l_0\,/r \tag{3.2}$$
$$\beta_{max} = (l_0 - l_5)\,/r \tag{3.3}$$

where β_0 is initial angular position (revolution) of roller shaft of actuator and β_{max} is its maximal value. Consequence of other values is evident from Figure 3.

3. 1 Return spring and its characteristics

The task of return spring is acting by force F_{pr} against the force of artificial muscle F_m. Muscle contraction increases until F_{pr} is less than artificial muscle F_m. This increase is stopped in position when forces are balanced. Spring force is changed in dependency on their length *l*.

Assuming that this relation of spring is linear, its characteristics will be linear. It is shown in Figure 4. Horizontal axis is length l of spring, vertical axis is spring force F_{pr}. Initial length of unloaded spring is l_b and its length is increasing with increasing tensile force. Its practical exploitation is assumed in length range from l_{min} to l_{max}. It corresponds to the range of tensile force from F_1 to F_2. Thus, it will be used section of characteristics limited by segment BA. Spring is set to initial point B by extending to length l_{min} [3].

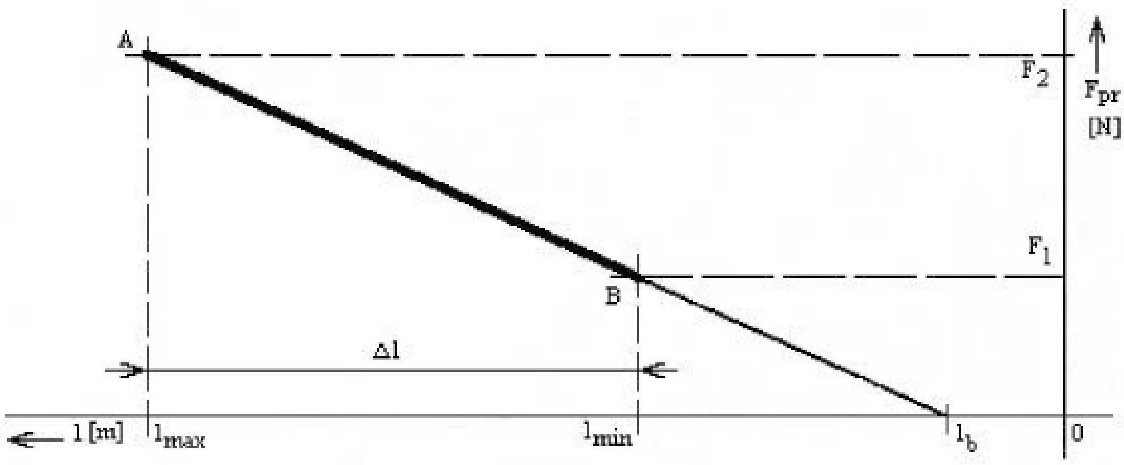

Figure 4 Linear characteristics of spring

Linear characteristics of spring has tendency given by its force conditions in relation to the length of extension:

$$K_{pr} = (F_2 - F_1)/\Delta l \tag{3.4}$$

where

$$\Delta l = l_{max} - l_{min} \tag{3.5}$$

where l is changing in range (l_b, l_{max}) and work range of spring length l is (l_{min}, l_{max}). For course of characteristics, it can be stated:

$$F_{pr} = K_{pr}(l - l_b) \tag{3.6}$$

Preload of spring: $F_1 = K_{pr}(l_{min} - l_b)$ (3.7)

and maximal tension of spring: $F_2 = K_{pr}(l_{max} - l_b)$ (3.8)

3. 2 System with PM and return spring

Pneumatic muscle filled by compressed air shortens its length and acts by tensile force F_m. Relation between tensile force, air pressure p and length l (value of contraction k) of PM is shown by characteristics, which are shown in Figure 5 together with the characteristics of return spring.

Concrete values of parameters and characteristics of PM depend on selected type of PM and are available in documentation of individual producers. Also, the way of characteristics creation with results is a subject of individual publications (for example [1], [2], [6]).

Figure 5 shows nonlinear characteristics of PM in various values of air pressure from p_1 to p_5 [4], [5]. Tensile forces of PM and spring are shown on vertical axis; their lengths are shown on horizontal axis. Intersections of characteristics of PM and spring are points from 1 to 5. The balance between tensile forces of PM and spring is reached in these points. Each such point is point of balance in defined range, where PM filled by air of some pressure shortens to some length under corresponding tensile force of spring. It is obvious, that infinite number of values of air pressure in PM gives infinite number of positions in range from l_1 to l_5. Tensile forces of PM and spring will vary in range from F_B to F_F, which determines also the range of force and stiffness oscillation of mechanism (actuator). Position l of end point of artificial muscle is in range $(l_0, l_0 - \Delta l)$. Contraction k of PM is difference between actual position of PM and its initial position. Then:

$$k = l_0 - l \tag{3.9}$$

Maximal value of contraction is:

$$k_{max} = \Delta l \tag{3.10}$$

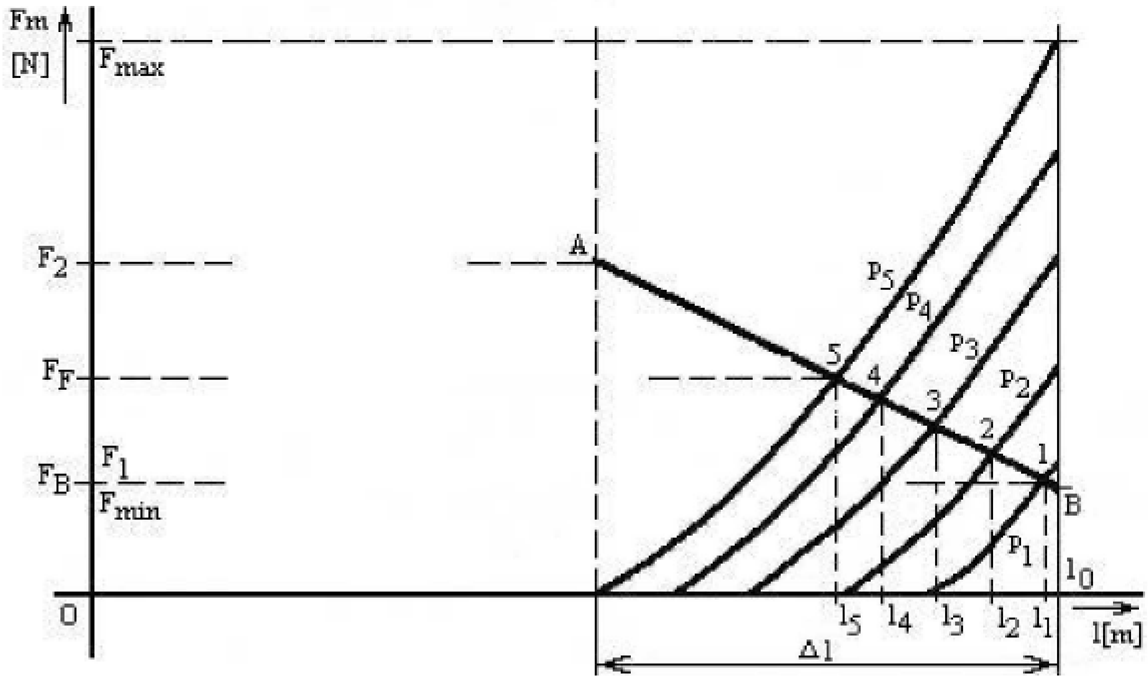

Figure 5 Static characteristics of pneumatic artificial muscle in antagonistic configuration with return spring

Characteristic of tensile force of pneumatic artificial muscle is nonlinear and its course depends on muscle length l (or contraction k) and filling air pressure p:

$$F_m = g_N(p,l) \tag{3.11}$$

Since, balance of forces $F_m = F_{pr}$ is valid for every position of considered kinematics configuration, resulting position l is given by their equilibrium. It means that relations (3.11) and (3.6) are equal:

$$F_m = g_N(p,l) = F_{pr} = K_{pr}(l- l_b)= K_{pr}l-C_1 \tag{3.12}$$

Relation (3.12) gives constant $C_1 = K_{pr}\, l_b$.

$$g_N(p,l) = K_{pr}l - C_1 \tag{3.13}$$

If all members dependent on value l of this equation are united and l is formulated as searched parameter, resulting nonlinear function yielding the relation between length (contraction) of artificial muscle and its filling pressure is obtained:

$$l = C_1\, f_N(p) \tag{3.14}$$

$$k = l_0 - l = l_0 - C_1\, f_N(p) \tag{3.15}$$

Relating to the fact that tensile force of spring F_{pr} is, in this case, dependent only on position l, final position l of whole system will be dependent only from one parameter, filling air pressure p of pneumatic artificial muscle [5]. Pressure is actuating variable input into the actuator and determines resulting position in form of muscle contraction k, or slew of arm r.

3. 3 Static characteristics of spring actuator with artificial muscle

System described in sections 3 and 3.2 creates power unit of servosystem – actuator. Together with load, it creates regulated system, which output is position (or velocity, acceleration),

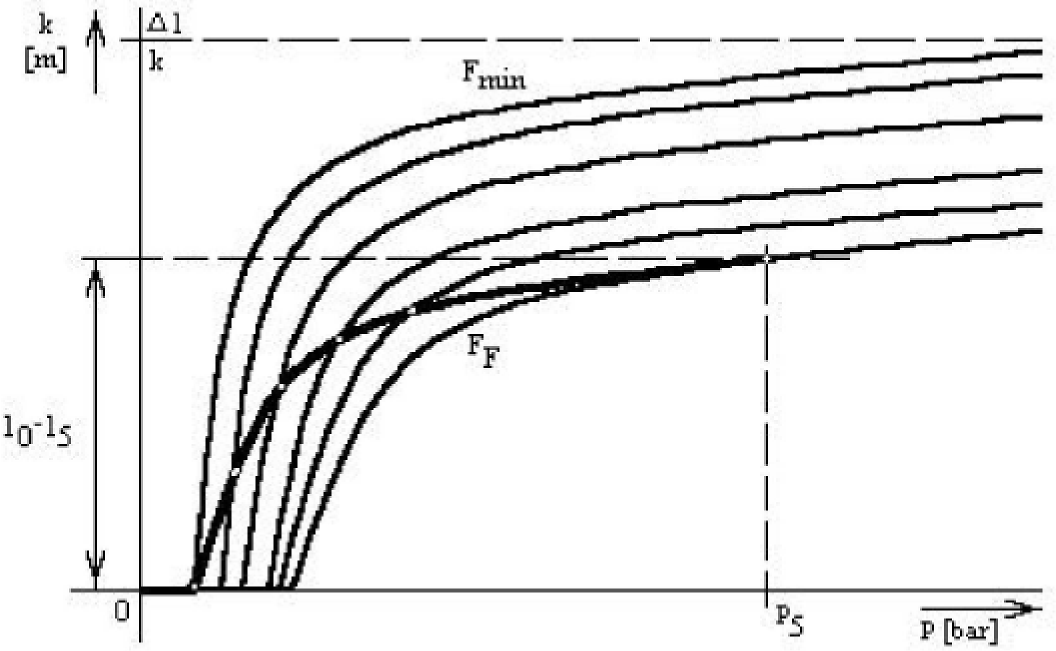

Figure 6 Static characteristics of spring actuator with pneumatic artificial muscle

and which can be expressed as muscle contraction k, or angle of arm slew r. Air pressure is input to actuator, entering into PM. Figure 6 shows nonlinear characteristics of PM, where value of muscle contraction k is dependent on filling air pressure p. Characteristics pf PM create net dependent on load force F, which is constant for given characteristics.

Static characteristics of system PM – spring is curve, which every point is defined by filling pressure p on muscle characteristics for load force developed by return spring under defined contraction. Points 1–5 on Figure 5 are intersections of resulting characteristics of system with muscle characteristics. Point 5 on Figure 5 is intersection of pressure p_5 on Figure 6 and similarly. Static characteristic of actuator is combined nonlinearity including continuous nonlinear curve of saturation type and dead band. Each point of this nonlinearity is result of mutual action of actuator components, from which PM is also nonlinear unit.

4 Pneumatic artificial muscles in antagonistic configuration

Regulated system of proportional position servosystems is servomotor with applied load. In case of pneumatic bioservosystems with artificial muscles, these are individual artificial muscles (PM) with applied mass load m. Actuating variable entering to each PM is pressure p of compressed air, which flows from electropneumatic valve that plays role of actuating unit. In case of use of two PM acting each against other, resulting position is determined by balance of forces of individual PM in nonequal filling pressures and contractions. Actuator in such configuration is shown in Figure 7. Artificial muscles have nonequal filling pressures. Muscle AM1 has maximal filling pressure p_{max}, muscle AM2 is without pressure. Muscle AM1 reaches maximal contraction k, its length l reached minimum l_{min}. Muscle AM2 has minimal (zero) contraction, its length l reached maximum l_{max}. Arm of actuator r is in limit position (point C). Total displacement of cable Δl_{max} through perimeter of roller kl (with radius r_{kl}) is defined by difference of lengths l of individual PM in shown position:

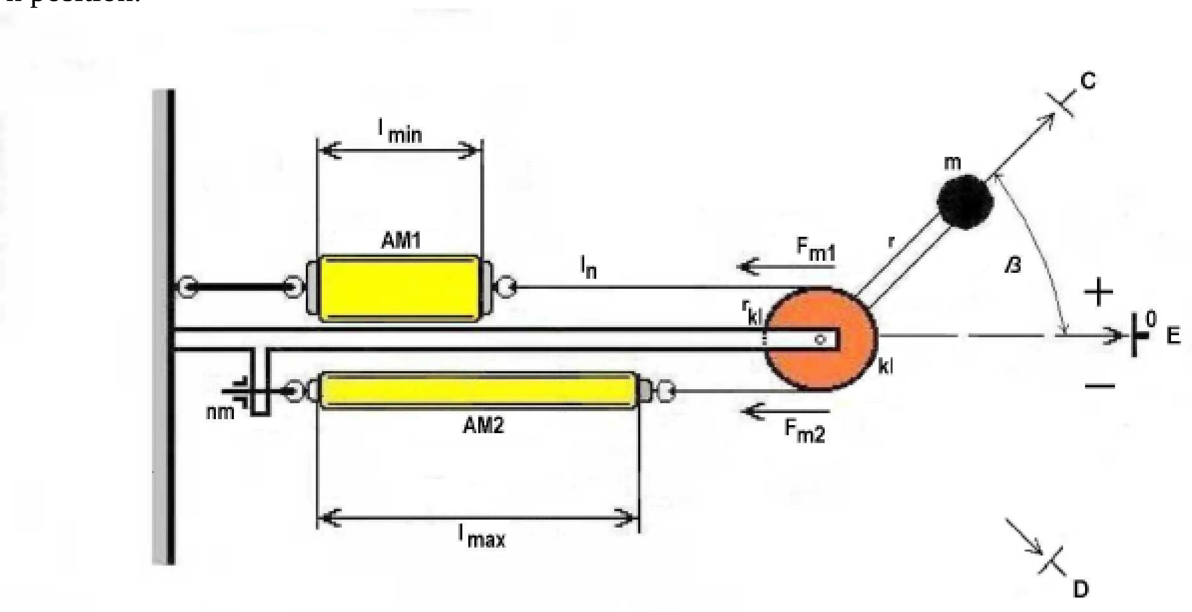

Figure 7 Actuator with pneumatic artificial muscles in antagonistic configuration. Pneumatic muscles have nonequal filling pressures. Muscle AM1 has maximal filling pressure, muscle AM2 is without pressure. Actuator arm is in limit position.

$$\Delta l = l - l_{min} \tag{4.1}$$

$$\Delta l_{max} = l_{max} - l_{min} \tag{4.2}$$

where Δl is displacement of cable (change of PM length) in any position, and l is changing in range from l_{min} to l_{max}. Total displacement Δl_{max} (total change of PM length) determines limits of arm r in positive and negative sense of rotation with zero (referential) position in the middle. As next, these points will be marked as follows: point C – position of positive maximum, point D – position of negative maximum, point E – zero position (referential point). Contraction of PM k in relation to its actual length l is:

$$k = l_{max} - l \tag{4.3}$$

$$k_{max} = l_{max} - l_{min} = \Delta l_{max} \tag{4.4}$$

where k is changing in range from $k_{min} = 0$ to $k_{max} = \Delta l_{max}$.

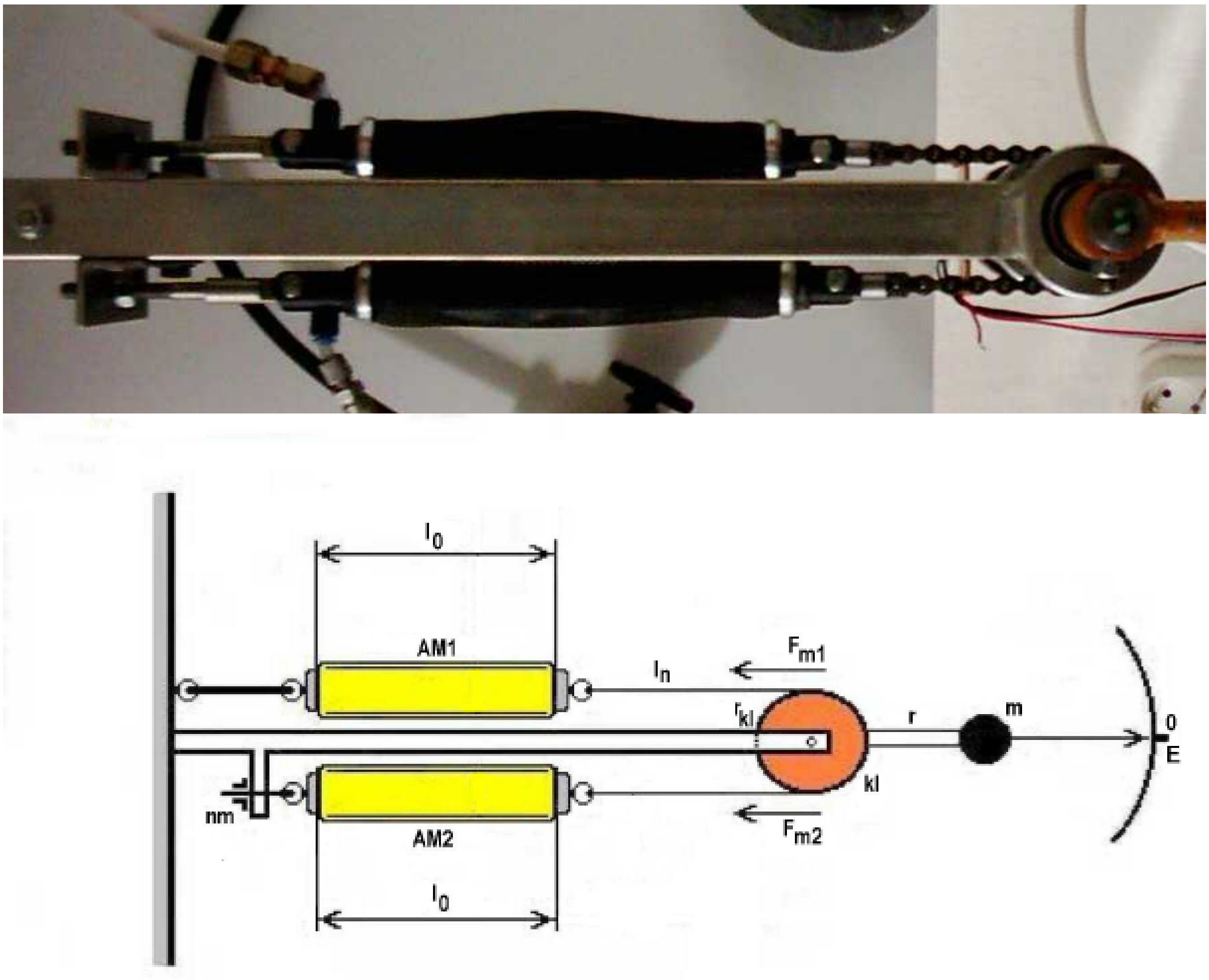

Figure 8 Actuator with pneumatic artificial muscles in antagonistic configuration. The function model (above) and schema (below). Artificial muscles have equal filling pressures and resulting positon of arm is in initial point E.

With respect to the fact that producers of muscles provide all their characteristics in translational values, we will use these values as output values. Angular position β of arm r depends on radius r_{kl} of roller kl under the same changes of muscle length. The relation valid between these values characterizes also its limits, since contraction k of PM and thus also Δl has finite value:

$$\beta = \Delta l / r_{kl} \tag{4.5}$$

$$\beta_{max} = \Delta l_{max} / r_{kl} \tag{4.6}$$

where β is position (angular position) of arm *r* or slew of actuator roller shaft and β_{max} is its maximal value. Others values are clear from Figure 7.

Figure 8 shows two same pneumatic artificial muscles AM1 and AM2 of lengths l_{max}, which are shortened to lengths $l_0 = l_{max} - \Delta l_{max} /2$ after filling by compressed air. Tensile force F_{m1} of AM1 is transmitted by cable *ln* through roller *kl* to muscle AM2, which acts by its force F_{m2}. If there are nonequal filling air pressures, arm of actuator is stabilized in position corresponding to balance of both PM forces. If there are equal filling pressures in both muscles, tensile forces of PMs are equal under the same values of their contractions. System is stabilized in steady position, which is considered as initial state of actuator. Precise initial position is additionally set by tension gear *nm*. Gravity force of mass load *m* is perpendicular to planes of Figures 7 and 8 and thus does not have the influence to force relations between PMs. Object of research are not dynamic states of actuator, we will describe only static steady states. Also, forces dependent on length *l* or angle β derivations are not taken into account as same as friction moments in roller *kl* bearings are not considered.

Actuator shown in Figure 8 has pneumatic artificial muscles with same filling pressures and resulting position of arm is in initial point 0 (referential point E). Change (decrease) of air pressure in, for example, AM1 changes (decreases) also its contraction *k* (active PM). It consequences in performing rotational movement of load mass *m* on arm *r*, mounted to the axis of roller. This sense

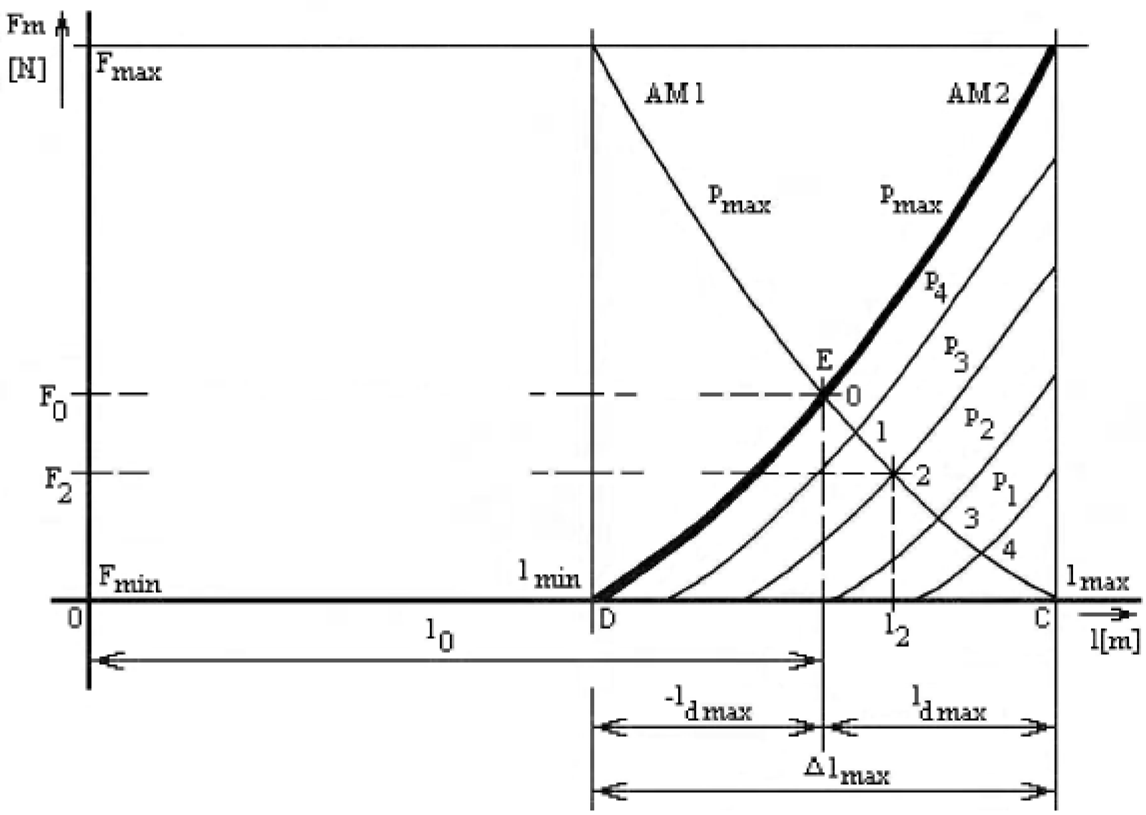

Figure 9 Characteristics of pneumatic artificial muscles (in variable filling pressure) of actuator with antagonistic configuration of pneumatic artificial muscles

of motion in considered as negative (-) in relation to the initial point. Filling pressure in artificial muscle AM2 is not changed, only its length is changing with respect to changing tensile force F_{m1}

of AM1. AM2 acts as a pneumatic spring with nonlinear characteristics (passive PM). Same action can be done with changed activity of individual muscles. Sense of load mass motion will be then reversed (+), roles of active and passive PMs are inverted to previous case. Active PM is always PM with variable air pressure, passive PM plays role of nonlinear spring under constant air pressure.

4. 1 Antagonistic system with pneumatic artificial muscle

AM2 expands its length during outlet of compressed air and acts by tensile force F_{m2}, which value is gradually decreased. Relation between tensile force F_m, air pressure p and length l (contraction k) of this artificial muscle is expressed by characteristics shown in Figure 9, which are sketched together with characteristics of AM1. Air pressure is not changed in this artificial muscle, and therefore it is shown only one its characteristics, corresponding to initial filling pressure p_m. Characteristics is sketched in order to represent antagonistic force action of AM1 against AM2. AM1 plays role of nonlinear pneumatic spring. It ensures balance of forces for each position of positive value. Also, it ensures stiffness of actuator mechanism. Points of intersections of characteristics in segment EC correspond to increasing trend of contraction of passive PM AM1 during gradual decrease of pressure in active PM AM2. Thus, it is possible to reach any positive value of l_d (till l_{dmax}).

Actuator reaches negative position values by the same way as described in the above paragraph. Only the actions of muscles are interchanged. AM1 has variable air pressure, AM2 works as nonlinear pneumatic spring.

If configuration of antagonistic actuator is as shown in Figure 8 (position in referential point E), nonlinear functions g_N and also tensile forces will be identical if identical PMs are used:

$$F_{m1} = g_N(l_1) = F_{m2} = g_N(l_2) = F_0 \tag{4.7}$$

where, it is valid: $l_1 = l_2 = l_0$ a $p_1 = p_2 = p_m$.

If configuration of antagonistic actuator is as shown in Figure 7, nets of nonlinear functions g_N and also tensile forces will be identical if identical PMs are used:

$$F_{m1} = g_M(l_1, p_1) = F_{m2} = g_M(l_2, p_2) \tag{4.8}$$

where, it is valid: $l_1 <> l_2$ a $p_1 >< p_2$ a $k_{AM1} + k_{AM2} = k_{max} = \Delta l_{max}$.

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If nonlinear function $g_M(l, p)$,([1], [2], [3]) in relation (4.8) is known, then the relation between actuator output (length l, or l_d) and input (air pressure p) can be written as a nonlinear function f_N:

$$abs(l_d) = f_N(p) \tag{4.9}$$

$$\mathrm{abs}(\beta) = l_d / r_{kl} = \{f_N(p\}/r_{kl} \tag{4.10}$$

It is obvious from relations (4.9), (4.10) and Figures 7 and 9 that values of corresponding parameters β and l_d will be reached with positive and also with negative polarities. Therefore, also their input parameter – pressure p have to be considered with both polarities, despite to a fact that its value in individual muscles is always positive ($p_{AM1} > 0$ a $p_{AM2} > 0$). This procedure is performed according to sign of required motion of PM l_{dD}, or required angular motion β_D, as follows:

if $sign\ \beta_D = +$, then $p = p_{AM2}.sign\ \beta_D > 0$ where $sign\ \beta = +$ and $p_{AM1} = konst. > 0$
if $sign\ \beta_D = -$, then $p = p_{AM1}.sign\ \beta_D < 0$ where $sign\ \beta = -$ and $p_{AM2} = konst. > 0$

Shown conditions of angular displacement β are valid also for displacement of PM l_d, but $sign\beta_D$ is substituted by $sign\ l_{dD}$ in conditions:

if $sign\ l_{dD} = +$, then $p = p_{AM2}.sign\ l_{dD} > 0$ where $sign\ l_d = +$ and $p_{AM1} = konst. > 0$
if $sign\ l_{dD} = -$, then $p = p_{AM1}.sign\ l_{dD} < 0$ where $sign\ l_d = -$ and $p_{AM2} = konst. > 0$

Total angular displacement of actuator roller is:

$$\beta = l_d / r_{kl} = \{abs(l_d).sign(l_d)\}/r_{kl} \tag{4.11}$$

$$\beta = \text{abs}(\beta).\ sign(\beta) \tag{4.12}$$

where displacement and total length of PM actuator are:

$$l_d = abs(l_d).sign(l_d) \tag{4.13}$$

$$l = l_0 + l_d = l_0 + abs(l_d).sign(l_d) \tag{4.14}$$

also value of PM contraction is:

$$k = l_{max} - l = l_{max} - l_0 - abs(l_d).sign(l_d) \tag{4.15}$$

Displacement l_d against referential point E will correspond to intersection points of PMs characteristics, for example points 1 – 4 in Figure 9. Figure represents such situation in which AM1 is under constant air pressure and pressure in AM2 is changing from maximum to zero values. Then, position of actuator arm is in point C, it means maximal positive deviation from referential point E. The same procedure is possible for reversed air pressures in PMs. Then, position of actuator arm is in point D, it means maximal negative deviation. Work point of actuator position will move from initial referential point E to points C or D over corresponding characteristics with pressure p_m during changes of pressure in individual muscles.

4. 2 Static characteristics of antagonistic actuator

System described in sections 4 and 4.1 creates power unit of servosystem – actuator. It creates regulated system together with load, which output is position (or velocity, acceleration), and which can be expressed as change of length l_d of PM against referential point E (or change of muscle contraction *k)*, or as slew angle β of arm *r*. Air pressure *p* entering corresponding PM is input of actuator.

Static nonlinear characteristic of actuator is shown in Figure 10. It is result of measurements of functional sample of actuator. It was realized by application of two McKibben PMs of type Shadows Air Muscle SAM 30x290x6, made by British company The Shadow Robot Company, London, UK. Internal area of PM cross-section was 30 mm, length 290 mm, under contraction max. 25%. Internal area of air supply pipe cross-section was 6 mm. Diameter of roller *kl* was $d_{kl} = 2r_{kl} = 60\ mm$. Working pressure of compressed air was 3,62 bar (maximal allowed pressure is 6 bar). Mass load *m* was created by actuator arm ($m = 0, 4\ kg$).

Figure 10 shows trends of nonlinear characteristics of actuator with PMs according to Figures 7 and 8, where value of displacement (change of muscle length) l_d against initial position l_0

depends on filling air pressure *p* (right scale). This figure shows resulting position of arm expressed also in form of angular displacement β (left scale). It is obvious that $abs(l_{dmax}) = 30\ mm$ and $abs(\beta_{max}) = 60\ deg$ as shown in Figure 10.

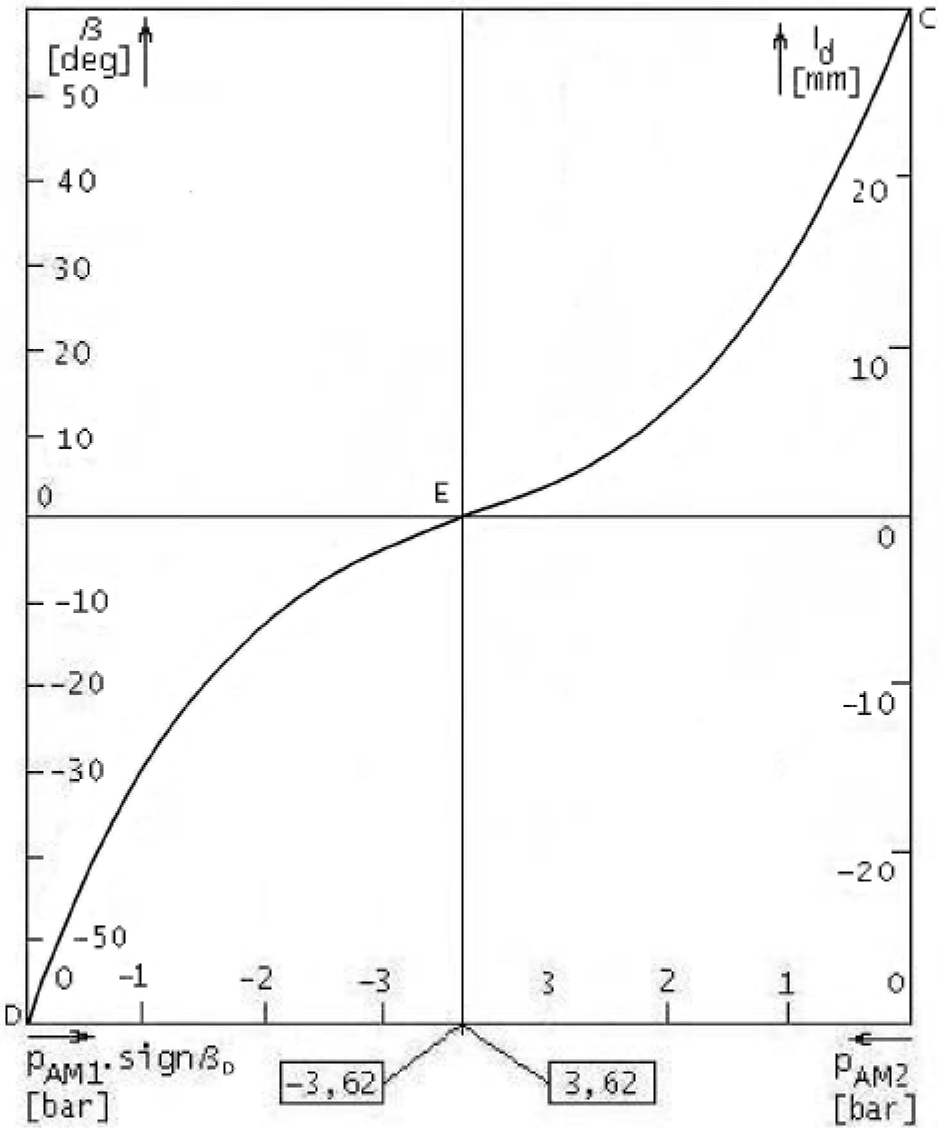

Figure 10 Static characteristics of actuator with antagonistic configuration of pneumatic artificial muscles SAM 30 x 290

Horizontal axis contains scale of compressed air pressure *p*, where pressure sign in individual PMs is determined by polarity of desired value of position β_D, which system reaches after activation of corresponding PM. Real pressures in both muscles are positive, change of pressure in PM AM1 causes changes of positions with negative sign. Scales of pressures are also oriented descending, it means from maximal value to zero. If values of air pressures in both muscles are maximal, actuator is in referential point E, what means position in intersection point in the middle of Figure 10.

Decreasing pressure in one of PMs changes position of actuator arm according to measured curve, to the left or right. Pressure in second PM is kept at maximal value. Limits of arm are shown in Figure 10 as points C and D and correspond with their position in Figure 7, or Figure 9.

Besides parameters of used PMs and after measurements characteristics of actuator (Figure 10), the functional relation of angular displacement of actuator shaft β on filling air pressure p was set:

$$abs(\beta) = A\,(p_{max} - p)^3 + B\,(p_{max} - p) \qquad (4.16)$$

where A = 0,9669, B = 3,3029, p_{max} = 3,62 bar for used types of PMs. Besides pressure p (bar) is value β in angular degrees (deg). Sign β depends on pressure of active PM in sense (4.12). Match of calculated function (4.16) with measured values has index of correlation IK = 0,999349.

5 Conclusions

Actuator consisting from pneumatic artificial muscle and return spring is nonlinear system, which limit position is nonlinear function of filling air pressure of PM. It enables realization of relatively simple position bioservosystem with seemly lower requirements to control and costs. Characteristics of limit position of actuator are nonlinear function of filling air pressure in artificial muscle and their trends are various under various values of actuator load. It is consequent from nonlinear characteristics of artificial muscle and nonconstant directive force of return spring. Also, it is necessary to take into account nonconstant tensile force (respectively torsion moment) of actuator, which magnitude is changing with the value of artificial muscle contraction. This property causes also nonconstant stiffness of mechanism under various values of position.

Artificial muscle has to overcome also variable directive force of return spring besides forces (moments) from load, therefore requirements to its nominal parameters (tensile force) are essentially higher as it can be derived only from load magnitude (acting of allowed external force or moment – outage). Load can be also gravity of mass *m* during change of actuator position against predicted initial value. It is assumed that forces of artificial muscles and spring have to be several times higher than is maximal loading force (moment) due to reach the adequate stiffness of mechanism. Ratio depends on used PM, allowed inaccuracy of position, allowed deviation under influence of outage, etc. Ideal case of absolute stiffness assumes that acting forces of PM and spring are approximating to infinity under zero value of outage.

Actuator with one pneumatic artificial muscle and spring, which acts against tensile force of artificial muscle, is appropriate solution in some cases. It needs only one inlet and outlet valve, what is useful in synthesis of „low cost“ bioservosystems. Then, main indicator is minimizing costs and simplicity of control under not too high requirements onto parameters of bioservosystem.

Pressure of actuator consisting of two pneumatic artificial muscles in antagonistic configuration is controlled only in one artificial muscle in each half of angular displacement of shaft of roller. Pressure of second artificial muscle is constant and acts as nonlinear pneumatic spring. Such actuator is nonlinear system, which limit position is nonlinear function of air filling pressure in PMs, symmetric by center. Angular displacement of roller shaft increases with raising trend while decreasing the pressure in active PM. Trend of static characteristics of such system shows that actuator gain depends on position of its arm, which depends on pressure and force relations in individual artificial muscles. Configuration of actuator together with simple control system enables construction of relatively simple position bioservosystem with adequate costs and requirements to control system. Characteristics of limit position of actuator are nonlinear function of filling air pressure in artificial muscle and their trends are various under various load of actuator. It is obvious from nonlinear characteristics of artificial muscles. Also, it is required to respect nonconstant tensile force (or torsion moment) of actuator, which value is changing with value of angular displacement of roller shaft of actuator (contraction of artificial muscle, displacement of artificial muscle). Simultaneously, this property also causes nonconstant stiffness of mechanism under various values of position, where maximal and symmetrical stiffness is reached in referential point.

Active artificial muscle has to overcome also variable directive force of passive artificial muscle besides load forces. Therefore, the requirements onto nominal parameters (tensile force) of artificial muscles are higher as it can be derived from load magnitude. Relating to the necessity of appropriate stiffness of mechanism, it is assumed that forces of artificial muscles of actuator are higher than maximal loading force.

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References

[1] Tondu, B., Lopez, P.: Modelling and Control of McKibben Artificial Muscle Robot Actuators, IEEE Control systems Magazine, April 2000, pp. 15- 38

[2] Novák - Marcinèin J.: Biomechanizmy, Elfa Košice, ISBN 80-7099-218-2, 1993, str. 34 – 47.

[3] Klute, GK. Hannaford, B.: Modeling pneumatic McKibben artifical muscle actuators: approaches and experimental results. Journal of Dynamic Systems, Measurements, and Control. November 1998

[4] Chou, C. P., Hannaford, B.: Measurement and modeling of artificial muscles, IEEE Transactions on Robotics and Automation, 1996,Vol. 12, pp. 90-102

[5] Petík, A., Balara, M.: Pneumatický umelý sval Shadow Air Muscle a jeho model. Mezinárodní vìdecká konference, Ostrava 5. – 7. 9. 2000, VŠB Ostrava, Fakulta strojní, Sekce 5, Production systems with industrial robots, ISBN 80 – 7078 – 799 – 6, pp. 44.1 – 44.8

[6] Balara, M., Petík, A.: Experimentálne meranie statickej charakteristiky umelého svalu MB0124. New Trends in the Operation of Production Technology. 4 – th international scientific conference. 21. – 22. 11. 2001, Prešov, Slovakia. ISBN 80 – 7099 – 723 – 0. pp. 97 - 100

[7] Balara, M. Petík, A.: Nelineárny model pneumatického umelého svalu. Strojárstvo v hospodárstve a priemysle, 11/2000, roèník IV. Žilina, ISSN 1335 – 2938, pp. 54 – 55