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Design of simulation experiments to predict triboelectric generator output using structural parameters

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ABSTRACT

Ambient energy harvesting has gained considerable interest as a potential power source for portable electronic devices and wireless sensor networks since the last decade. Triboelectric generators based on contact electrification and electrostatic induction have recently emerged as a promising mechanical energy harvesting technique. However, due to the complex nature of contact electrification, the underlying mechanism of charge transfer between two contacting surfaces when at least one of them is insulating, remains an unresolved problem in physics. Determining and controlling surface charge density is therefore a significant problem, making prediction of the output voltage of a triboelectric generator a challenge. In addition, structural parameters such as area, gap, and dielectric thickness, which affect the output voltage of the generator, have previously been investigated individually but their interaction effects have not been taken into account. Presented here, for the first time, is a method to design finite element simulations of triboelectric generators using experimentally derived surface charge density as a boundary condition in order to investigate the overall effect of the structural parameters on generator's output voltage. Two metamodels have been established as a result of a 2^3 full factorial design and a central composite design. The models have been experimentally verified, and have shown to predict the output voltage within one order of magnitude.

1. Introduction

A growing demand for portable electronic devices and wearable sensor networks coupled with advances in low power design has stimulated worldwide interest in ambient energy harvesting [1,2]. Triboelectric generators (TGs) based on contact electrification and electrostatic induction have recently emerged as a promising mechanical energy harvesting technique because they offer several benefits such as high output power density, high energy conversion efficiency, low weight, cost-effective materials, and high adaptability design to different applications [3,4]. The theoretical systems of the four fundamental modes of TGs have been thoroughly analyzed to show their different output characteristics [5]. Furthermore, a TG-based self-powered system that incorporates a power management circuit and a low-leakage energy storage device has been shown to provide continuous DC power in a regulated manner to meet mW requirement of personal electronics [6]. This paper focuses on the vertical contact-separation mode (hereinafter referred to as the contact-mode), which has been used to harvest energy from finger typing, engine vibration, human walking, and biomedical systems. In addition, it has

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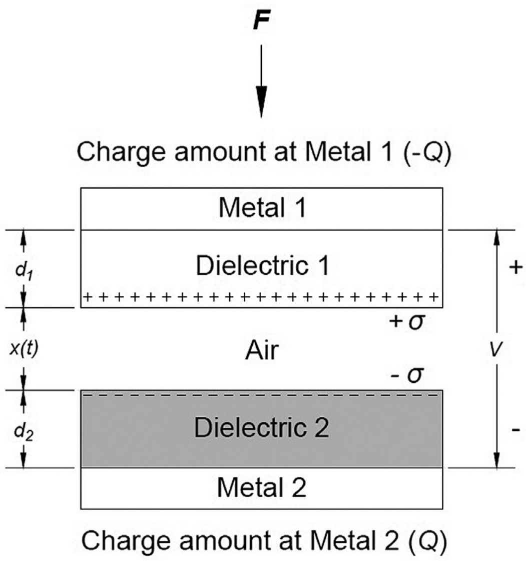

Fig. 1. Theoretical model for dielectric-to-dielectric contact-mode triboelectric generator.

also been developed to build self-powered sensor systems, including magnetic sensors, pressure sensors, vibration sensors, mercury ion sensors, and acoustic sensors.

The electrodynamics based theoretical model for dielectric-to-dielectric contact mode TG [7], defines a V-Q-x relationship given by:

$$V = (-Q/A\,\varepsilon_0)(d_0 + x(t)) + \sigma x(t)/\varepsilon_0 \quad (1)$$

where V is output voltage between the electrodes, Q is the amount of transferred charge between the electrodes, x is the gap between the two dielectric films, A is the area of the dielectric films coming in contact, and d_0 is the effective thickness constant, which is equal to $d_1/\varepsilon_{r1} + d_2/\varepsilon_{r2}$. In Fig. 1, the two dielectric films with thickness d_1 and d_2, and the relative dielectric constants ε_{r1} and ε_{r2}, respectively, are stacked face to face as two triboelectric layers. Metal electrodes are deposited on the non-contact side of these layers. The gap (x), between the two dielectric layers changes due to applied mechanical force (F), assuming dielectric 2 deposited with metal 2 is stationary. After coming in contact, the two dielectric layers will have opposite static charges with equal density σ, as a result of contact electrification. As F is removed, x increases and a potential difference V is induced between the two electrodes. If the two electrodes are connected by a load, free electrons flow from one electrode to the other to balance the electrostatic field. When contact is made again, the potential drop due to triboelectric charge disappears, and the induced electrons flow back in the reverse direction. Thus, a periodic contact and separation between the two materials results in an AC output in the external circuit.

Contact electrification or triboelectric effect is one of the oldest and most universally existing phenomena, and has attracted many investigations. However, the underlying mechanism of charge transfer between two contacting surfaces when at least one of them is insulating, remains an unresolved problem in physics. The governing phenomena spans different scales of material behavior, and several competing possible mechanisms such as electron transfer, ion transfer, bond dissociation, chemical changes to surface, and material transfer, have been proposed. Depending on structure and morphology of insulating materials, and environmental conditions, different mechanisms may be involved [8–11]. Characterizing the charged surfaces and studying the charge transfer mechanisms often requires specialized equipment [12]. Owing to these uncertainties, it is difficult to determine and control the surface charge density. Therefore, the theoretical model described above, although helpful as a guide in rational design of the TG structure, is not sufficient to appropriately predict the output voltage of a contact-mode TG. This problem also extends to finite element simulations, wherein σ is a boundary condition. Finite element simulations of the electric potential distribution in triboelectric nanogenerators performed by assuming triboelectric surface charge densities serve the purpose of validating the working principle, but do not produce realistic predictions [13–15]. It should also be noted that contact force plays an important role in charge generation. The output voltage increases with increase in contact force, as the effective contact area between the dielectric layers increases due to distortion of one or both surfaces on a microscopic scale, resulting in an increase in the charges transferred [13,16].

Furthermore, the effects of contact-mode TG's structural design parameters and their interactions on its performance have not been studied appropriately. During recent years, efforts have been made in the direction of finding optimum load capacitance and resistance and their dependence on TG's structural parameters and operating conditions [7,17]. Finding optimum load capacitance is important because storage elements such as capacitors or batteries are necessary to stabilize and regulate output to power electronic devices because of the intrinsic unstable characteristics of various mechanical energy