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Robust Positioning Control of Pneumatic Muscle Actuator at Different Temperatures

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Abstract ***– Pneumatic muscle actuator (PMA) or pneumatic artificial muscle (PAM) is the less well-known type of pneumatic actuators. It consists of a thin, flexible, tubular membrane with fibre reinforcement. When the membrane is pressurized the gas pushes against its inner surface and against the external fibre. Then the PAM expands radially and contracts axially with the result that the volume increases. The force and motion produced by PAM are linear and unidirectional. It differs from general pneumatic cylinder actuators as they have no inner moved parts and there is no sliding on the surfaces. Besides, they have small weight, simple construction and low cost. During action they reach high velocities, while the power/weight and the power/volume ratios reach high levels.***

Because of their highly nonlinear and time varying nature, PAMs are difficult to control thus robust control method is needed. In this paper a LabVIEW based sliding mode controller is developed to eliminate the effects of these drawbacks. The positioning error of a pneumatic muscle actuator at different temperatures is determined. The error of the experiments shows 0.01 mm.

This paper is organized in four sections. After Introduction, Section II illustrates the steps to designing sliding mode controller. In this section the experimental rigs and LabVIEW programs are also shown. The internal and external temperatures of the PAM at different operating frequencies are compared and the effect of temperature on the accuracy of the positioning is given in Section III. Finally, conclusion and future work are summarized in Section IV.

Keywords: ***Pneumatic muscle actuator, robust control, sliding mode controller, LabVIEW, temperature effect, accurate positioning.***

I. INTRODUCTION

Fluidic Muscles produced by Festo Company and Shadow Air Muscle manufactured by Shadow Robot Company are two types of commercially available PAMs. Fluidic Muscles can be characterized such as powerful, dynamic (even 6000 N, 50 $m \cdot s^{-2}$), judder-free and resistant to dirt and dust, therefore these actuators are widely used in industrial environment besides electric motors or hydraulic actuators.

Working principles of different types of pneumatic artificial muscles are well described in [1] and [2]. On the basis of these professional literatures, three types of PAMs can be distinguished: braided muscles (McKibben muscles), netted muscles and embedded muscles. Although the load carrying structure of Fluidic Muscles is embedded in its membrane some researches mention the Fluidic Muscles as McKibben type [3], [4].

The main disadvantage of PAMs is the highly nonlinear behaviour due to compressibility of air and the viscoelastic material [5], [6]. Choi et al. in [7] highlight to overcome the nonlinearity several easier models have been developed, but the most results are limited and valid only on simulation.

Static and dynamic investigations and modelling of PAMs can be found in [8-14]. In these professional literatures the PAMs are analysed in single or antagonistic configuration.
Various control methods have been applied to control PAMs such as classical linear control, adaptive control, fuzzy control, neural network control and sliding mode control. Generally, proportional directional control valves, proportional pressure valves or ON/OFF solenoid valves are used [15]. In this paper a proportional directional control valve and a LabVIEW based sliding mode controller is applied for accurate positioning.

The service life (10^5-10^7 cycles for typical applications) of Fluidic Muscles depends on the operating pressure, the contraction (relative displacement) and the temperature. Festo in [16] emphasizes the high loads or the high operating frequencies of Fluidic Muscles lead to a temperature rise. The service life can be improved with reducing the contraction and the applied pressure. The thermal load can be reduced if the pressurisation on one side and the venting on the other side are enabled.

For this study a Fluidic Muscle type DMSP-20-400N-RM-RM is selected (Table 1) and [17] is extended.

TABLE 1. Technical data of Fluidic Muscle type DMSP-20-400N-RM-RM.

General technical data	
DMSP	Pressed end caps and integrated air connectors
RM	Radial pneumatic connection
Inside diameter [mm]	20
Nominal length [mm]	400
Lifting force [N]	0…1500
Maximal permissible pretensioning	4%
Maximal permissible contraction	25%
Operating pressure [kPa]	0…600
Ideal ambient temperature [°C]	-5…+60

II. LABVIEW BASED CONTROL AND MEASUREMENT SYSTEMS AND EXPERIMENTAL RIG

The theory of sliding mode control is well documented in [18-22]. To understand it let us consider the next nonlinear system:

$$x^{(n)} = f(X) + B(X) \cdot u(t)\,, \tag{1}$$

where
x: state variable,
X: state vector

$$X = \left[x, \dot{x}, \ldots, x^{(n-1)} \right]^T, \tag{2}$$

u(t): control input,
f(X) and B(X) are not exactly known, continuous functions.

The tracking error can be written as

$$\widetilde{X} = X - X_d = \left[\widetilde{x}, \dot{\widetilde{x}}, \ldots, \widetilde{x}^{(n-1)} \right]^T, \tag{3}$$

where
$x_d(t)$: desired state

$$X_d = \left[x_d, \dot{x}_d, \ldots, x_d^{(n-1)} \right]^T. \tag{4}$$

The design of a sliding mode controller consists of three main steps. First one is the design of the sliding surface (sliding mode), the second step is the design of the control which holds the system trajectory on the sliding surface, and the third step is the chattering-free implementation. The purpose of the switching control law is to force the nonlinear plant's state trajectory to this surface and keep on it.

The sliding mode can be defined as

$$S(t) = \{ X \mid s(X,t) = 0 \} \tag{5}$$

with

$$s(x,t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} \cdot \widetilde{x}(t)\,, \tag{6}$$

where
λ: constant and λ > 0.

If n = 2,

$$s = \left(\frac{d}{dt} + \lambda \right) \cdot \widetilde{x} = \dot{\widetilde{x}} + \lambda \cdot \widetilde{x}\,. \tag{7}$$

On the surface S(t), the error dynamics can be written as

$$\left(\frac{d}{dt} + \lambda \right)^{n-1} \cdot \widetilde{x} = 0\,. \tag{8}$$

On this surface the error will converge to 0 exponentially. The tracking problem can be reduced to that of keeping the scalar s at zero. It can be achieved with the next sliding condition:

$$\frac{1}{2} \cdot \frac{d}{dt} s^2 \le -\eta \cdot |s|\,, \tag{9}$$

where
η: constant and η > 0.

Using a relay (as a controller) is a simple way that can lead to sliding mode:

$$u = k \cdot \mathrm{sign}(s)\,, \tag{10}$$

where
k: gain and k > 0.

The discontinuity creates an unfavourable dynamic behaviour in the environment of the surface that is called chattering. It is the main problem of sliding mode control, therefore an important phase in the design of a sliding mode controller is the chattering free implementation. To avoid the chattering the signum function can be replaced by a saturation function (Fig. 1). Then inside a boundary layer (H) the control signal changes continuously:

$$u' = k \cdot \mathrm{sat}(s) = \begin{cases} k \cdot \mathrm{sign}(s), & \text{if } |s| > \varepsilon \\ \frac{k}{\varepsilon} \cdot s, & \text{if } |s| \le \varepsilon \end{cases}, \tag{11}$$

$$H(t) = \{ X, |s(X,t)| \le \varepsilon \}. \tag{12}$$

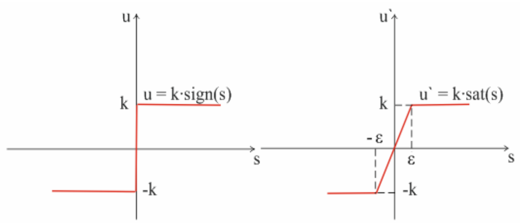

Fig. 1. Signum and saturation functions.

In this study a LabVIEW based sliding mode controller (Fig. 2) is designed to control the pneumatic system. The chattering-free implementation of the sliding mode controller is developed in Formula Node. Despite the graphical programming, the Formula Node is a text-based environment in LabVIEW using the C/C++ syntax structure that can be applied to execute mathematical operations or statements and loops (e.g. if, while, for) on the block diagram. To eliminate the chattering a barrier zone (precision zone) along the sliding surface is defined. LabVIEW is widely used for measurement and control applications [23], [24].

The controller responds to the error of the system that can be measured without knowing f(X) or B(X) in (1). The next input signals are used to control the 5/3 proportional directional control valve type MPYE-5-1/8 HF-010B made by Festo Company: 4 V (fast backward), 4.65 V (slow backward), 5 V (in position), 5.35 V (slow forward) and 6 V (fast forward) (Fig. 3).

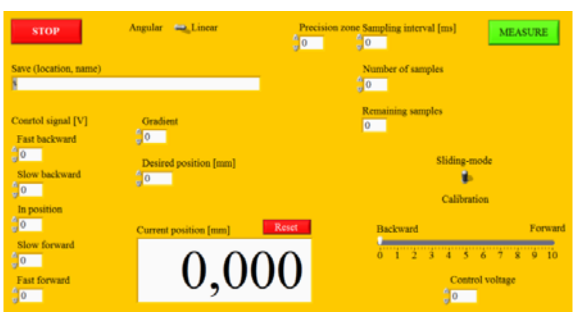

Fig. 2. Front panel of the LabVIEW based sliding mode controller.

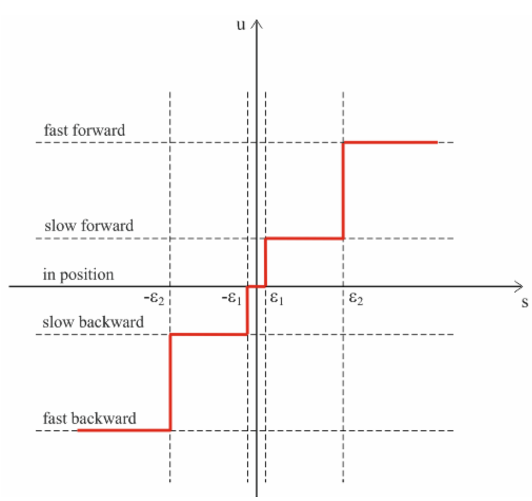

Fig. 3. Input signals.

Fig. 4 shows the Fluidic Muscle is built horizontally into the test bed. Another LabVIEW program is used for periodic movement of PAM and monitoring of internal and external temperatures (Fig. 5). The internal and external temperatures are measured using thermocouples type K. In all cases before the operation the PAM is cooled with a compressed air spray to -10 °C. The moved load m is 20 kg. The position of slider is determined by an incremental encoder type LINIMIK MSA 320 with 0.01 mm resolution.

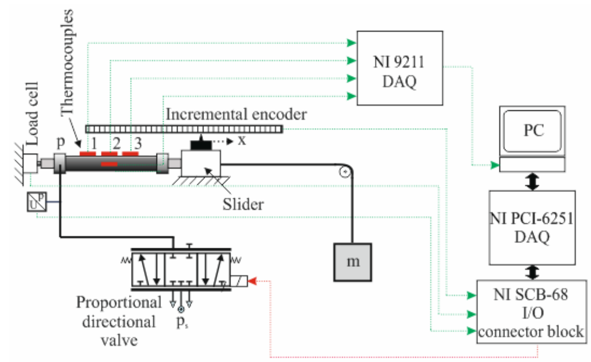

Fig. 4. Experimental setup for investigation of Fluidic Muscle.

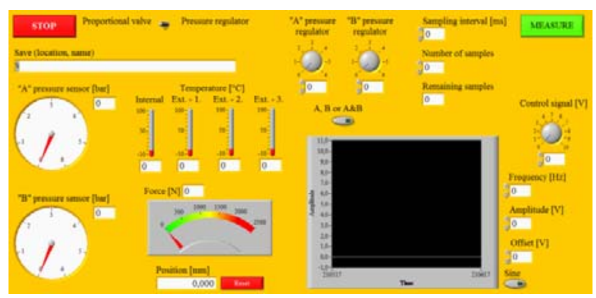

Fig. 5. Front panel of the LabVIEW program for periodic movement and measuring temperature.

III. RESULTS

The air temperature entering the PAM is 24 °C, the air pressure is 600 kPa, the sampling time is 250 ms and the proportional directional control valve is operated by sinusoidal signals with different frequencies (0.1 Hz, 0.25 Hz, 0.5 Hz, 0.75 Hz and 1 Hz) for periodic movement. The temperature changes as a result of the 0.5 Hz periodic movement can be seen in Fig. 6.

The experimental results are summarized in Table 2. As shown in Table 2, inside the PAM the temperature varies with the airflow, but increasing the frequency causes higher steady-state internal temperatures. Outside the PAM the temperatures stabilise, furthermore higher external temperatures are measured away from the pneumatic jack. Thermocouple 1 determines the same temperatures (24 °C) at all frequencies, while thermocouple 3 measures the highest temperature values. The highest external temperature (70 °C) at a frequency of 0.5 Hz can be noticed. This temperature value can negatively affect the service life of Fluidic Muscle. At 0.5 Hz the temperature trend changes: external temperatures show similar results at 0.1 Hz and 1 Hz as well as 0.25 Hz and 0.75 Hz.

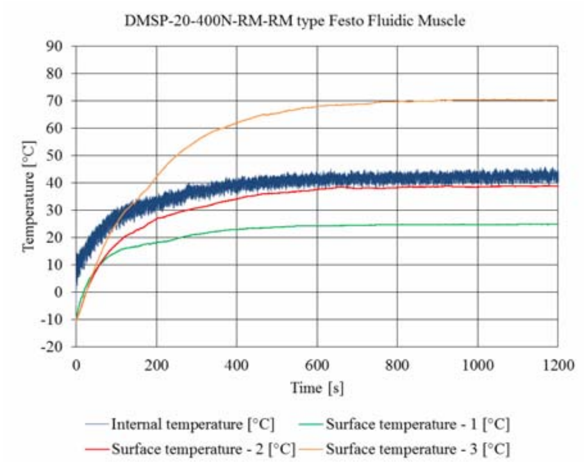

Fig. 6. Internal and surface temperatures (f = 0.5 Hz).

TABLE 2. Internal and external steady state temperature values of Fluidic Muscles driven at varying frequencies.

Frequency [Hz]	**Temperature [°C]**			
	Internal	External - 1.	External - 2.	External - 3.
0.1	30-42	24	33	50
0.25	35-43	24	37	63
0.5	40-45	24	39	70
0.75	45-50	24	38	61
1	45-50	24	38	52

The investigations of positioning error at several temperatures are carried out at a pressure of 600 kPa. The sliding surface gradient is 0.35 and the sampling time is 10 ms. Thermocouple 2 is used as reference sensor and thus the slider is positioned at temperatures of -10 °C, 0 °C, 10 °C, 20 °C, 30 °C and a maximum of 39 °C (Fig. 7-12).
Fig. 7 depicts reaching the desired position of 40 mm the positioning lasts for 1.4 s at a temperature of -10 °C and an overshot of 0.02 mm and a steady-state error of 0.01 mm are experienced. Fig. 12 presents the positioning lasts for 1.2 s at a temperature of 39 °C and the overshot and steady-state error remains within 0.01 mm. It is important to note that at all temperatures the steady-state error is within 0.01 mm and by increasing the temperature the positioning time decreases.

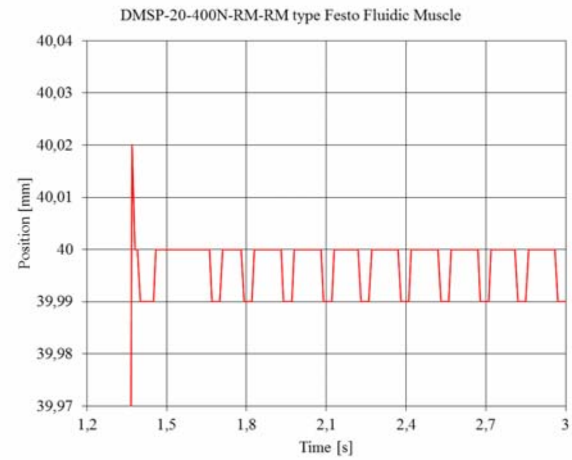

Fig. 7. Positioning at a temperature of -10 °C.

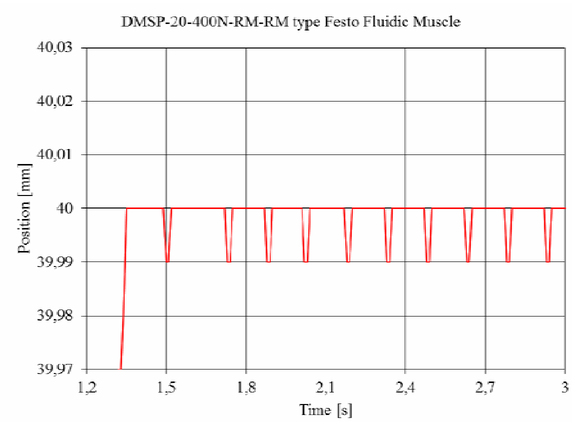

Fig. 8. Positioning at a temperature of 0 °C.

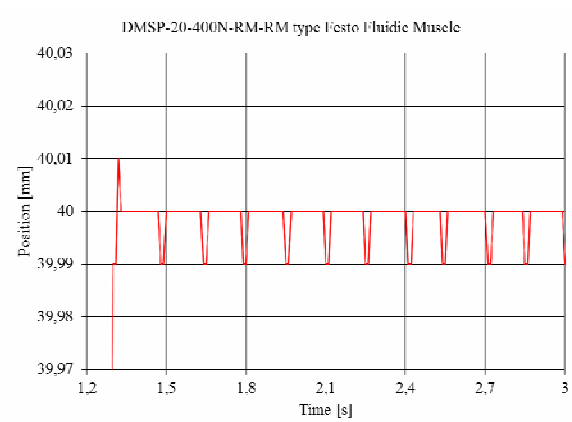

Fig. 9. Positioning at a temperature of 10 °C.

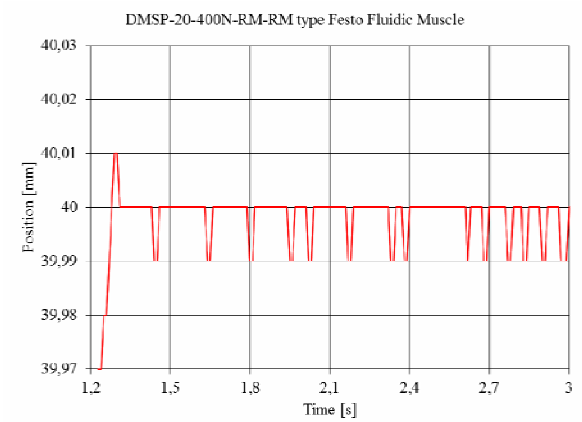

Fig. 10. Positioning at a temperature of 20 °C.

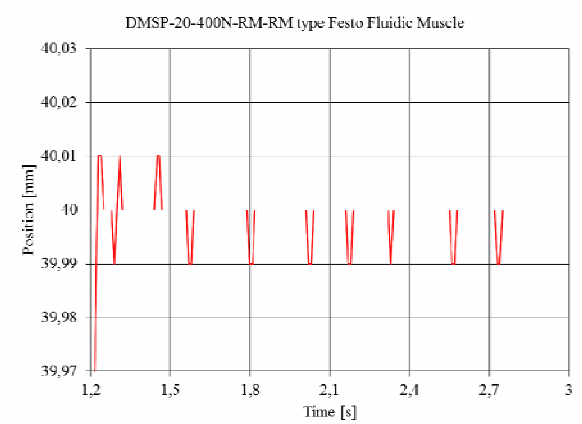

Fig. 11. Positioning at a temperature of 30 °C.

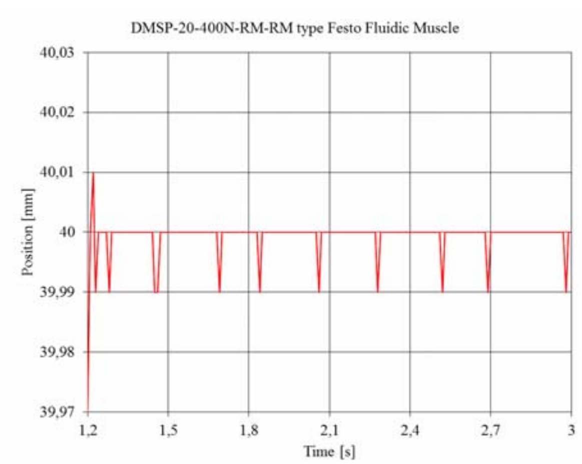

Fig. 12. Positioning at a temperature of 39 °C.

IV. CONCLUSION AND FUTURE WORK

In this paper accurate positioning of Fluidic Muscle using sliding mode controller is described and 0.01 mm steady-state error is achieved. The error cannot be favourable because of the resolution of the applied incremental encoder.

The controller is designed in LabVIEW that is capable of eliminating the influence of temperature. It is proved that the frequency of input signal influences the temperatures inside and outside the PAM and increased temperature can shorten the positioning time.

In the future the position error will be investigated using Balluff incremental encoder with 0.001 mm resolution.

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