ARTICLE IN PRESS

Extreme Mechanics Letters ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Extreme Mechanics Letters

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

On constitutive relations for a rod-based model of a pneu-net bending actuator

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ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form 4 February 2016
Accepted 4 February 2016
Available online xxxx

Keywords:
Soft robots
Euler's elastica
Rod theories
Pneumatic actuation
Pneu-net actuator

ABSTRACT

The recent surge of interest in soft robotics has led to interesting designs and fabrication of flexible actuators composed of soft matter. Modeling these actuators to obtain quantitative estimates of their dynamics is challenging. In the present paper, a rod-based model for a popular pneumatically activated soft robot arm is developed. The model is based on Euler's theory of the elastica and is arguably the simplest possible model. Through a synthesis of experiment and theory, we find that the constitutive relations needed to accurately capture the deformation of the arm differ considerably from the simple classical relation that the bending moment is linearly proportional to a change in curvature. The present paper also provides a framework to evaluate whether future soft robot actuator designs can be captured using simple models.

1. Introduction

The design of pneumatically actuated flexible arms have been championed by several research groups for the past two decades. The most notable proponents are Koichi Suzumori and his colleagues at Okayama University [1–4] and, more recently, George Whitesides and his colleagues at Harvard University [5,6]. The latter group merged pneumatic artificial muscle technologies with emerging paradigms in soft lithography and microfluidics to produce new classes of soft biologically-inspired robots. Of particular relevance to the present paper is the so-called pneu-net architecture in which soft silicone elastomer is embedded with an array of connected air pockets that can cause each limb to bend when inflated. Modeling these flexible devices is challenging and, apart from a handful of works including [7–9], is dominated by finite element models that capture the coupling between the state of pressure in the air chambers of the arm and the resulting overall deformation. While the results produced by finite element models are interesting and compelling, they are difficult to use to generate tractable dynamic models for the arms. Developing models of the latter type are desirable for the development of control algorithms and improved understanding of the design parameters for soft robots.

The present paper seeks to examine the efficacy of using a simple rod-based model to predict the dynamics of a pneumatically actuated flexible arm shown in Fig. 1. The design of the actuator can be found on the popular online resource [10] and the arm also features in several recent articles [5,6]. We seek to develop a rod-based model for this actuator. The development has two experimental stages. In the first series of experiments, one end of the arm is clamped and the curvature of the rod as a function of pressure is measured. This data is then used to determine the constitutive relations for a rod-based model of the arm which is terminally loaded at the free end. The complexity of the resulting constitutive relations is surprising (see Eq. (10)). The series of tests that we perform to determine the constitutive relations are simple and can be used to examine future designs of soft robot arms with a goal of

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http://dx.doi.org/10.1016/j.eml.2016.02.007
2352-4316/

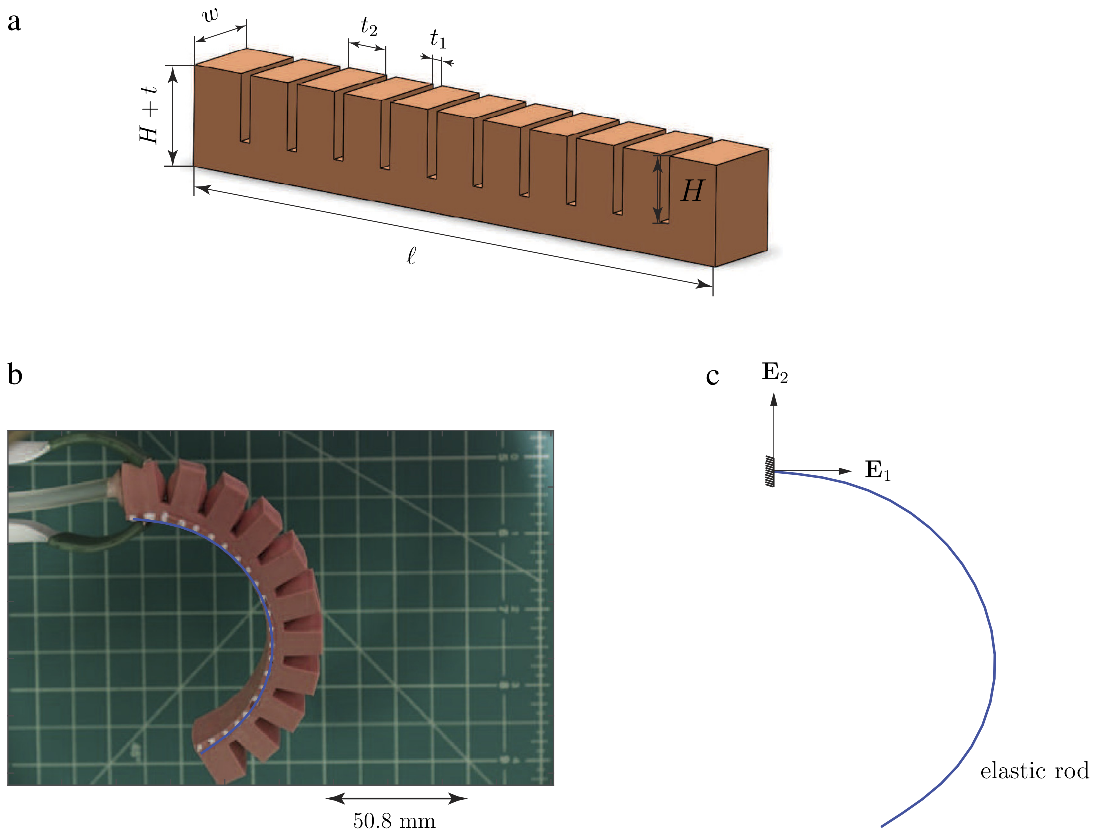

Fig. 1. The pneumatically actuated soft robot limb. (a) Schematic of the actuator with the labeling of its dimensions; (b) the actuator which is clamped at one end and free at the other subject to an air pressure of 31 kPa; (c) the elastica model for the deformed arm. The dimensions of the arm featured in (a) and (b) and throughout this paper are $w = 15$ mm, $H = 12$ mm, $t = 3$ mm, $t_1 = 2$ mm, $t_2 = 8$ mm, and $\ell = 112$ mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

producing designs that are easier to model using a rod theory. Our work is closely related to the modeling work of Majidi et al. [7] however our model and the particular soft robot arm design considered are different and, partially as a result, we find constitutive equations that are dramatically different from those presented by these authors.

2. Methods

We use the popular design of a pneu-net actuated soft robot limb shown in Fig. 1. Details on the fabrication of this device can be found at [10]. In our case, the limb is composed of silicone rubber ADDV M 4601 (2-part silicone rubber, parts A & B) purchased from Wacker Chemie AG and manufactured using a 3D printer at the Institute for Machine Elements, Engineering Design and Manufacturing at the Technische Universität Bergakademie Freiberg in Germany. The chambers on the upper surface of the actuator can be filled with air and, by controlling the pressure, the arm can be deformed. Examples of this situation are presented in Fig. 2(b).

As shown in Fig. 2, one measure of the characterization of the deformation of the arm is to measure the deformed shape of a material line embedded on the bottom surface of the arm. Clearly, as the pressure increases, the curvature of the material line increases.

It is possible to estimate the curvature using standard numerical techniques from the shape of the material line. To this end, a series of white dots (optical targets) with a distance of 5 mm are painted along the lower part of the soft robot arm. Then the arm is clamped on one side and horizontally positioned. Due to the large flexibility of the soft actuator, an out-of-plane deformation is inevitable. However, because this deformation is small compared to the bending deformation, we neglected it for the subsequent analysis. During experiments, air was pressured into the arm and its deformed shape was digitally recorded. The amount of air was gradually increased by 2 ml and the corresponding pressure was measured with a pressure gauge PCE-P50.

For analyzing the digitized images of the deformed arm, we first performed a correction of the lens distortion and then loaded the images in MATLAB. The image processing toolbox provides a convert-function from RGB to gray scale, which is used to specify a color spectrum to detect the white targets. By converting the image to black and white, only areas in the defined color spectrum remained white, while the surroundings were black. Before locating the white areas, small holes are closed and objects smaller then a defined threshold are deleted in the digital image. We then used the MATLAB image processing toolbox to export the position of the center points of the optical

Please cite this article in press as: K.M. de Payrebrune, O.M. O'Reilly, On constitutive relations for a rod-based model of a pneu-net bending actuator, Extreme Mechanics Letters (2016), http://dx.doi.org/10.1016/j.eml.2016.02.007