Research Article

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Angular position control system of pneumatic artificial muscles

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Abstract: This article presents a test stand used to determine the angle control of a pair of pneumatic artificial muscles PAM, which work antagonistically like natural muscles, e.g. in the human arm. The muscles were designed and produced at the Kielce University of Technology. The technical and functional parameters of the muscles were determined on the basis of experimental research. The Ziegler-Nichols method of tuning a PID controller on the basis of the step response measurement of the open system is also presented for the analysed problem. Experimental research was performed on angle control of a pair of pneumatic muscles with a PID controller.

Keywords: pneumatic artificial muscle PAM, angular position control, pneumatronics

1 Introduction

Pneumatic artificial muscles can be used as driving elements of mobile, anthropomorphic, bionic and humanoid robots; rehabilitation and physiotherapeutic manipulators as well as devices for the automation of manufacturing processes [1, 2]. Research on the technical parameters of pneumatic artificial muscles is very important to determine their application possibilities. The previous works concerned with static and dynamic characteristics of the pneumatic artificial muscles [3] and the control system applied in the Delta electro-pneumatic manipulator [4]. The subject of this work were simulation and experimental research of two types of pneumatic artificial muscles produced by two companies: Festo (Fluidic Muscle MAS and DMSP) and Shadow Robot Company (Shadow Air Muscle SAM). Due to the design and the simple structure, the pneumatic artificial muscles can be easily made indepen-

dently. Many works have been created on pneumatic artificial muscles at academic and scientific centres worldwide [5–11]. Figure 1 shows a general view of various pneumatic artificial muscles, while Figure 2 presents pneumatic artificial muscles produced at the Kielce University of Technology.

Figure 1: Pneumatic artificial muscles: a) Festo Fluidic Muscle MAS b) DMSP, c) Shadow Air Muscle SAM, d) Pleated Pneumatic Artificial Muscles PPAM.

The designed and produced muscle is a rubber bladder surrounded by a plastic braided mesh sleeve. The muscle connections are sealed threaded joints with bladder clamped at the ends. Before the clamping, the bladder was pre-extended to increase the relative muscle contraction and to minimize the hysteresis effect.

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Figure 2: Pneumatic artificial muscles made at the Kielce University of Technology: a) general view, b) connections – clamping method.

2 Test stand

The test stand was made on the basis of patent No. PL 223042 B1 registered at the Patent Office of the Republic of Poland [12]. The stand was made of stainless steel. The T-shaped stand consists of a base, a main column and a pivot arm, centrally attached to the column. The base has two handles to which pneumatic artificial muscles are attached. The other end of the muscles are attached to the pivot arm. The muscles act in an antagonistic manner modelled on human muscles, e.g. triceps and biceps in human arm. The contraction of one muscle under compressed air pressure extends the other muscle and rotates the arm. Muscles contract and extend alternately causing the arm to rotate. Figure 3 shows a diagram of the complete test stand and its general view.

Other elements of the stand include: MAB36A angle sensor attached to the pivot of the arm, MPYE-5-1 / 8-HF-010-B proportional flow control valve, air handling unit, PE5 pressure sensors, Matlab xPC Target real time system, PC and DA/AD card PCI-DAS1602/16.

The computer system uses the Rapid Control Prototyping (RPC). The system is based on Matlab xPC Target software, PCs and a card with DA/AD converters [13]. The pressure sensors and the angle sensor generate analogue voltage and are connected to the AD inputs on the card. The angle sensor measures angle of the arm rotation due to the contraction and extension of the pneumatic artificial muscles. Muscles are powered by compressed air and controlled by pressure changes inside the muscle. As the air pressure increases, the circumference simultaneously increases, and the muscle length shortens which leads to an increased muscle contraction and an axial tractive force corresponding to the stresses in the elastic mesh. The initial stage of the muscle contraction generates the greatest force, which decreases to zero with the maximum contrac-

tion, but only at constant pressure. By controlling the pressure, the transmitted force and degree of the pneumatic artificial muscle contraction can be controlled.

Despite the fact that the muscles are controlled by pressure changes, the proportional flow control valve was proposed to control the pair of pneumatic muscles. This option was chosen due to the way the valve works (Figure 4) as well as easy and optimal control of a pair of muscles.

MPYE is a 5/3-way function valve (5 - way, 3 - position). The MPYE valve is controlled by an analogue voltage. The mid position corresponding to 5V voltage closes all valve ways. The control voltage change from 5V to 0V opens the way 2 and closes the way 4 with simultaneous venting by the way 5. The control voltage change from 5V to 10V opens the way 4 and closes the way 2 with simultaneous venting by the way 3. Because pneumatic artificial muscles are connected to the ways 2 and 4, this causes alternating muscle contractions and extensions, and thus rotation of the arm. To control the pair of muscles, a part of the pressure characteristics of the valve, shown in Figure 5, was used. Accurate author's research presented in the works [14, 15] showed asymmetry in the valve operation, leakage and non-linearity.

3 Experimental research

The pneumatic artificial muscles, made by a team of scientists from the Kielce University of Technology, were functionally marked as PAM-20-330. The two PAM-20-330 antagonistic muscles were used in the experimental research. All parameters of the muscles are not known yet because muscle tests are still being performed. Table 1 shows selected parameters of the PAM-20-330 muscle.

3.1 PID controller

Based on experimental observations of the PID controller tuning strategies in industrial processes, Ziegler and Nichols proposed two tuning methods. One of the methods requires measurement of the system response and is commonly used for static systems, most commonly found in control systems. The tuning method developed by Ziegler and Nichols is applicable in such systems in which the step response of an open system is without overshoots as shown in Figure 6.

Identification of properties of controlled objects is a basic condition for designing proper and well-functioning

(a)

(b)

Figure 3: Test stand: a) diagram, b) general view.

Table 1: Parameters of pneumatic artificial muscle PAM-20-330.

Parameter	Value
Symbol	PAM-20-330
Mode of operation	Single-acting, pulling
Internal diameter D_n	20 mm
Nominal length L_n	330 mm
Length of the muscle when fully contracted, L_{min}	290 mm
Length of the muscle when fully extended, L_{max}	410 mm
Max. operating pressure p	0.5 MPa
Max. permissible pre-tensioning ε_{min}	-24.2 % of L_n
Max. permissible contraction ε_{max}	29.3 % of L_{max}
Lifting force at max. permissible operating pressure F_{max}	775 N

Figure 4: Flow characteristics of MPYE valve. **Figure 5:** Pressure characteristics of MPYE valve.

control systems. The analysed pneumatic muscle belongs to a group of static objects with transport delay. In order to conduct the object identification process, a step input signal was set to the proportional flow control valve. Input signal directly results from the pressure characteristics of the valve (Figure 5). The actual response obtained (black colour diagram in Figure 7) is characteristic for inertial ob-

(a) **(b)****Figure 6:** The method for determining the parameters k , T , T_0 on the basis of the step response of a system for a multi-inertial static object a), square decay rate b).

jects and can be approximated by the characteristics of the first-order inertial element with transport delay. Transfer function of the object takes the form:

$$G(s) = \frac{k}{Ts + 1} e^{-T_0 s} \quad (1)$$

where:

k – gain coefficient,

T – alignment time,

T_0 – delay time.

The parameters k , T and T_0 of the equation (1) was calculated based on the method proposed by Ziegler-Nichols as shown in Figure 6a. The tangent is drawn at the inflection point of the response curve. The slope of the tangent line is given by the formula $R=k/T$. Parameter a (Table 2) is given by: $a = T_0 R = T_0 k/T$. The controller tuning is based on a decay coefficient of approximately 0.25. This means that the dominant transient component decays to one fourth of its maximum value after one oscillation period (Figure 6b). The Ziegler-Nichols method based on the step response gives good results when the following condition is met:

$$0.15 < \frac{T_0}{T} < 0.6 \quad (2)$$

In the analysed case $T_0/T=0.17$ thus this controller tuning method can be applied. The calculated parameters have the following values: $k=0.021$; $T=0.64$; $T_0=0.11$. As you can see, the correlation between real and simulation characteristics is adequate, and the correlation coefficient is: Pearson – 0.9991, Spearman – 0.9822, Kendall – 0.9213.

The PID controller was tuned on the basis of Table 2:

Table 2: The controller tuning parameters according to the Ziegler-Nichols method.

Controller	Optimal parameters		
	k_p	T_i	T_d
P	$1/a$	-	-
PI	$0.9/a$	$3T_0$	-
PID	$1.2/a$	$2T_0$	$0.5T_0$

Experimental research on angle control of a pair of pneumatic muscles were performed for *ramp-type* input signal. Figure 8a shows the characteristics of the angle change, while Figure 8b error.

On the basis of experimental research, performance of the PID controller was assessed. Basic and integral performance indices [16], which were collected in Table 3, were used for the assessment.

Table 4 presents the obtained values of indices.

Figure 7: Step response of the open system.

(a)

(b)

Figure 8: Experimental results: a) angle, b) error.

Table 3: Performance indices.

Index	Formula	Description
settling time	t_R	With the assumed over-adjustment, it is demanded that the adjustment time was as short as possible.
steady-state error	$e_{st} = \lim_{t \rightarrow \infty} e(t) $	Adjustment error e_{st} appears in the system either after the change of the set value or after the change of one of the disruptions, which can potentially affect the system, or simultaneously due to the two above mentioned reasons.
IAE (Integral of Absolute Error)	$IAE = \int_0^{\infty} e(t) dt$	The modified Sartorius' criterion indicates all errors in the adjustment system resulting from over-adjustment and under-adjustment.
ISE (Integral of Squared Error)	$ISE = \int_0^{\infty} e^2(t) dt$	The criterion in which the significance of small errors is decreased, and the significance of large errors is emphasized, because of that the ISE criterion gives a more objective image of reality. The control system optimized with the use of <i>ISE</i> may indicate a small, slowly disappearing error of adjustment.
ITSE (Integral of the Time-weighted Squared Error)	$ITSE = \int_0^{\infty} te^2(t) dt$	Optimization with the use of that criterion is used to achieve a control system in which the disappearance of the error is faster.
ISC (Integral of Control)	$ISC = \int_0^{\infty} u^2(t) dt$	Criterion indicating the costs of control.

Table 4: Values of the performance indices.

Index	Value
t_r	8.5
e_{st}	5.129
IAE	0.1927
ISE	0.0055
$ITSE$	-0.0716
ISC	1.181

4 Conclusion

The use of a proportional directional control valve is very convenient when it is necessary to control two antagonistic pneumatic artificial muscles, as explained in Chapter 2. This type of system enables gentle and smooth inflating of the muscles with compressed air. It is possible to control the strength and the degree of muscle contraction. Due to the high dynamics of the valve, a dynamic control of the muscles, as with the use of standard divide valves, is also possible. However, the use of this type of valve does not give very good results in the analysed case of angle control. It results directly from the high sensitivity of the valve with a very small range of control voltage variations 4.8-5.2V, as seen in the pressure characteristics of the valve (Fig-

ure 4). This type of system can be applied in less demanding industrial processes, where high positioning accuracy is not required. The manual [17] presents 99 examples of industrial processes in which this type of system can be successfully implemented. In order to improve the adjustment quality, two proportional pressure valves should be used, and implementation of another type of controller can be analysed, e.g. fractional controller or fuzzy logic controller [18].

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