Available online at www.sciencedirect.com
ScienceDirect
Journal of the Mechanics and Physics of Solids 56 (2008) 2669–2686
JOURNAL OF THE MECHANICS AND PHYSICS OF SOLIDS
www.elsevier.com/locate/jmps

On the dynamic electromechanical loading of dielectric elastomer membranes

J.W. Fox, N.C. Goulbourne*

Center for Intelligent Materials Systems and Structures, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Received 24 August 2007; received in revised form 17 February 2008; accepted 7 March 2008

Abstract

Dielectric elastomer actuators (DEAs) have received considerable attention recently due to large voltage-induced strains, which can be over 100%. Previously, a large deformation quasi-static model that describes the out-of-plane deformations of clamped diaphragms was derived. The numerical model results compare well with quasi-static experimental results for the same configuration. With relevance to dynamic applications, the time-varying response of initially planar dielectric elastomer membranes configured for out-of-plane deformations has not been reported until now. In this paper, an experimental investigation and analysis of the dynamic response of a dielectric elastomer membrane is reported. The experiments were conducted with prestretched DEAs fabricated from 0.5 mm thick polyacrylate films and carbon grease electrodes. The experiments covered the electromechanical spectrum by investigating membrane response due to (i) a time-varying voltage input and (ii) a time-varying pressure input, resulting in a combined electromechanical loading state in both cases. For the time-varying voltage experiments, the membrane had a prestretch of three and was passively inflated to various predetermined states, and then actuated. The pole strains incurred during the inflation were as high as 25.6%, corresponding to slightly less than a hemispherical state. On actuation, the membrane would inflate further, causing a maximum additional strain of 9.5%. For the time-varying pressure experiments, the prestretched membrane was inflated and deflated mechanically while a constant voltage was applied. The membrane was cycled between various predetermined inflation states, the largest of which was nearly hemispherical, which with an applied constant voltage of 3 kV corresponded to a maximum polar strain of 28%. The results from these experiments reveal that the response of the membrane is a departure from the classical dynamic response of continuum membrane structures. The dynamic response of the membrane is that of a damped system with specific deformation shapes reminiscent of the classical membrane mode shapes but without same-phase oscillation, that is to say all parts of the system do not pass through the equilibrium configuration at the same time. Of particular interest is the ability to excite these deformations through a varying electrical load at constant mechanical pressure.

Keywords: Membrane; Dielectric sensors and actuators; Dynamics; Shells and membranes; Rubber material

*Corresponding author. Tel.: +1 540 231 0436; fax: +1 540 231 2903.
E-mail address: nakg@vt.edu (N.C. Goulbourne).

0022-5096/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jmps.2008.03.007

1. Introduction

Dielectric elastomer actuators (DEAs) are electroactive polymers characterized by large strain and low force output in comparison to non-polymeric smart materials. Dielectric elastomers have garnered significant attention as actuation sources primarily due to large strains, shape conformability, cost, and ease of fabrication. Dielectric elastomers consist of an elastic, incompressible, dielectric material coated on either side by compliant electrodes. Applying a voltage to the DEA creates an electrostatic effect, which causes thickness contraction and in-plane expansion of the dielectric elastomer. These actuators can be configured into several different shapes, which utilize a variety of actuation modes such as axial elongation and both in-plane and out-of-plane expansion. The configuration considered in this paper is an edge-clamped circular membrane. When the membrane is inflated by a bias pressure, the application of an electric field causes the membrane to deform further. On removal of the electric field, the membrane recoils to its initial inflated state. By cycling the membrane in this way, a pumping action is achieved. Applications of these materials include biomedical prosthetics and orthotics, soft robotics, pumps/micropumps, valves, and fluid transport. In most pumping scenarios, the membrane will be driven at frequencies that may lead to a breakdown of quasi-static modeling assumptions. It is this departure from the quasi-static domain that drives the need to explore the dynamic behavior of DEA membranes.

So far, there have been studies to investigate dielectric elastomers for several actuator applications such as a cardiac membrane pump (Goulbourne et al., 2004; Tews et al., 2003), an artificial bicep for orthotic and prosthetic technology (Herr and Kornbluh, 2004), a hopping robot (Pei et al., 2004), and a six-legged robot (Pei et al., 2004), just to name a few. Using DEAs for these applications invariably requires a complete understanding of how these actuators behave. To this end, various researchers have developed static as well as dynamic models to predict DEA behavior. Static models have been proposed to describe the response of extensional strip actuators (Choi et al., 2002b; Kofod, 2001; Pelrine et al., 1998), cylindrical actuators (Carpi and de Rossi, 2004), and inflated membrane actuators (Goulbourne et al., 2005). Bhattacharya et al. (2003) outlined a methodology that blends finite elasticity and electrostatics in treating actuators with an externally applied electrical force system. Lumped parameter dynamic models have been formulated by Choi et al. (2002a) and Sommer-Larsen et al. (2001), who describe small-strain (uniaxial) dynamic behavior of DEAs using linear elastic material models. Previously, the quasi-static behavior of dielectric elastomer membranes was investigated by the authors using Rivlin's approach for modeling the response of hyperelastic membranes (Goulbourne et al., 2005). Specifically, Rivlin's inflation model was adapted to account for electrostatic effects.

In this paper an experimental analysis of the dynamic response of dielectric elastomer membranes is conducted. For DEA membranes, the dynamics become complicated since the response is an amalgam of deformation mechanisms induced by a nonlinear electrical input load interacting with a nonlinear elastic material. The dynamic response of passive elastic membranes has been investigated by several researchers. Akkas (1978) and Verron et al. (1999) studied the dynamic inflation of spherical elastic membranes, and Verron et al. (2001) and Katsikadelis (2002) considered the dynamic inflation of planar membranes. More recently, Mockensturm and Goulbourne (2006) proposed a dynamic model of DEA spherical membranes. These models offer various insights into the behavior of dynamic membrane inflation.

Up until now, there has been little experimental work done on the dynamic inflation of rubber-like membranes. Various quasi-static experiments, on the other hand, have been conducted. One of the first researchers to consider the inflation of hyperelastic materials was Treloar, who extensively studied, both theoretically and experimentally, the mechanical properties of rubber-like solids. In a paper published in 1944, he conducted experiments on rubber membranes, calculating the principle strains by drawing points on the membrane surface and measuring the displacement at different inflation states (Treloar, 1944). This type of experiment developed by Treloar is known as the bubble inflation test, and has been employed by other researchers throughout the years (Derdouri et al., 1998; Joye et al., 1972; Schmidt and Carley, 1975) mainly in order to determine material parameters. More recently, Charrier et al. (1989) conducted this type of experiment on the inflation of circular and elliptical membranes made of natural latex. The elliptical membrane was shown to develop a central bulge during inflation, which inflated at a faster rate than the rest of the membrane. Verron et al. (2001) formulated a FEM model of an elliptical membrane that predicts the bulge phenomenon, and the results from experiments conducted by Charrier et al. (1989) are used to verify it.