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Research paper

Application of mechanical stretch to tune the resonance frequency of hyperelastic membrane-based energy harvesters

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ABSTRACT

Vibration-based energy harvesting has been widely investigated as a means to generate low levels of electrical energy for applications such as wireless sensor networks. However, for optimal performance it is necessary to ensure that resonant frequencies of the device match the target ambient vibration frequencies for maximum energy harvested. Here a novel resonant frequency tuning approach is proposed where the application of membrane stresses generated by different stretch ratios applied to circular hyperelastic membranes is used to tune the vibration response. Specifically, tuning via mechanical stretch is described in terms of effective stiffness theory, where the mechanical stretch of the hyperelastic membrane induces membrane tuning stresses and a corresponding reduction in membrane thickness. A finite element model (FEM) using ANSYS agrees well with an analytical model of the tuned hyperelastic membrane. Lastly, using a mass-loaded circular membrane vibration model, the effective resonant frequency of the energy harvester can be determined as a function of changes in membrane tension due to the applied stretch. Preliminary experiments verify the resonant frequencies predicted from the analytical and FEM models as a function of different levels of mechanical stretch, centrally-loaded added mass, and membrane initial thicknesses. The proposed mechanical stretch tuning approach for hyperelastic membranes provides an alternative tuning strategy to enable energy harvesting from different ambient vibration sources in various environments.

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1. Introduction

Energy harvesting is a rapidly growing field which seeks to generate small but useful levels of electrical energy from mechanical vibrations present in most environments. ID Techex [1] summarized the energy harvesting market and discussed potential applications in areas such as healthcare, electronics, and automotive applications, with emerging uses such as a potential power source for micro/nanorobots also envisioned [2]. A particularly compelling application is to replace the batteries of individual sensor nodes comprising wireless sensor networks due to the potential of small size, ease of implementation, and the ability to facilitate the placement of sensors in inaccessible locations, suggesting energy harvesting may have tremendous impact when integrated with ubiquitous wireless microsensors used to provide continuous monitoring of machine and structural health [3,4]. A comparative analysis suggests that mechanical vibration shows potential as a high power density and long lifetime energy source among a variety of potential ambient energy harvesting sources [5], and thus a vibration-based energy source is the focus of the current work.

1.1. Frequency tuning for vibration-based energy harvesting

A comprehensive discussion of vibration based energy harvesting for wireless, self-powered microsystems is available in the literature [6]. Generally, it is desired to ensure that the resonant frequencies of an energy harvesting device match the ambient vibration frequencies to maximize the energy harvested, and a review of strategies for tuning the frequency range of vibration based energy harvesting has been described elsewhere [7]. For example, Challa et al. [8] presented a resonance frequency tuning approach using a magnetic force applied perpendicular to a cantilever beam, achieving ±20% of the unturned frequency based on the mode (attractive, repulsive) of the magnetic force and the separation distance between the magnets. Zhu's research group [9] designed a horizontal tunable electromagnetic vibration-

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based micro-generator via induced variable axial magnetic forces. More recently, a two-dimensional resonant frequency magnetic tuning approach was developed which further generalizes these approaches [10]. The tuning model is based on effective stiffness theory, where the effective resonant frequency of the system is related to two variable stiffness terms which the two-dimensional placement of the magnets adds to the system. A two-dimensional tuning method may be useful, in particular, for applications where space constraints impact the available design space of the energy harvester. In addition, approaches developed at small length scales to tune the effective stiffness of NEMS and MEMS devices operating at very high frequencies [11–13] may be adapted for energy harvesting applications targeting appropriate frequencies. From a systems-level perspective, one must obviously account for any energy required to tune the harvesting device when evaluating the efficiency and performance of a tunable energy harvesting system [14–16].

In addition to the cantilever-based energy harvesting geometries typically described above, a membrane-based energy harvester could also be implemented. For example, Rezaeisaray et al. [17] designed and analyzed an SU-8 membrane-based energy harvester which uses a nonlinear stiffness effect based on a Duffing oscillator to obtain a frequency bandwidth of 146 Hz. Mo et al. [18] developed a theoretical model for a piezoelectric circular membrane subjected to pressure fluctuations, concluding that the optimization of energy harvesting performance is highly dependent on the ratio between the thickness and radius of the membrane. A piezoelectric circular membrane array connected in parallel was shown by Wang et al. [19] to increase the device performance compared to the power generated from a single membrane. In addition, Palosaari [20] conducted an experimental study that suggests that pressure fluctuations could be a potential method for tuning the resonant frequency of membrane-based energy harvesters. (Note that the term *pre-stress* used in [20] refers to the membrane out-of-plane stress, which differs from its use to denote the in-plane membrane stress as used below.) Recently, membrane geometry-based energy harvesters have become increasingly attractive as a means to leverage the properties of emerging soft materials, which could be utilized to target lower frequency vibration sources. In particular, hyperelastic polymers with large strain capability are investigated here.

1.2. Hyperelastic and electroactive membranes

Piezoelectric materials (including single crystals, ceramics, and polymers) are commonly used materials for vibration-based energy harvesting due to their higher efficiencies and specific power output. In recent years, in addition to those widely used piezoelectric materials, electroactive polymers, which can deform in response to the application of an electrical stimulus, have been explored for potential mechanical energy harvesting applications [21]. Among electroactive polymers, dielectric elastomers (DEAs) have drawn great attention due to their outstanding overall performance [22], including large elongation, high speed of response, and high energy density. Among commercial products [23–26], 3M VHB 4910 acrylic tapes show impressive performance due to their high dielectric constant ($\varepsilon_r = 4.7$) and the potential for high actuation strain up to 6 times the axial stretch in both planar directions [26] and will be the focus of the work presented here.

Because relatively high strains (well over 100%) can be produced through mechanical stretch of dielectric elastomers, DEAs typically demonstrate hyperelastic material behavior, where the stress-strain relationship derives from a strain energy function. The mechanical behavior of hyperelastic materials can be characterized by different functional forms of the strain energy, and the most common of which are those first described by Yeoh [27], Ogden [28] and Mooney-Rivlin [29]. Previous work found that when using the Ogden and Mooney-Rivlin material models the membrane thickness decreases in an unstable manner, with the resulting membrane stress overestimating the material response [30]. Thus the Yeoh form of the strain energy function is used in this work, with the necessary parameters for the Yeoh hyperelastic material model for 3M VHB 4910 listed in Table 1 [30].

Table 1
Material parameters of hyperelastic membrane.

Membrane (3M VHB 4910)			
Symbol	Description	Value	Units
r_0	Initial radius	19.05	*mm*
t_0	Initial thickness	1000	μm
λ	Stretch ratio	1.1–5	*unitless*
ε_r	Dielectric constant	4.7	*unitless*
E	Young's modulus	1.44	*MPa*
α	Thermal expansion coefficient	1.8×10^{-4}	*m/m-°C*
C_{10}		0.0693	*MPa*
C_{20}	Yeoh model	-8.8×10^{-4}	*MPa*
C_{30}		16.7×10^{-6}	*MPa*

2. Mechanical stretch tuning mechanism

In this section a model of resonance frequency tuning via mechanical stretch of a hyperelastic membrane-based energy harvester is described. Based on effective stiffness theory, the effects of variable membrane tension on the overall device stiffness are used to tune the effective resonant frequency of the system. Section 2.1 describes the general tuning model for energy harvesting membranes via the application of applied tension. Section 2.2 then presents the relationship between the applied stretch ratio and the membrane tension of a circular hyperelastic membrane. The vibration of a central mass-loaded circular membrane as a function of membrane tuning tension is then presented in Section 2.3, with a theoretical calculation of membrane stretching stiffness derived which can be used in the effective stiffness model to tune the primary resonant frequency of a stretched hyperelastic membrane.

2.1. Hyperelastic membrane tuning via mechanical stretch

A theoretical lumped parameter tuning model for stretching of a membrane-based energy harvester is shown in Fig. 1. When the membrane is subjected to mechanical stretch, the membrane radius expands from r_0 to r_1, and the thickness contracts from the original thickness $t_0$to the new thickness t_1. Following the common approach of modeling a vibration-based energy harvesting device as a spring-mass-damper system [31], the tuning model for a stretched membrane-based vibration energy harvester is schematically shown in Fig. 1b. The model consists of a spring of variable stretching stiffness (which can be changed to tune the resonant frequency), a mass, and dampers denoted as mechanical dashpot b_{m} and electrical dashpot b_{e} which represent the mechanical losses and the mechanical energy transformed into electrical energy, respectively. Here the stretching stiffness $k_{stretch}$ is related to the external applied stretching forces and can be determined as a function of the stretch ratio of the hyperelastic membrane as discussed in Section 2.3 below.

Based on the effective stiffness tuning model, the effective frequency $f_{stretch}$ of the energy harvester tuned via mechanical stretch of the membrane can be expressed as shown in Eq. (1), where $k_{stretch}$ is the membrane stretching stiffness and m_{eff} is the effective mass of the system.

$$f_{stretch} = \frac{1}{2\pi}\sqrt{\frac{k_{stretch}}{m_{eff}}} \tag{1}$$

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