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On energy harvesting from a vibro-impact oscillator with dielectric membranes

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ABSTRACT

A vibro-impact mechanical system comprising of a ball moving freely between two dielectric membranes located at a certain distance from each other is studied. The system generates electricity when the ball moving due ambient vibrations impacts one of the membranes. The energy harvesting principle of the proposed system is explained and then used to formulate a numerical model for estimating the system output voltage. The dynamic behavior and output performance of the system are thoroughly studied under a harmonic excitation, as well as different initial conditions and various values of the restitution coefficient of the membranes. The delivered research results are useful for selecting the system parameters to achieve its optimal output performance in a realistic vibrational environment. Potential application of the proposed system for energy harvesting from car engine vibrations is presented.

1. Introduction

Energy associated with various sources of ambient vibrations is considered to be renewable, clean and can be converted into electricity [1]. Energy harvesting (EH) devices utilizing ambient vibrations can produce high energy density and be of low cost and small size, which can very useful for automotive [2–4], aeronautical [5], wireless sensors networks [6,7], wearable devices [8], and other applications [9–11].

There are three conventional transduction methods converting vibrational energy into electrical one: electromagnetic, electrostatic, and piezoelectric. A triboelectric effect has also been rapidly gaining popularity. The transduction process of electromagnetic (EM) EH is based on Faraday's law of induction. Poor scaling qualities make EM EH unfeasible for micro scale applications where it can only provide a rather small voltage output, while for large scale applications such devices become heavy and bulky. Due to dependence of the induced voltage on the relative velocity of a magnet and coils, the larger size applications, like linear generators for wave energy converters, have also not been successful so far. Electrostatic (ES) EH is based upon the use of a variable capacitor with one fixed plate and one plate connected to a vibrating body. Its advantages and disadvantages are both related to the requirement for an input voltage. Since the output voltage is quadratically proportional to it, the higher the input voltage the larger the energy gain. The majority of investigations on EH from ambient vibrations have been focused so far on the use of piezoelectric (PZT) materials [12–16]. These PZT EH devices have simple

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structure and relatively high energy conversion efficiency. However, these devices can only work within a limited frequency for a special type of motion [17] and produce relatively small power density. These factors greatly restrict the areas of application of PZT EH devices.

In recent years, dielectric elastomers (DEs) have shown their advantages for vibrational energy conversion and attracted much attention from researchers. DE generators [18–21] are fabricated using highly flexible elastic materials (such as acrylic, silicones, polyurethanes, etc.), sandwiched between flexible electrodes that convert mechanical work to electrical energy. DE-based generators can convert linear, nonlinear or rotational motion under a wide frequency range [22]. DEs also possess such advantages as a low mass density, large deformability, high energy density, rather good electro-mechanical conversion efficiency, moderate or low cost, solid state monolithic embodiment with no sliding parts, good chemical resistance to corrosive environments, silent operation, as well as easiness to manufacture and recycle [23]. If to add to those the ability of DEs to work at micro scale and diversity of structure, it is clear that they have significant potential for being used in EH from vibrational energy.

To convert vibrational energy into electrical one DE acts as a variable capacitance capacitor. A DE generator was first proposed by Pelrine et al. back in 2001 [24]. Suo et al. [25] established the DE theory based on thermodynamics and continuum mechanics. Following their work, many researches related to the DE use for electricity generation have been published. The basic material properties, failure mechanisms and identification methods have been studied [26–28]. A detailed model that describes the four cycling phases of DE-based EH was developed in [29], whereas the influence of the material dielectric coefficient on the EH performance and bias voltage was considered in [30]. These researches have emphasized that 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 the specific energies of EM, ES and PZT generators [31], especially at low frequencies, and high stretching capabilities. The highest power density that has been achieved with DE is up to 3.8 $\mu W/mm^3$ [5], which is much higher compared to EM (2.21 $\mu W/mm^3$ [32]), ES (2.16 $\mu W/mm^3$ [33]) and PZT (0.375 $\mu W/mm^3$ [34]). These researches have demonstrated the benefits of using DEs in EH and laid the foundation for further investigations of DE-based EH systems.

The main principle of DE EH is based on the deformation of a DE material in or out of plane by applying either an external force or pressure, depending on the design and application of the DE generator. For instance, in a novel wave energy converter (WEC) [35] a membrane made of a DE material is stretched by pressured air pushed into a chamber by waves, which is similar to the oscillating water column principle. Another idea of a WEC that utilizes a DE material and harness energy of surge motion has also been recently reported [36]. Many papers are currently available on the material properties of DEs [26,28]; however, only a few have studied various concepts of DE-based generators and their performance that limits the application of DE for vibrational EH in real life. Therefore, there is a clear need for further study of DE-based generators and their EH performance under simulated or natural ambient vibrations.

Irrespective of a conversion method used, it is apparent that the effectiveness of a parametric [37,38] or nonlinear [39] EH system is higher than that of a linear system in realistic environmental conditions, where the excitation frequency is not fixed. Dynamic systems with a vibro-impact (VI) interaction [40–43] belong to a class of strongly nonlinear systems that are used in various machines [44,45] and can be used as vibro-impact dampers and nonlinear energy sinks [46–49]. Impacts are usually associated with high kinetic energy, which can be harnessed. VI systems consist of a mass-spring element colliding against a motionless stopper, but in some advance cases a motion of two mechanical systems can be coupled through impacts [50]. Apparent difficulty in dealing with a VI motion comes from very rich, complex and highly nonlinear behavior and bifurcation pattern of such systems under deterministic [43,44,51,52] and stochastic load [53] and as a result should be studied numerically for each and every new layout. Several layouts of VI EH devices have been reported based on PZT material [54–57] and electromagnetics [58–60], whereas a DE-based dynamic VI system was studied in our previous work [61,62].

Our previous studies of the DE EH device were focused on the introduction and basic analysis of the system, whereas the restitution coefficient between the membrane and the ball was, for simplicity, set to unity. Building on those works, the dynamic behavior and the EH performance of the DE-based dynamic VI system are further studied in this paper. Results of the study can be used to optimize the device design. The basic principles of EH using the DE-based device are introduced in Section 2. The dynamic behavior and EH performance of the device for different initial conditions as a function of excitation amplitude and frequency are thoroughly studied in Section 3. A discussion of how the results can be used to optimize the device performance in a real vibrational environment, including an illustrating example, is presented in Section 4. Conclusions are drawn in Section 5.

2. Basic principles

The principle of power generation by a DE generator relies on increased capacitance due to mechanical deformation of the elastomer. In order to convert vibrational energy into electrical one by taking advantage of DE, an inclined vibro-impact model has been presented [62], as shown in Fig. 1. The system comprises a cylinder, an inner ball sliding freely inside the cylinder and two pre-stretched circular DE membranes at both ends of the cylinder. Both pre-stretched membranes are sandwiched between compliant electrodes and wires are connected to both sides of each membrane. Each membrane is fixed between two identical cylindrical frames and then connected to the cylinder. The system is inclined with an angle of β ($0^\circ \leqslant \beta \leqslant 90^\circ$) between the direction along its symmetry axis (denoted as z-direction in this paper) and the horizontal plane.