(Article begins on next page)

Force Impact Effect in Contact-Mode Triboelectric Energy Harvesters: Characterization and Modeling

Marco Lasagni, Paolo Pavan
DIEF – Dept. of Engineering "Enzo Ferrari"
University of Modena and Reggio Emilia
Modena, Italy
marco.lasagni@unimore.it
paolo.pavan@unimore.it

Alessandro Bertacchini, Luca Larcher
DISMI – Dept. of Sciences and Methods for Engineering
University of Modena and Reggio Emilia
Reggio Emilia, Italy
alessandro.bertacchini@unimore.it
luca.larcher@unimore.it

Abstract—In this paper we investigate the effect of the contact force on the voltage generated by Contact-Mode Triboelectric Energy Harvesting Devices (CM-TEHD). The electrical energy harvested from mechanical shocks increases with the contact force. In order to investigate the role of the contact force in the triboelectric energy generation, we developed a physical model, which allows understanding the physical mechanisms of this process, while predicting the output voltage and power at given conditions. Prototypes of the CM-TEHD made of low-cost commercial silicone were fabricated using a very low cost process. The prototypes provide up to 5.5µW when subjected to repetitive impacts with a contact force of 65N.

Keywords— Triboelectric Generator, Energy Harvesting, Low Cost Devices, Impact Force Effect

I. INTRODUCTION

Among the variety of energy sources, harvesting the mechanical energy is widely considered an interesting option to replace or prolong the battery lifetime of mobile devices like IoT or wireless sensor nodes. Mechanical energy can be harvested by means of different physical principles (i.e. electrostatics, electromagnetism, piezoelectricity). Recently, also the triboelectric effect has been subjected to strong attention in the scientific community because of their advantages, i.e. broadband behavior, energy density and easy fabrication process exploiting low-cost materials.

The operating principle of Contact-Mode Triboelectric Energy Harvesting Devices (CM-TEHDs) is based on the combination of contact electrification and electrostatic induction, [1]. In CM-TEHDs triboelectricity is generated when two different materials are put in contact. Due to the consequent charge transfer, electrostatic induction drives an electric current.

Several works presented in the literature demonstrated empirically that CM-TEHDs can be used as energy sources as well as sensors (e.g. [1],[2]). In order to maximize the device performances, a simulation aided custom design is needed to explore different options for device optimization. For this reason, we developed a CM-TEHD model that takes explicitly into account other application dependent parameters like the effect of the impact force between the materials. This model, validated by means of measurements performed on low-cost silicone-based CM-TEHD prototypes, allows understanding the contact-mode triboelectric generation operating principles and their dependence on the impact force, while predicting correctly the electrical performances. In particular, the developed model allows the estimation of the surface charge density of the dielectric materials used in the CM-TEHD. While in the classic models, e.g. [1], it is considered constant and dependent only on material properties, in the proposed one it is demonstrated to be a function of the impact force. This represents an important improvement compared to models proposed for the CM-TEHD up to now in the literature, which neglect the effect of the impact force. In addition, the model equations allow also to estimate the impact force required to obtain a given output voltage accordingly with the voltage/power requirements of a specific application. Consequently, they can be used to design custom CM-TEHDs.

The paper is organized as follows. In Section II we present the CM-TEHD prototypes, the measurement set-up and the results derived from the experimental characterization. The model including the impact force effect is described in Section III, while simulation results are presented in Section IV. Section V concludes the paper.

II. CM-TEHD PROTOYPE, MEASUREMENT SET-UP AND EXPERIMENTAL RESULTS

The CM-TEHD prototypes we fabricated have the dielectric-to-dielectric structure shown in Fig. 1, where the Dielectric 1 is Acrylic Silicone (with $\varepsilon_{r1} = \varepsilon_{acry} = 10$, and thickness $d_1 = 1.9$ mm) and the Dielectric 2 is Acetylic Silicone (with $\varepsilon_{r2} = \varepsilon_{acet} = 2.2$, and thickness $d_2 = 1.9$ mm). Two classic FR4 boards for PCB applications with 35 µm of Cu have been used to realize Contact 1 and Contact 2. The device prototypes were realized using a very simple and low cost in-house fabrication process: the silicone-gel dielectrics are manually deposited at room temperature, and they are let solidifying for 24 hours. The obtained device has an active triboelectric area, *S,* of 37x35 mm.

The realized CM-TEHD has been characterized exploiting the setup shown in Fig. 2. It comprised of a laser vibrometer, an electromagnetic shaker, an impact hammer and an oscilloscope. For each test, this set-up allowed to measure: i) the output voltage generated by the CM-TEHD when the two triboelectric layers (i.e. the two dielectric layers) are repetitively put in contact at a given force; ii) the relative displacement, the relative
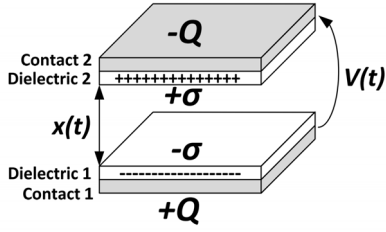
Fig. 1. Sketch of the realized Dielectric-to-Dielectric CM-TEHD prototypes.
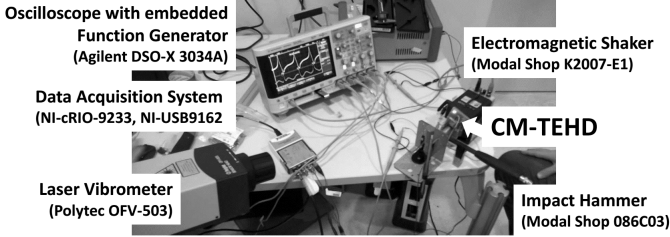

Fig. 2. Measurements Set-up.

velocity and the impact force between the two dielectric layers of the CM-TEHD.

In particular, the device plate of the CM-TEHD with the layer of Acrylic Silicone is fixed to the impact hammer, that it is used to measure the contact force of the mobile plate of the device. The mobile plate, with the Acetylic Silicone triboelectric layer, in turn, is fixed to an electromagnetic shaker for the frequency and amplitude controlled generation of the mechanical stimulus. Velocity and displacement of the CM-TEHD's mobile plate are measured by means of a laser vibrometer. All the measured signals are acquired and processed in real time by a NI-cRIO board, while the generated output voltage is visualized and acquired using a classic oscilloscope by means of a 10MΩ // 11pF probe acting also as load for the CM-TEHD.

Figure 3 shows three different output voltage waveforms generated by the CM-TEHD for three different peak impact forces (i.e. 12N, 25N, 50N respectively). The acquisitions have been synchronized in post processing thanks to the velocity, displacement and contact force of the CM-TEHD mobile plate measured by means of the laser vibrometer used. It is possible to note as the contact force influences the voltage generated across the device terminals and consequently the CM-TEHD generated output power, as shown in the following. In order to model the CM-TEHD devices by purposely including the contact force effect, we extended the popular models proposed in [1] for the operation and the power generation.

III. THE TRIBOLECTRIC DEVICE MODEL ACCOUNTING FOR THE CONTACT FORCE EFFECT

The most popular models proposed for the operation and the power generation modeling of a CM-TEHD consider the so called "V-Q-x relationship" (e.g. [1]), where V is the voltage generated between the two CM-TEHD contacts, Q is the amount of transferred charge between the contacts, and x is the distance between the two CM-TEHD dielectric layers, that varies accordingly with the mechanical stimulus. According to this models, the generated voltage by the CM-TEHD device depends on the charge transferred and on the displacement as:
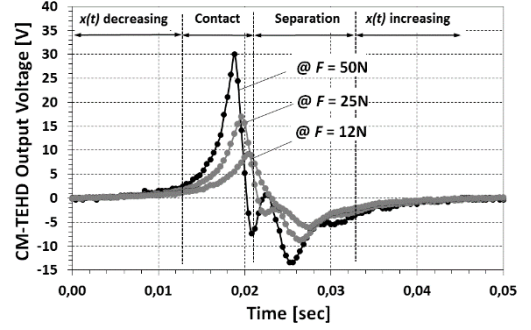

Fig. 3. Output voltage waveforms generated by the CM-TEHD at different forces. The waveforms are used as input of the develped Matlab-based model. The positive peak is larger than the negative one: this is due to the faster contact phase between the triboelectric layers than the separation one, while the total amount of charge transferred is the same.

$$V = -\frac{Q}{S\varepsilon_0}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + x(t)\right) + \frac{\sigma x(t)}{\varepsilon_0} \qquad (1)$$

where S is the active area of the CM-TEHD, ε_0 is the air dielectric constant, d_1 and ε_{r1} are the thickness and the relative permittivity of the dielectric 1, d_2 and ε_{r2} are the thickness and the relative permittivity of the dielectric 2, and σ is the constant surface charge density coefficient. These models consider the contact time instantaneous and do not take into account the effect of the contact force F between the two dielectric layers, which was shown to influence the generated voltage (see Fig.3).

This effect is included by considering that the charge density σ depends not only from the properties of the dielectric materials, but also on the contact force, i.e. $\sigma=f(F)$. This agrees with experimental results on triboelectric generators with specific surface structures (e.g. pyramid arrays) presented in the literature (e.g. [2],[3]). We included the force dependence of the generated surface charge by applying to macro scale CM-TEHDs the approach proposed in [5] to describe the triboelectric charging mechanisms of single particles hitting a wall. In particular, exploiting the same assumption used in [5] concerning the saturation of the amount of transferred charge, q, after a given number of impacts, n, and using the relation $q = \sigma S$, we applied the procedure described in [5] in order to obtain (2)

$$\sigma(F)|_{n\to\infty} = \sigma_\infty[1 - e^{-cF}] + \sigma_0 e^{-cF} \qquad (2)$$

where $\sigma(F)$ is the surface charge density, expressed in exponential form after a number of impacts n large enough to approximate a steady state condition of the charge transfer mechanism (i.e. $n \geq 10$), at a given impact force, F. While σ_∞, σ_0 are the saturation and the initial value of the charge density for the considered dielectric materials, respectively, and c is a coefficient obtained from the automatic iterative calibration procedure implemented in the model. The obtained $\sigma=f(F)$ can be directly included in (1) to account for the contribution of the impact force F on the output voltage V generated of the CM-TEHD, accordingly with the macroscopic behavior observed in the CM-TEHD prototypes.

The obtained model can be applied also to TEHDs with different structures, like the contact-to-dielectric devices (i.e. devices with only one triboelectric layer) by neglecting in (1) the terms ε_{r2}/d_2 related to the second dielectric layer.

IV. SIMULATION RESULTS AND MODEL VALIDATION

Considering the device stack described in Section II and the experimental output voltage waveforms shown in Fig. 3 as input parameters, the proposed model has been applied to the CM-TEHD prototype we realized. With reference to (2), the model produced $(\sigma_\infty, \sigma_0, c) = (12.3 \text{ uC/m}^2, 1.69 \text{uC/m}^2, 0.02459)$ for the considered CM-TEHD. Using these values in (2) and including the resulting $\sigma(F)$ in (1) it is possible to estimate the CM-TEHD output voltage for any given impact force.

An example of comparison between the MATLAB-based simulated output voltage waveforms and the corresponding measurements is reported in Fig. 4. A very good agreement between simulations and measurements is shown, supporting the validity of the proposed model. Moreover, the results confirm that, differently from the assumptions of previous models, the contact time is not zero and the impact produces a deformation of the triboelectric layers resulting in a variation of σ. This effect contributes also to the output power generation, which increases linearly with the increase of F, as reported in Fig. 5.

Finally, as mentioned before, the model can be used also to design custom CM-TEHDs. To this purpose, we realized and characterized a second prototype with: i) same materials stack and same active area of the first one; ii) different thicknesses ($d_1 = 3$ mm for acrylic silicone, $d_2 = 9$ mm for acetylic silicone).
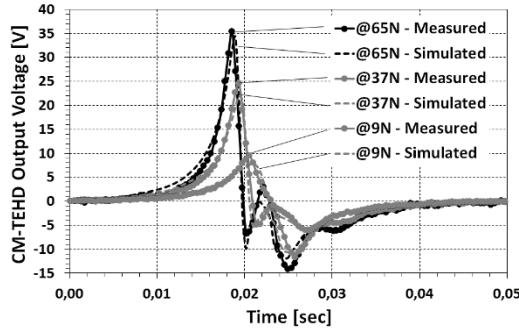
Fig. 4. Comparison between the measured output voltages generated by the implemented CM-TEHD prototype at 9N, 37N and 65N and the corresponding output voltages simulated by means of the proposed model.
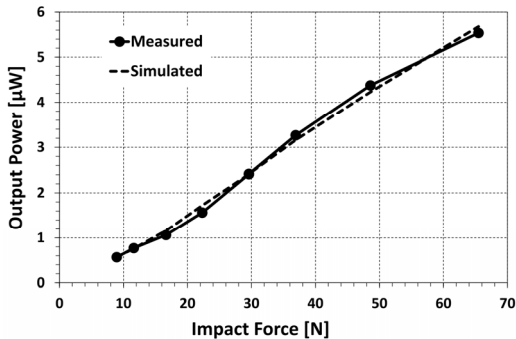
Fig. 5. Comparison between the output power of the implemented CM-TEHD prototype calculated from the measurements with a $Z_{load}=10M\Omega//11pF$ (oscilloscope's probe) and the simulated ones. $P_{OUT} = \frac{1}{TZ_{load}} \int_0^T V_{OUT}^2(t)dt$, where T=50msec is the period of the stimulus provided by the shaker.
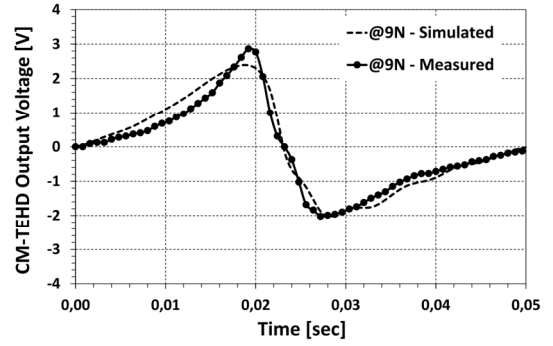
Fig. 6. Example of comparison between simulated and measured output voltages generated by the second CM-TEHD prototype for a desired F = 9N.

The surface charge density $\sigma(F)$, as well as the coefficients $(\sigma_\infty, \sigma_0, c)$, calculated by the model are specific parameters for the considered materials pair put in contact. Therefore, they can be used also for the simulation of the second CM-TEHD prototype. An example of comparison between simulated and measured output voltage for the second CM-TEHD prototype in case of a desired $F = 9$ N is shown in Fig. 6. Also in this case it is possible to note the good agreement between simulations and measurements, as further demonstration of the validity of the proposed solution. Comparing the results of Fig. 4 for $F = 9$ N and Fig. 6, it is possible to note as the second prototype generates a peak output voltage smaller than the first one. This is due to the effect of the thicker triboelectric layers on the equivalent capacitance of the device, as explained in other previous works presented in the literature on this topic (e.g. [6]).

V. CONCLUSIONS

In this paper we presented a model that can be used to design CM-TEHDs. Differently from previous ones it is applied to macroscale devices and takes into account the effect of the impact force resulting in a variation of σ at the interface of the triboelectric layers of the device. Low cost silicone-based CM-TEHD prototypes able to generate up to 5.5 µW when subjected to repetitive impacts at 65 N have been realized to validate the model.

REFERENCES

[1] S. Niu, S. Wang, L. Lin, Y. Liu, Y. Sheng Zhou, Y. Hua, Z.L. Wang "Theoretical study of contact-mode triboelectric nanogenerators as an effective power source" Energy Environ. Sci., vol. 6, pp 3576-3583, 2013.

[2] M. S. Rasel, M. A. Halim and J. Y. Park, "A PDMS based triboelectric energy harvester as self-powered, active tactile sensor system for human skin," *In Proc. IEEE SENSORS*, 2015, pp. 1-4.

[3] M. L. Seol, Jin-Woo Han, J. H. Woo, Dong-Il Moon, Jee-Yeon Kim and Y. K. Choi, "Comprehensive analysis of deformation of interfacial micro-nano structure by applied force in triboelectric energy harvester," *In Proc. IEEE IEDM*, 2014, pp. 8.3.1-8.3.4.

[4] D. Hong, Y. M. Choi and J. Jeong, "The quantitative analysis for a contact-mode triboelectric energy harvesting device," *In Proc. IEEE AIM*, 2015, pp. 563-566.

[5] S. Matsusaka, H. Maruyama, T. Matsuyama, M. Ghadiri, "Triboelectric charging of powders: A review", Chem. Eng. Sci., Vol. 65, Issue 22, pp 5781-5807, 2010

[6] A. Bertacchini, L. Larcher, M. Lasagni and P. Pavan, "Ultra low cost triboelectric energy harvesting solutions for embedded sensor systems," *In Proc. IEEE-NANO*, 2015, pp. 1151-1154.