Sensors and Actuators A 232 (2015) 195–201

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Sensing frequency design for capacitance feedback of dielectric elastomers

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form 13 May 2015
Accepted 13 May 2015
Available online 10 June 2015

Keywords:
Dielectric elastomer
Transmission line electrical model
Capacitance sensing

ABSTRACT

Dielectric elastomers, also known as artificial muscles have produced many biomimetic robots. One advantage is their ability to provide feedback through capacitance. However when the sensing frequency is too high, the measured capacitance can underestimate the true value. In this paper, the measured capacitance of dielectric elastomer stacked and rolled configurations were shown to reduce with increasing sensing frequency. A transmission line electrical model linked this to the result of high interconnect and sheet resistances of the electrodes. A design methodology to help determine the working limits of sensing frequency is presented.

1. Introduction

Our bodies have a sensory nervous system that can transmit signals at speeds over 200 mph [1]. Coupled with a direct and lightweight muscle drive mechanism, we are able to respond rapidly to threats in fractions of a millisecond. Equalling human performance for large scale robots has been a challenge with traditional motors and gearbox transmission systems [2]. A promising approach is with dielectric elastomers (DEs) also known as artificial muscles. Praised for performance characteristics comparable to biological muscles [3,4], DEs have produced many biomimetic robots from crawling inchworms [5], six legged insects [6] to aquatic [7] and flying fish [8]. In order for DEs to meet the same level of responsiveness as biological muscles, they first need to sense as fast as possible.

Unlike traditional actuators that require external sensors for feedback, DEs can use their intrinsic electrical properties to infer position feedback. Physically, the DE is constructed by sandwiching a soft dielectric material between stretchable electrodes. To a first degree, its electrode resistance can be used as an indicator of strain [9]. However, resistive sensing is highly susceptible to environmental noise from temperature and humidity which can lead to drift [9]. Surface irregularities in the electrodes can also cause hysteresis under different strain rates [10].

A more reliable parameter for strain is the DE's capacitance [9,11,12]. While there are many traditional capacitance sensing techniques such as Charge Transfer, Successive Approximation and Sigma-Delta, unfortunately they are not compatible with most DEs as they assume a pure capacitive load. To accurately measure the capacitance of the DE, we need to take into account the voltage drop across its electrode resistance and leakage current through the dielectric membrane (Fig. 1).

This can be achieved using frequency response methods [13–15] where a periodic sensing signal is applied to the DE to interrogate the resistance and capacitance of the DE simultaneously. One such technique is the Hyper-plane approximation [15], designed originally for self-sensing DEs. This method is based on the lumped parameter model in Fig. 1 and uses linear regression of the DE's voltage and current to decouple the resistive terms from the calculation of capacitance [15].

How quickly these methods can determine capacitance depends on many factors such as the hardware sample rate and processing power. But one tuneable property is the frequency of the sensing signal. A higher sensing frequency has the benefit of a shorter period or acquisition time and also produces a better signal to noise ratio [16] due to a lower impedance of the capacitor in the DE. Hence it is advantageous to use a high frequency sensing signal typically in the order of hundreds to thousands of Hz.

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http://dx.doi.org/10.1016/j.sna.2015.05.010
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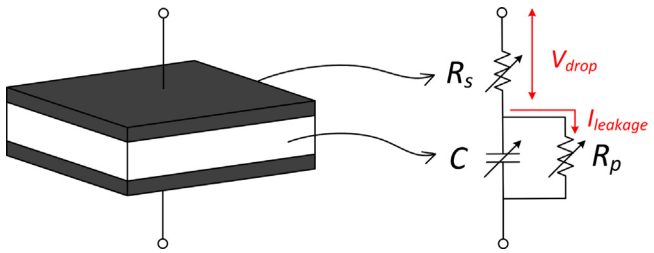

Fig. 1. To accurately measure the capacitance of a non-ideal dielectric elastomer, the voltage drop across its electrode resistance (Rs) and leakage current through the membrane resistance (Rp) needs to be considered. Note the top and bottom electrodes are typically lumped together as a single term Rs.

However just like in nature where large sizes often compromise speed, large DEs are limited in how fast their capacitance can be measured accurately. This paper demonstrates DE configurations that are particularly susceptible to capacitance errors at high sensing frequencies and explores the underlying cause of these errors.

2. Capacitance measurements

Two common designs used to amplify the force output of DEs for robotic applications are the stacked and rolled configurations. As their names imply, these configurations are constructed by stacking and rolling smaller DEs to multiply their output [17]. The capacitance sensing was carried out at low voltages to prevent unnecessary actuation and power supply limitations. This provided a static system with a benchmark capacitance to compare across different sensing frequencies. Also at this voltage, the membrane resistance (R_p) of the DE can be neglected as it is typically in the order of Giga-Ohms to Tera-Ohms [18]. A custom sensing circuit and LabVIEW programme captured the DE's raw voltage and current signals and then calculated the capacitance using the Hyper-plane method (Fig. 2).

The capacitance of two large DE stacks [19] and four DE rolls [20] were measured at multiple sensing frequencies using the Hyper-plane method [15]. The results showed a constant reading across low frequencies then started to roll off when the frequency was increased (Fig. 3). While the rolled DEs maintained a constant measurement up to 50 Hz, the stacked DEs had a much lower sensing bandwidth with stack 1 dropping off from 0.1 Hz. These results demonstrated that the capacitance measurement of these large dielectric elastomers reduced with sensing frequency. In the case of stack 1, the sensing bandwidth was limited to 0.1 Hz before its capacitance measurements became susceptible to frequency effects. This result severely constrains the responsiveness of this DE in close loop control. In order to establish the cause of the capacitance measurement roll-off, the next two sections looks into the electrical models of the stacked and rolled dielectric elastomer configurations.

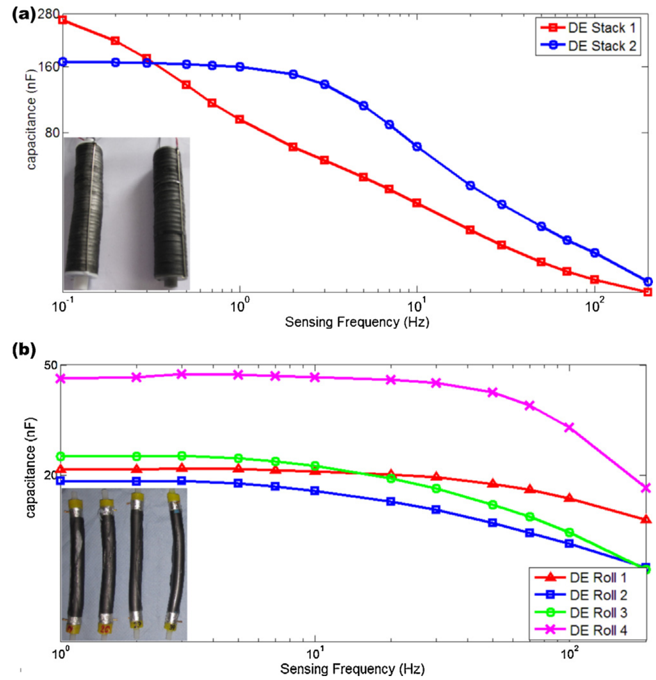

Fig. 3. The capacitance frequency sweep of (a) two different DE stacks and (b) four DE rolls all demonstrated a capacitance roll-off.

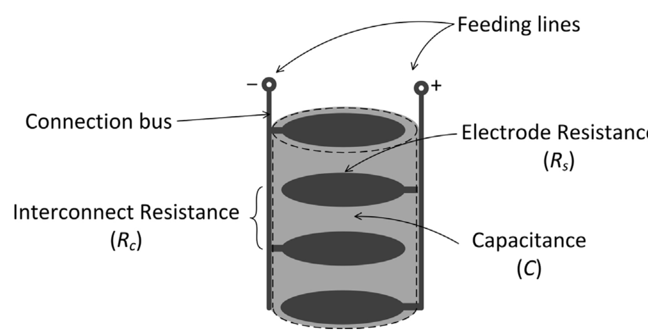

Fig. 4. The stacked dielectric elastomer configuration consists of multiple layers connected together in parallel.

3. Stacked dielectric elastomer electrical model

The stacked dielectric elastomer configuration is constructed by piling multiple DE layers on top of each other and connecting them in parallel to increase the total capacitance (Fig. 4).

Because the stack is usually connected at a single point via a pair of feeding lines, the sensing signal has to propagate through a connection bus to reach each subsequent layer. Typically the con-

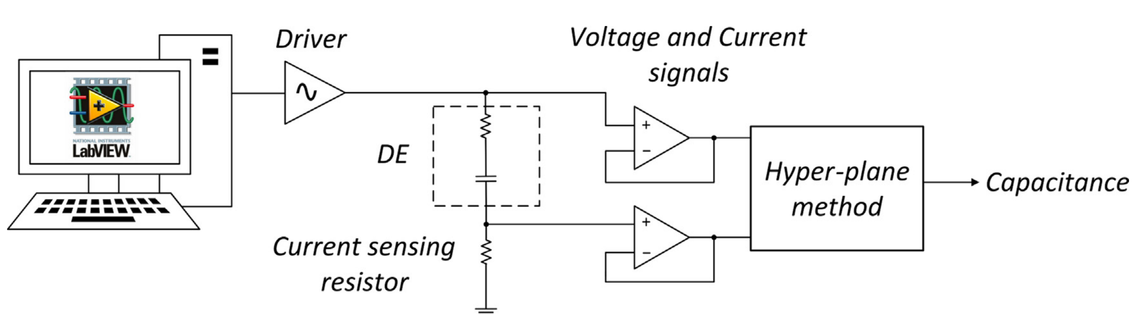

Fig. 2. The voltage and current of the DE were measured at different frequencies to calculate capacitance using the Hyper-plane method [15].