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[1.] József SÁROSI

DYNAMIC INVESTIGATION OF A PAM ACTUATED VIBRATING PENDULUM

[1.] Technical Institute, Faculty of Engineering, University of Szeged, HUNGARY

Abstract: The dynamic model of the pneumatic muscle actuator (PMA) introduced in this paper is a new one. In the published papers the model is assumed to be an ordinary one with one-degree-of-freedom which is described with an ordinary second order differential equation and based on that a general investigation on dynamics of PMA and its behaviour is discussed. In this paper the dynamic model of the system based on our static force model is developed. The model corresponds to a muscle of any arbitrary length, arbitrary diameter with any pressure. The investigations are carried out in MATLAB environment.
Keywords: pneumatic muscle actuator (PMA), dynamic model, MATLAB environment

1. INTRODUCTION

One of the least investigated types of pneumatic actuators is the pneumatic muscle actuator or in other words pneumatic artificial muscle (PAM). PMA is applied in medicine to move the artificial limb, in rehabilitation to provide the repeated motion, and also in robotics (jumping and walking robot). It is also applied as the working element for tab punching, sorting, lifting, positioning and vibratory hopper devices (Figure 1).

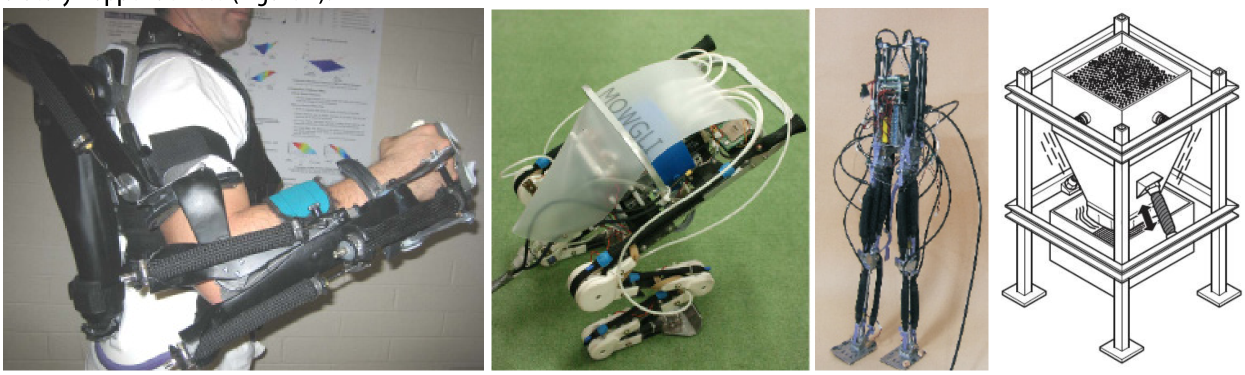

Figure 1. Usage of PMAs in different fields [1], [2], [3], [4]

Firstly, the PMA was investigated by a Russian inventor named S. Garasiev in the 1930's, but the widespread use of pneumatic systems was limited by the low-level technology. The first practical application of pneumatic muscle actuator was designed by Joseph L. McKibben in the 1950's who is often mentioned as a pioneer in PMA.

A PMA 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 PMA expands radially and contracts axially with the result that the volume increases. The force and motion produced by PMA 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.

Nowadays, Fluidic Muscle produced by Festo Company is the most investigated type of PMAs. For this study a Fluidic Muscle type DMSP-20-400N-RM-RM is selected (Table 1). According to [4], the next key features of Fluidic Muscles can be emphasized:

- ✓ high initial force and acceleration,
- ✓ judder-free operation,
- ✓ simple positioning, and
- ✓ hermetically sealed design.

It is important to note that simple positioning does not mean accurate positioning. Because of their highly nonlinear and time varying nature, PMAs are difficult to control accurately thus robust control method is needed [5].

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

This paper is organized in four sections. After Introduction in section 2 (Materials and Methods) the static and dynamic models are presented. The unknown parameters of the static force model are determined applying the optimization parameter identification method. The static model is extended with dynamic parameters. Namely, the dynamic model includes the statically determined force, too. In section 3 (Experimental Results) the dynamic model describes the dynamic properties of a vibrating system, but also determines the stiffness and the damping properties of PMA. The paper ends with conclusions and strategies for future investigation.

2. MATERIALS AND METHODS

Static and dynamic investigations and modelling of PAMs can be found in [6], [7], [8], [9] and [10]. In these professional literatures the PAMs are analysed in single or antagonistic configuration.

In Figure 2 a scheme of an embedded PMA (Fluidic Muscle) is shown. Inside the tube is the air under pressure. The tube is surrounded with a helical layer. The shape of such a muscle and the contracting and produced forces in the PMA depend on the geometric (Figure 3) and material parameters of the inner tube and outer layer.

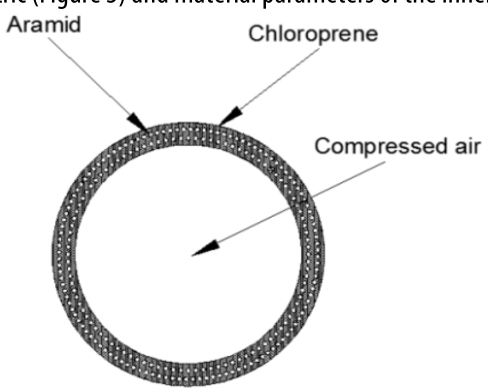

Figure 2. Model of an embedded muscle

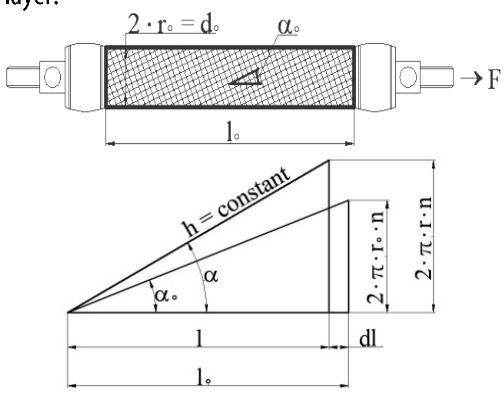

Figure 3. Geometric parameters of PMA

where *F* is pulling force, r_0, l_0, α_0 are the initial inner radius and length of the PMA and the initial angle between the thread and the muscle long axis, r, l, α are the inner radius and length of the PMA and angle between the thread and the muscle long axis when the muscle is contracted, *h* is constant thread length, *n* is the number of turns of thread.

The *F* static force produced by Fluidic Muscle can be described by the next formula [11], [12]:

$$F(p,\kappa)=(a_1\cdot p+a_2)\cdot \exp^{a_3\cdot\kappa}+a_4\cdot\kappa\cdot p+a_5\cdot p+a_6\,, \tag{1}$$

where $a_{1\text{-}6}$ are unknown constants, κ is contraction (relative displacement) and p is applied pressure. These constants are determined with MS Excel 2010 Solver which applies the Generalized Reduced Gradient - GRG method for optimization of the nonlinear problems.

Equation (1) can be used for calculating the stiffness of the PMA (for constant applied pressure):

$$k=\frac{(a_1\cdot p+a_2)\cdot a_3\cdot \exp^{a_3\cdot\kappa}+a_4\cdot p}{l_0} \tag{2}$$

In this study the oscillatory system (Figure 4) consists of a PMA and a mass *m*. The PMA can be replaced by a spring-damper system. Mathematical model of the whole system:

$$m\cdot\ddot{x}=-F_{spring}[\kappa(x)]-c[\kappa(x)]\cdot\dot{x}+m\cdot g\,, \tag{3}$$

where x is displacement, F_{spring} is nonlinear force (see (1)), g is gravity acceleration and c is the coefficient of damping:

$$c = 2 \cdot \zeta \cdot \sqrt{\frac{m}{l_0} \cdot \left[(a_1 \cdot p + a_2) \cdot a_3 \cdot \exp^{a_3 \cdot \kappa} + a_4 \cdot p \right]}, \qquad (4)$$

where ζ is the Lehr's damping ratio.

Figure 4. Oscillatory system using PMA

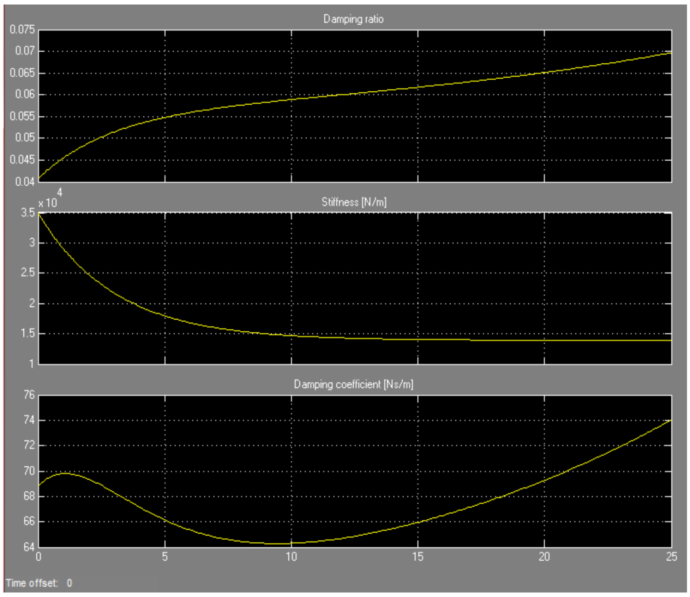

Figure 5. Damping ratio-, stiffness- and damping coefficient-contraction diagrams for a pressure of 600 kPa and a loading of 20 kg

3. EXPERIMENTAL RESULTS

Based on (2) and (4) the damping ratio-, stiffness- and damping coefficient-contraction diagrams for a PMA with 20 mm diameter and 400 mm length for a pressure of 600 kPa and a loading of 20 kg are determined (Figure 5). It can be concluded that the PMA is with variable stiffness. The stiffness increases if the pressure is increased.

Equation (3) can be used to analyse a vibrating pendulous system containing PMA. With the simulation in MATLAB environment $F_{spring} = 198$ N is obtained (Figure 6). This result verifies the method developed for the dynamic model as well as the static force model's accuracy.

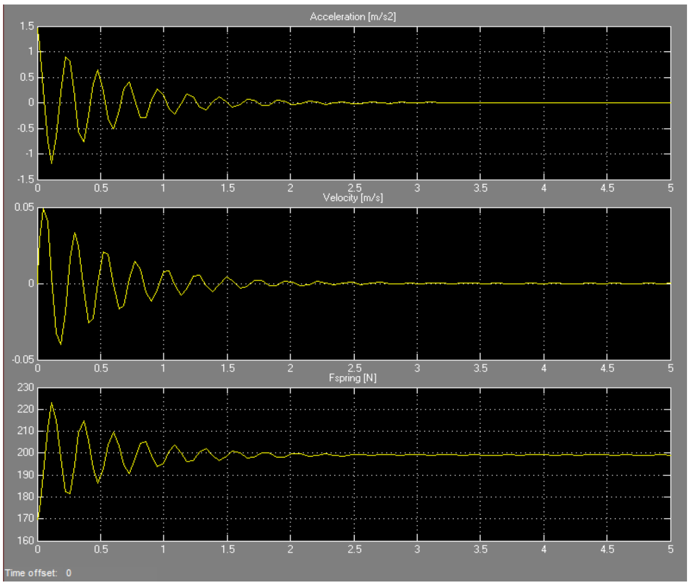

Figure 6. Dynamic behaviour of a vibrating pendulum: acceleration-, velocity- and F_{spring} force-time diagrams for a pressure of 600 kPa and a loading of 20 kg

4. CONCLUSION AND FUTURE WORK

In this paper static and dynamic models are applied for modelling the PAM and its behaviour. The dynamic model for solving of the second order differential equation gives the stiffness and damping of PAM and also of the vibrating pendulum with PMA. Future investigation will be directed toward a frictionless vibrating pendulum with PAM and also to a horizontal system with friction.

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