International Journal of Mechanical Sciences 78 (2014) 183–192

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Prediction of the mechanical performance of McKibben artificial muscle actuator

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A R T I C L E I N F O

Article history:
Received 18 January 2013
Received in revised form
1 November 2013
Accepted 15 November 2013
Available online 21 November 2013

Keywords:
Textile composites
Braided fabrics
McKibben-type actuator
Mechanical properties
Analytical modeling

A B S T R A C T

In this study, the deformation mechanism of McKibben artificial muscle actuator is investigated through experimental and theoretical approaches. Especially, the relationship among the applied load, the actuator's length and the internal pressure for the actuator is analyzed by considering several types of energy losses associated with the actuator's deformation. The relationship between the applied load and the internal pressure of the actuator under both pressurization and decompression process can be predicted well by using our theoretical model. Also the effects of the sleeve's geometry on the performance of the actuator are discussed by using the proposed model. The contraction ratio of the actuator is the key for evaluating the actuator's performance, but enhancing the contraction ratio may result in increasing the possibility of the rubber's protrusion between threads. Moreover, based on our results, the appropriate number of threads, the way of braiding and the cross-sectional shape of a thread are proposed for improving the performance of the actuator.

1. Introduction

Pneumatic artificial muscle actuators like McKibben were first developed in the 1950s for an orthotics limb system, and have been widely used such as artificial muscles in wearable robots and wide variety of robotic systems [1–5]. Fig. 1 shows a picture of the McKibben actuator. The McKibben muscle is an actuator which converts hydraulic energy into mechanical form by transferring the pressure applied on the inner surface of its bladder into the shortening tension. The actuator is composed of an elastomeric rubber tube inside mesh sleeve. By applying high pressure inside the tube, it swells in the radial direction and contracts strongly in the longitudinal direction, which is in a similar way in human muscles. Since this type of actuator needs no heavy metallic parts or bulky electric motors, it can be characterized by lightweight, high output and flexible. Also, being intrinsically safe, the demand for McKibben actuators is rapidly growing, and many researches concerning the mechanical behavior of McKibben-type actuators have been reported up to now [6–26].

The relationship between the tensile force F and inner pressure P' for the McKibben actuator has been proposed by some researchers. For example, Schulte [6] derived an estimation equation between F and P' by considering the effect of tube elasticity. Also, Chou and Hannaford [9] revised the equation by including the effect of the actuator's thickness and that of frictional force between sleeves. Moreover, Klute and Hannaford [11] proposed another equation for the relationship between F and P' by modeling the inner bladder as an incompressive Mooney–Rivlin material. However, since the mechanisms of the McKibben actuator during the inflation and deflation deformation process, are very complex, the above equations cannot be used to predict the relationship with high accuracy.

The main purpose of this study is to provide effective guidelines for improving the performance of McKibben actuators, such as the maximum contraction ratio, which is an important index in the development of a muscle suit [4]. In order to achieve the goal, a theoretical model, even it is complex, is necessary to express the contraction ratio as a function of the tension force and the injected air pressure with sufficient accuracy. In the present study, the deformation mechanisms of the braided mesh sleeve and the rubber tube are investigated closely in relation to the lengthening and shortening deformations of a McKibben actuator, and a theoretical model for considering energy losses is proposed to predict the static tension–length–pressure relationship. Finally, the effects of sleeve's geometry on the performance of actuator are also discussed by using the proposed model.

2. Material

In this study, the McKibben actuators developed by Hitachi Medico Cooperation are used. The actuator is composed of

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0020-7403/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ijmecsci.2013.11.010

elastomeric bladder made of butyl rubber (Young's modulus E_r=2.5 MPa, Poisson's ratio ν_r=0.48) and nylon sleeve (Young's modulus E_n=2.0 GPa, Poisson's ratio ν_n=0.34).

3. Methodology

3.1. Experiment

In the present study, some experimental investigations have been conducted to obtain the static relationship between the actuator's length L and the injected air pressure P under some several loads.

Fig. 2(a) shows the geometry of the McKibben actuator. The parameters L, D and γ shown in Fig. 2(a) represent the length, the diameter and the rotational angle of a thread in a sleeve, respectively. Fig. 2(b) shows the cross section of the McKibben actuator, and Fig. 2(c) shows a spread-out mesh sleeve where n rounds (in the figure, n=2) of m (in the figure, m=3) threads of length b are wrapped around the outer surface of the rubber tube. As shown in Fig. 2(a)–(c), the angle γ changes as the actuator expands and contracts. Here, the length L and the diameter D can be expressed in terms of the angle γ given by the following:

$$L = b\ \cos\gamma, \quad D = \frac{b\ \sin\gamma}{n\pi}. \tag{1}$$

Fig. 3 shows the experiment setup of the McKibben actuator. In the experiments, a spindle, which is used to apply the prescribed tension force F, is first attached to the lower end of a suspended actuator, as shown in Fig. 3, and compressed air is gradually injected into and vented from the rubber tube, and the change of the length L is measured.

As pointed out by Kothera et al. [17], since the activation concept of McKibben actuators is for their length to shorten under an increase in applied pressure, the longitudinal contraction ratio η is the most common means of describing this phenomenon, and defined by the following equation:

$$\eta = \frac{L_0 - L}{L_0}. \tag{2}$$

Here, L_0 and L represent the length of the actuator under air pressure $P' = 0$ and $P' \neq 0$, respectively.

Also, in our experiments, two kinds of McKibben-type actuators (hereinafter, these are called Actuator 1 and Actuator 2) were used. The geometrical parameters for these McKibben-type actuators are listed in Table 1.

Fig. 1. McKibben actuator.

3.2. Theoretical modeling

As explained in Introduction, the relationship of the axial force F and inner pressure P' for the McKibben actuator has been discussed by many researchers. In this section, two kinds of estimation

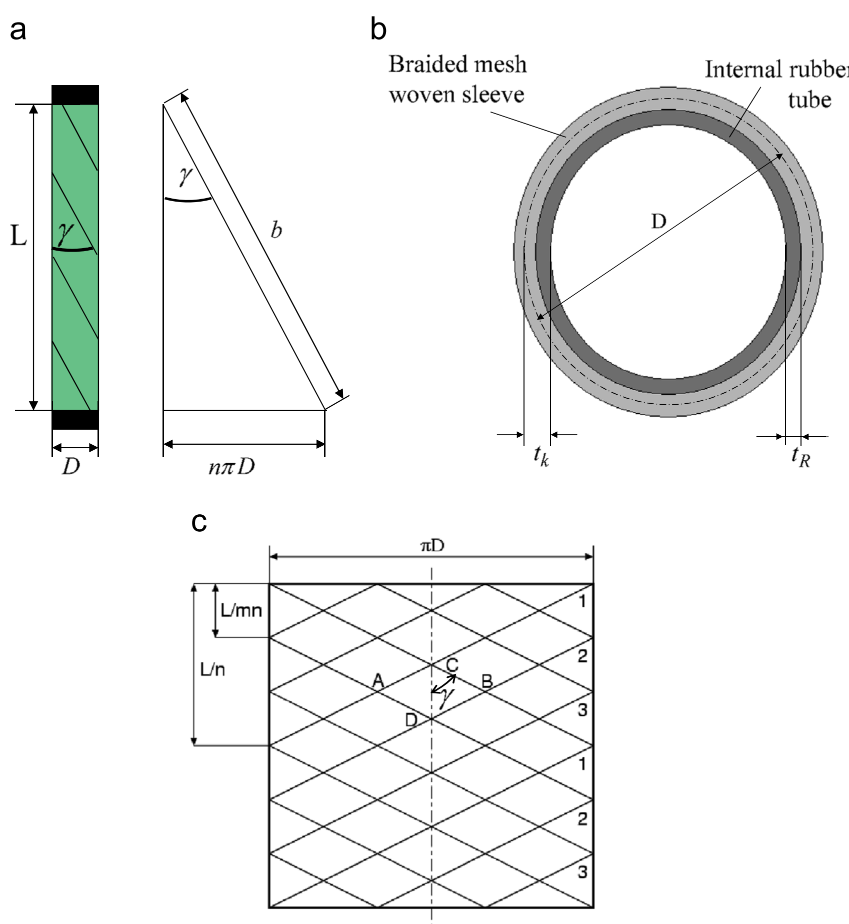

Fig. 2. Schematics of McKibben actuator. (a) Overall shape, (b) cross-section, (c) diagram of unfolded sleeve.