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Parametric study of a novel vibro-impact energy harvesting system with dielectric elastomer

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HIGHLIGHTS

- Novel vibro-impact energy harvesting system with dielectric elastomers is proposed.
- Complex dynamics of the device is studied under an external harmonic excitation.
- Output energy depends on an inclination angle of the device and initial conditions.
- Presented results can be used to optimize the device design and inclination angle.

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ABSTRACT

A vibro-impacting mechanical system with two dielectric elastomeric membranes for harvesting energy from ambient vibrations is proposed. The purpose of the paper is to study the system performance under different angles of its inclination with respect to a horizontal position in the effort to determine the best layout of the system. The dimensional, electrical and dynamic parameters of the dielectric elastomeric membrane are analysed and then used to numerically estimate the output voltage of the proposed system. The electrical properties of the dielectric elastomer membrane are validated experimentally, and the dynamic behaviors of the system are fully studied under different initial conditions. The system output performances under harmonic excitation are further discussed. The approach and an application example for the design of the proposed device subjected to a certain vibrational environment is presented.

1. Introduction

Ambient vibrations are a source of renewable energy that can be converted into electricity [1]. Energy harvesting (EH) devices utilizing ambient vibrations can produce high energy density at low cost and various scales, in particular small-size and micro scales. This makes these devices suitable for many applications, e.g. in automotive [2,3], aeronautical [4], wireless sensors networks [5,6], wearable devices [7] and other sectors [8–10].

There are three conventional transduction methods of converting vibration energy into electrical energy: electromagnetic, electrostatic and piezoelectric. The transduction process of electromagnetic (EM) EH is based on Faraday's law of induction. Poor scaling qualities make EM EH unsuitable for micro scale applications, where it can only produce a small voltage output. Moreover, due to the dependence of the induced voltage on the relative velocity of a magnet and coil, larger scale applications, like linear generators for wave energy converters, have also been mainly unsuccessful so far. Electrostatic (ES) EH is based upon the use of a variable capacitor with one plate fixed and another connected to a vibrating body. This method has also been of limited applicability because it can only produce rather low energy density. Thus, up to now the majority of investigations on EH from ambient vibrations have been focused on the use of piezoelectric (PE) materials [11–15]. PE EH devices have a simple structure and relatively high energy conversion efficiency. However, these devices are less versatile than desired [16] and have certain limitations and shortcomings, one of which is their ability to generate only a relatively small amount of energy. These factors restrict the areas of application of PE EH devices.

In recent years, dielectric elastomers (DEs) have shown a great promise in converting vibration energy to electricity. A DE generator,

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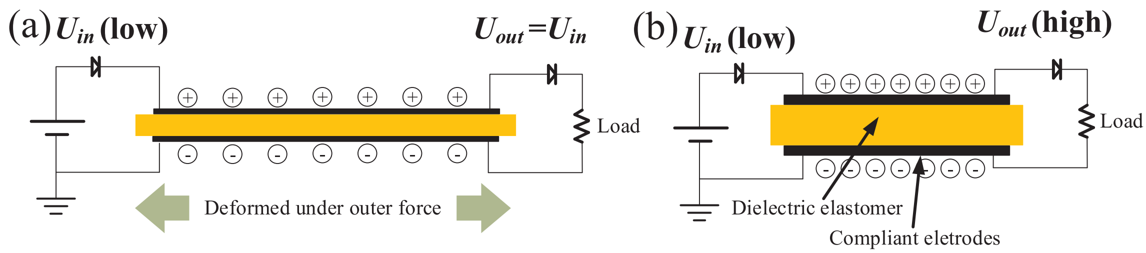

Fig. 1. Operating principle of a DE-based energy generator.

first proposed by Pelrine et al. in 2001 [17], consists of a variable capacitor made of highly deformable elastomeric material (e.g. acrylic, silicone, polyurethane, etc.) sandwiched between flexible electrodes [18–21]. Suo et al. [22] established the DE theory based on thermodynamics and continuum mechanics. Following their work, many studies related to DE generators have been published. The basic material properties, failure mechanisms and identification methods have been investigated [23–25]. A detailed model that describes the four cyclic phases of DE-based energy harvesting was developed in [26], whereas the influence of the material dielectric coefficient on the EH performance and bias voltage was studied in [27].

Compared with PE generators, DE-based generators can convert linear, nonlinear or rotational motion within a wide frequency range [28]. Major advantages of DE-based generators are their high energy density (up to 0.4 J/g); which is at least an order of magnitude higher than that of EM, ES and PE generators [29] (especially at low frequencies); and high deformability. Moreover, the highest power density that has been achieved in DE is 3.8 $\mu W/mm^3$ [5], which is much higher than that in EM (2.21 $\mu W/mm^3$ [30]), ES (2.16 $\mu W/mm^3$ [31]), and PE (0.375 $\mu W/mm^3$ [32]). Other DE advantages include low mass density, good electro-mechanical conversion efficiency, chemical resistance to corrosive environments, and moderate cost [33].

The main principle of DE EH is based on stretching a DE membrane used as a capacitor core by applying an external force or pressure in or out of the membrane plane, depending on the design and application of the DE converter. For example, in a novel wave energy converter (WEC) a DE membrane is stretched by compressed air pushed into its chamber by waves [34], which is similar to the oscillating water column principle. Recently, another idea of using DE in a WEC to harness energy of a surge motion has been reported [35]. However, there are still only a few works which have considered different design solutions of DE generators for harvesting vibration energy.

A dynamic vibro-impact (VI) system [36–41] offers an interesting option for designing a DE generator to harvest vibration energy. Usually, such a system consists of a spring, mass, damper and mechanical stopper, which limits the amplitude of the mass oscillations. Energy associated with impacts between the mass and the stopper can be harnessed. Up to now, VI EH devices with PE materials have been mainly proposed and investigated [42–46]. A novel VI EH device using DE was recently proposed by the authors and its basic performance characteristics were studied [47]. In particular, it was shown that the performance was governed by very rich, complex and highly nonlinear behaviour of the VI system with stoppers made from DE, which could be analysed only numerically and strongly depended on the device layout.

Since [47] was the first study of the proposed device it was limited to the performance of the system oscillating only in a horizontal plane. More realistically, oscillations can also occur in planes inclined to the horizontal plane so that an inclined layout of the device can be more efficient in terms of energy conversion. However, to analyse such a layout the effect of gravity on the VI system behaviour needs to be taken into account and that makes the analysis more complicated. Thus, the present paper aims to further investigate the performance of the novel DE EH device considering various inclined layouts. Results of the paper can be used to optimise the device design, in particular in the context of selecting an optimal inclination angle.

The basic principles and the dynamic model of the proposed DE-based EH device are described in Section 2 of the paper. Section 3 presents experimental validation of the electrical performance of the DE membrane along with results of the numerical simulations of the device behaviour under various initial conditions and excitation parameters. The influence of the excitation parameters on the device performance is discussed in Section 4, which also includes an example illustrating how the results can be used for real applications. Conclusions are drawn in Section 5.

2. DE generator and its modelling

2.1. Basic principle of DE generator

A DE-based generator consists of a thin elastomer membrane between two electrodes, i.e., a deformable capacitor with a DE core. The principle of power production by the generator relies on an increase in the electrical potential due to mechanical deformation of the elastomer. The capacitance of the DE capacitor is:

$$C = \frac{\varepsilon_0 \varepsilon_r A_{DE}}{h} = \frac{\varepsilon_0 \varepsilon_r V}{h^2} \tag{1}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ is the vacuum permittivity, ε_r is the relative permittivity of the DE, A_{DE} is the effective area (i.e. area coated on each side by electrodes), h and V are the thickness and volume of the elastomer, respectively. The second equality in Eq. (1) can be written because the volume of an elastomer is a constant due to the elastomer incompressibility, i.e., $A_{DE}h = V =$ constant. Another important formula relates the charge, Q, on the membrane and voltage U: $Q = CU$.

Suppose that a DE membrane undergoes a mechanical deformation that causes an increase in the effective area and reduction of the membrane thickness, as shown in Fig. 1(a). Therefore, according to Eq. (1), the capacitance of the deformed DE membrane increases. The deformed DE membrane is then charged from an electrical power source with a constant input voltage U_{in}. Thus, the energy stored in the DE capacitor is $E_1 = QU_{in}/2$, where Q is the amount of charges across the DE membrane. Minor deformation due to electro-elastic pressure can be neglected because it is relatively small compared with the total deformation of the DE membrane. As the mechanical force causing the deformation is removed, the DE shape is restored instantaneously, while the amount of charges still remains temporarily equal to Q, as shown in Fig. 1(b). Therefore, according to charge/voltage relationship, the output voltage between the electrode layers (U_{out}) increases due to the decreased capacitance of the DE membrane and the energy stored in the DE capacitor increases to $E_2 = QU_{out}/2$. Thus, charges with elevated electrical potential can be used for energy harvesting.

2.2. Model of an inclined dynamic VI system

In order to convert vibrational energy to electrical energy by taking advantage of DE, an inclined VI model is presented in this paper, as shown in Fig. 2. The system comprises a cylinder, an inner ball sliding freely inside the cylinder and two pre-stretched circular DE membranes