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Dynamic modeling of a pneumatic muscle actuator with two-direction motion

J. Sarosi [a,*,1], I. Biro [b], J. Nemeth [c], L. Cveticanin [d]

[a] Faculty of Engineering, University of Szeged, Moszkvai krt. 9, 6725 Szeged, Hungary
[b] Faculty of Engineering, University of Szeged, Mars ter 7, 6724 Szeged, Hungary
[c] Faculty of Mechanical Engineering and Informatics, University of Miskolc, Egyetem ut 1, 3515 Miskolc, Hungary
[d] Faculty of Technical Sciences, Trg D. Obradovica 6, 21000 Novi Sad, Serbia

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ABSTRACT

In this paper a new dynamic model for an actuator applied as a pneumatic artificial muscle (PAM) is developed. The model simulates the two-direction motion of a PAM caused by a nonlinear force which depends on pressure and deformation. Parameters of the acting force are obtained analytically, applying the optimal parameter identification method, and experimentally proved on the model tested on an experimental rig. In the dynamic model the stiffness and also the damping are nonlinear functions of displacement. The nonlinear displacement force causes self-excited vibrations of PAM. Influence of different loadings on the system is investigated. Using MS Excel software and MATLAB Simulink the simulation of motion of the system is given.

1. Introduction

Nowadays, many types of actuators exist which may be applied as artificial muscles in medicine (to move the artificial limb), in rehabilitation (to provide the repeated motion) and also in robotics (for jumping and walking robots). These muscles are applied as working elements for drilling machine, transportation equipment, vibration device and machines in paper industry. Various types of muscles are already produced. Let us mention some of them: the magnetostrictive, piezoelectric, polymeric, shape memory alloy actuators and also pneumatic artificial muscles.

The first investigations in PAM were done by a Russian researcher Garasiev in 1930 (see [1,2]). Due to lacks in technology, the production was limited. In 1950, Joseph L. McKibben was the first who designed an artificial muscle for practical use in medicine. McKibben is often mentioned as the pioneer in PAM. In 1980, engineers in Birdgestone Co. in Japan produced the so called Rubbertuator PAM which was installed in the Soft Arm Robots [3,4]. Recently, the most often applied are the Shadow Air Muscle (SAM), produced by the Shadow Robot Co., and the Fluidic Muscle, developed by Festo Co.

The PAM is a system which dilates or compresses due to pneumatic driving. During the radial elongation, a membrane is axially compressed and it causes an axial force. The force and the motion are straight and inline. As PAM gives only the dragging force, the motion in two opposite directions needs two mechanisms, similar as is the case in real muscles in the living bodies. One mechanism moves (drags) the load, while the other serves as a brake. During the motion in opposite direction the mechanisms commute their action [1,5–8]. These serially connected muscles are named antagonistic pair, the muscle for motion is a flexor while the braking muscle is named an extensor or antagonist [9]. There is a significant number of contracting pneumatic devices in PAM (see [1,10]). Nevertheless, they can be divided into three groups: braided muscles, netted muscles and embedded muscles. Braided muscles

* Corresponding author.
E-mail addresses: sarosi@mk.u-szeged.hu (J. Sarosi), biro-i@mk.u-szeged.hu (I. Biro), altnemet@uni-miskolc.hu (J. Nemeth), cveticanin@uns.ac.rs (L. Cveticanin).
[1] Tel.: +36 62 546 571.

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contain an elastic tube made of latex and silicone rubber, for example, and a surrounding helical shaped layer made from nylon, fiberglass or aramid along the muscle. If the muscle is pressed, the elastic tube acts radially on the layer and moves the load which is allocated on the muscle. Two types of braided muscle are usually applied: one, where both the tube and layer ends are fixed and second, only the ends of layer are clamped. The first type of muscles named McKibben ones, is mostly treated. The maximum pressure is limited with the stiffness of the tube. If the pressure is too high, the tube gets out of the layer and the muscle bursts. The maximal contraction is approximately 25%. The difference between netted and braided muscles is in the density of fastening threads in the membrane: it is higher for the braided muscles. In embedded muscles the loaded threads are settled into the elastic tube.

Recently produced PAMs have no inner moving 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 [10–14]. The power/weight ratio varies for various types of PAM and has the value: 1 kW/kg (see [12]), 1.5–3 kW/kg (after [15]), 5 kW/kg (after [16]), or 10 kW/kg (see [17]). In the paper [18] the efficiency of the system is suggested to be measured as the energy/mass ratio. In the papers [1,8,10] it is emphasized that an important property of the PAM is that for the constant pressure the force is a function of displacement. According to [1,4,7,8,11,12,19], disadvantage of PAM is that the accurate positioning and control are difficult. The reasons are: variable elastic property of the system, nonlinear and time variable behavior of the system, existence of hysteresis, step-jump pressure and also to existing of two PAM for antagonistic positioning for two-direction motion. In the paper [5] another model for two direction motion is introduced. It is a Spring Over Muscle (SOM) which model contains a spring for bidirectional motion.

The paper is organized in 5 sections. After Introduction, in Section 2, the force model of the PAM is considered. The model is innovated with new parameter values of the PAM force which are determined applying the optimization parameter identification method. In Section 3 the dynamic model of the PAM is developed. The dynamic model includes the active PAM force which causes self-excited vibrations. To prove the correctness of the static and dynamic model, experiments are done. In Section 4 the applied experimental rig is shown. The parameters of the system obtained numerically are compared with experimentally obtained ones (Section 5). The paper ends with Conclusions.

2. Contraction (elongation) force

The contraction or elongation force produced in the PAM depends on the geometric and material parameters of the inner tube and outer layer and also on the air pressure p [1].

Introducing the contraction parameter κ

$$\kappa = \frac{l_0 - l}{l_0}, \tag{1}$$

the dragging force F in the muscle is, according to [19,20], a function of κ and p

$$F(p, \kappa) = r_0^2 \cdot \pi \cdot p \cdot \left(\frac{3}{tg^2 \alpha_0} \cdot (1-\kappa)^2 - \frac{1}{\sin^2 \alpha_0} \right), \tag{2}$$

where r_0 is the inner radius of the tube before contraction, l_0 and l are the nominal length and the length after contraction, α_0 is the angle between the folded thread and the axle before contraction of the muscle.

The authors of [20] stated that the force model (2) is convenient only if the thickness of the tube wall in comparison to the inner radius of tube is approximately 1:10.

In the papers [20,21] an improvement to the model (2) is done by introducing the correction parameter ε. The suggested model is appropriate up to the boundary value of air pressure p = 200 kPa. Recently, Sarosi and Fabulya [22] extended the previous mathematical models and formed a more complex one

$$F(p, \kappa) = (a_1 \cdot p + a_2) \cdot \exp^{a_3 \cdot \kappa} + a_4 \cdot \kappa \cdot p + a_5 \cdot p + a_{,6}, \tag{3}$$

where a_1, a_2, a_3, a_4, a_5 and a_6 are unknown constants.

In this paper we suggest the parameters in Eq. (3) to be determined with the MS Excel 2010 Solver which applies the Generalized Reduced Gradient — GRG method for optimization of the nonlinear problems.

The relation (3) can be used for calculating the parameters of the system. Namely, based on the relation (3) the stiffness of the model for the constant pressure is calculated as

$$\begin{aligned} k = k(\kappa) &= \frac{dF(l)}{dl} = \frac{dF(\kappa)}{l_0 \cdot d\kappa} = \frac{1}{l_0} \cdot \frac{dF(\kappa)}{d\kappa} = \frac{1}{l_0} \cdot \frac{dF(p, \kappa)}{d\kappa} = \\ &= \frac{1}{l_0} \cdot \frac{d\left[(a_1 \cdot p + a_2) \cdot \exp^{a_3 \cdot \kappa} + a_4 \cdot \kappa \cdot p + a_5 \cdot p + a_6\right]}{d\kappa} = \frac{(a_1 \cdot p + a_2) \cdot a_3 \cdot \exp^{a_3 \cdot \kappa} + a_4 \cdot p}{l_0}. \end{aligned} \tag{4}$$

The coefficient of stiffness k will be used in dynamic analysis of the system.