

A New CAD Tool for Energy Optimization of Diagonal Motion Mode of Attached Electrode Triboelectric Nanogenerators

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Abstract— Triboelectrification effect was known since the ancient Greek time. A triboelectric nanogenerator (TENG) was invented and is used to convert the mechanical energy to the electrical energy. The TENG is a promising candidate for the new transducers generation recommended for energy harvesting. It is used to harvest the mechanical energy with a great number of advantages. In this research, a new diagonal motion mode is proposed and is studied intensively in attached electrode mode using COMSOL finite element analysis. Diagonal motion mode offers a new degree of freedom which is the angle of motion allowing for further energy optimization. A new CAD tool is built based on semi-analytical equations derived from both COMSOL simulation results and theoretical framework. The tool optimizes the energy based on both the angle and the distance of motion in a few seconds which is very time efficient compared to the time consuming COMSOL simulations. The tool results show great consistency with the data obtained from time consuming COMSOL results.

Keywords— TENG, Triboelectric, nanogenerators, renewable, energy, harvesters, diagonal mode, attached electrode

I. INTRODUCTION

Energy harvesting is considered as a promising technology to compensate the lack of fuel sources. On the large scale, large amount of resources have been involved to find alternative energy sources for fuel. The techniques to harvest energy such as photovoltaic and mechanical energy help to solve the huge energy demand of the modern society. The energy source problem for electronic devices is solved by energy harvesting when the traditional energy sources are not available. [1]

Due to the rapid growth of the worldwide energy demand, finding a new source of renewable energy has a great role in fulfilling this increasing energy demand [2]. Mechanical energy is considered, among different types of sources, the best energy harvesting because it is green energy source and environmental friendly. Moreover, the mechanical energy is highly obtainable [3]. Energy from the surrounding environment is harvested by new technologies. Recently, triboelectric nanogenerators (TENGs) have become an important technology for converting the mechanical energy to electrical energy [4]. TENG is applied in mechanical harvesting in life for example, motion, flowing water, wind, and tire rotation [5]. The advantages of the TENGs are that

they are very cheap; they produce a high output power; they have high efficiency; and finally, they are fabricated easily. The principal effects of TENG are electrostatic induction and triboelectrification. The triboelectrification is a kind of contact electrification such that specific materials are charged electrically after friction with another different material [6]. Electrostatic induction is the principal mechanism for conversion of the mechanical energy to electrical energy [7]. There are three basic configurations which are attached electrode TENG, single electrode TENG and free standing TENG. For every configuration, there is a certain structure and choice of the materials and also, the triggering order. Each configuration consists of two modes which are vertical contact mode and lateral sliding mode. Each mode consists of two main categories which are Conductor-to-Dielectric category and Dielectric-to-Dielectric Category [8, 9]

The organization of this paper is as follows. Section II presents the different modes of the attached electrode. A proposed attached electrode diagonal mode and a new CAD tool of TENG are presented in Section III. The analytical equations are discussed in Section IV. Results are discussed in Section V. Design recommendations are presented in Section VI. Finally, the conclusion is drawn in Section VII

II. ATTACHED ELECTRODE TENG MOTION MODES

A. Lateral Sliding mode

The sliding mode consists of two main types which are Conductor-to-Dielectric and Dielectric-to-Dielectric. Figure 1 shows the setup of the sliding mode.

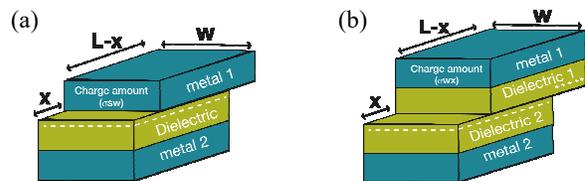


Fig. 1. Geometrical configuration of the (a): Attached-electrode lateral sliding mode of type Conductor-to-Dielectric. (b) Attached-electrode lateral sliding mode of type Dielectric-to-Dielectric.

In Dielectric-to-Dielectric type, two metal electrodes are attached to two dielectric layers. The lower part is fixed while

the upper part slides through the lateral direction. During the separation, the two dielectrics have charges but with opposite signs at the non-overlapped regions because of the triboelectric effect. By induction, the metal electrodes are polarized during separation and accordingly, the charges are transferred between the electrodes. The whole structure is surrounded by air. [8]

In Conductor-to-Dielectric type, the geometrical structure is the same as in the Dielectric-to-Dielectric type. The only difference is that there is no upper dielectric and the metal layer has two roles which are the upper triboelectric layer and the top electrode.

B. Vertical Contact mode

The vertical contact mode consists of two main categories which are Conductor-to-Dielectric and Dielectric-to-Dielectric as in the lateral sliding mode. Figure 2 shows the setup of the vertical contact mode.

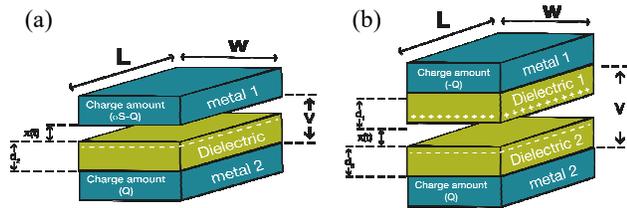


Fig. 2. Geometrical configuration of the (a): Attached-electrode vertical contact mode of type Conductor-to-Dielectric. (b) Attached-electrode vertical contact mode of type Dielectric-to-Dielectric.

The geometrical structure of the vertical mode is the same as in lateral sliding mode. However, the upper layers move in the vertical direction not in the lateral direction [9].

III. PROPOSED ATTACHED ELECTRODE DIAGONAL MOTION MODE AND NEW CAD TOOL FOR ENERGY OPTIMIZATION

A new motion mode of the attached electrode TENG has been proposed. This mode is a diagonal motion regime in which motion angle, namely theta, offers a new degree of freedom. By consequence, theta could be optimized to reach the maximum energy for each TENG configuration. Figure 3 shows the setup of the diagonal mode

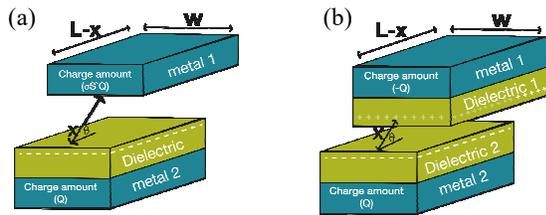


Fig. 3. Geometrical configuration of the (a): Attached-electrode diagonal mode of type Conductor-to-Dielectric. (b) Attached-electrode diagonal mode of type Dielectric-to-Dielectric.

Semi-analytic equations describing attached electrode diagonal mode have been developed. A new MATLAB CAD tool is developed using the analytical equation. The tool calculates the maximum energy and the corresponding

optimized motion parameters of diagonal mode of TENG. Moreover, the equations developed in the tool can be further used to develop circuit model for attached electrode TENG working in the diagonal mode using Verilog-A [10]. This will help in characterizing the generated current and the output power of the TENG in a specific circuit. Analytical equations of different attached electrode modes

In order to make the analysis of different modes, relationship between the voltage and charge has to be derived. This relationship depends on electrostatics. V-Q-x relationship is based on Gauss theorem and charge distribution. [8, 9]

A. Lateral sliding mode

In Dielectric-to-Dielectric mode, the strength of the electric field at every region inside dielectric 1 is given by the following equation [8]:

$$E = \frac{\sigma x}{\epsilon_0 \epsilon_r (w - x)} \quad (1)$$

where σ = The surface charge density

ϵ_r = The relative permittivity of the dielectric

ϵ_0 = The vacuum permittivity = 8.854×10^{-12} F/m

w = The width of the dielectric

x = The separation distance

The strength of the field inside dielectric 2 is the same as (1) but with the different relative permittivity. So, the open circuit voltage is derived by the following equation [8]:

$$V_{oc} = \frac{\sigma x d_1}{\epsilon_{r1} * \epsilon_0 * (w - x)} + \frac{\sigma x d_2}{\epsilon_{r2} * \epsilon_0 * (w - x)} \quad (2)$$

where d_1 and d_2 are the thicknesses of dielectric 1 and dielectric 2 respectively.

(2) is simplified as follows:

$$V_{oc} = \frac{\sigma x d_0}{\epsilon_0 (w - x)} \quad (3)$$

where d_0 is called the effective thickness and is equal to

$$\frac{d_1}{\epsilon_{r1}} + \frac{d_2}{\epsilon_{r2}}$$

The capacitance C is calculated from the equation using the model of the parallel plates [8]:

$$Cap = \frac{\epsilon_0 * l * (w - x)}{d_0} \quad (4)$$

where l is the length of the dielectric

So, the short circuit charge can be calculated from the following equation

$$Q_{sc} = Cap * V_{oc} = \sigma l x \quad (5)$$

In Conductor-to-Dielectric mode, equations of open circuit voltage, short circuit charge and capacitance are the same as that of Dielectric-to-Dielectric mode but the only difference is that there is only one dielectric (i.e., $d_1=0$)

B. Vertical contact mode

In Dielectric-to-Dielectric mode, the strength of the electric field at every region inside dielectric 1, from the Gauss theorem is given by the following equation [9]:

$$E = -\frac{Q}{wl\epsilon_0\epsilon_r} \quad (6)$$

The strength field inside dielectric 2 is the same as (6) but with the different relative permittivity.

This mode has a top layer moving in the vertical direction leaving the air gap. The electric field inside the air gap is given by [9]:

$$E_{Air} = \frac{-(Q/(wl)) + \sigma}{\epsilon_0} \quad (7)$$

Thus, the open circuit voltage is given when Q is equal to 0

$$V_{oc} = \frac{\sigma x}{\epsilon_0} \quad (8)$$

The capacitance is given by the following equation [9]:

$$Cap = \frac{wl\epsilon_0}{d_0 + x} \quad (9)$$

The short circuit charge can be derived from the open circuit voltage and capacitance

$$Q_{sc} = Cap * V_{oc} = \frac{wl\sigma x}{d_0 + x} \quad (10)$$

C. Diagonal mode

This is a new mode in which the upper layers move in a certain distance with a specific angle. The analysis of this mode is the combination between two modes (vertical mode and sliding mode).

Since the equation of the open circuit voltage is linear, the open circuit voltage of the diagonal mode can be derived using this equation from (3) and (8):

$$V_{oc} = A * \frac{\sigma x \sin(\theta)}{\epsilon_0} + B * \frac{\sigma(x \cos \theta) * d_0}{\epsilon_0 * (w - x \cos \theta)} + C \quad (11)$$

where A, B, and C are fitting parameters, and θ is the diagonal mode angle in degrees

The capacitance of the diagonal mode is given by the following equation:

$$Cap = D * \left(\frac{\epsilon_0 l (w - x \cos \theta)}{d_0 + x \sin \theta} \right) + F \quad (12)$$

where D and F are fitting parameters

IV. SIMULATION AND TEST RESULTS

Based on COMSOL simulation results and using interpolation, a semi-analytic equations describing both open circuit voltage and capacitance have been developed as discussed earlier. From these equations, the energy obtained from TENG can be evaluated according to the following equation, then, the maximum energy and the corresponding optimum working angle can be deduced. Figure 4 shows a sample of the open-circuit voltage, the capacitance, the energy calculation and the corresponding energy of both interpolated semi-analytic equations and COMSOL simulation data at width=100 μm

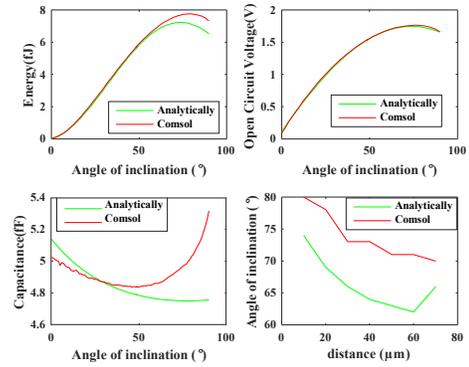


Fig. 4. Sample of (a) Energy, (b) V_{oc} , (c) Cap and (d) diagonal mode angle produced by the equations in comparison with COMSOL results.

From figure 4, the energy is very small because the width is very small. The energy is directly proportional to the dimensions of the TENG. Based on these equations, a CAD tool is developed to automate these calculations giving the user the maximum energy and the corresponding optimum angle according to the geometry dimensions specified. The proposed CAD tool also calculates the energy loss (compared to the maximum energy) if any other angle is used. Figure 5 shows the output maximum energy from the Comsol versus the CAD tool at Conductor-to-Dielectric mode.

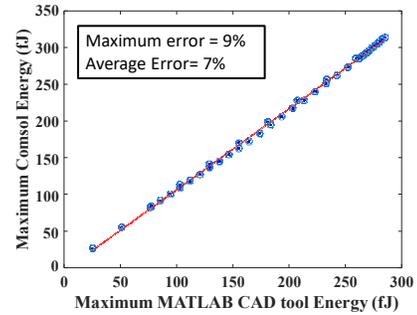


Fig. 5. Results of the Maximum Energy by using Comsol and CAD tool

The developed tool can effectively obtain accurate results in comparison with results extracted from COMSOL with average error of 7% as shown in figure 5. It is also 300x faster on average than COMSOL

V. DESIGN RECOMMENDATIONS

The TENG is placed in a box such that there is a very small air gap. The separation of the TENG from the box is nearly about 2 μ m because the TENG is sensitive to the air [11]. Table I. shows the set of specified parameters for the studied attached electrode TENG. These parameters are used due to their wide use in research.

Table I. UTILIZED PARAMETERS IN THE STUDY

Relative dielectric constant (ϵ_r)	2
Thickness of the dielectric (d)	25 μ m
Surface charge density (σ)	10 μ C/m ²
Thickness of the metal electrode (d_m)	10 μ m
Length of the dielectric (l)	30 μ m

Tables II and III summarize the tool optimized outputs in terms of maximum energy, maximum distance, and the corresponding optimum angle for Conductor-to-Dielectric and Dielectric-to-Dielectric respectively.

Table II. Design recommendation for diagonal mode attached electrode TENG of type Conductor-to-Dielectric

Width (μ m)	Maximum distance (μ m)	Optimum angle (°)	Maximum Energy(FJ)
100	60	62	76.7
200	40	67	164
300	40	68	262
400	30	72	285
500	20	75	24.9

Table III. Design recommendation for diagonal mode attached electrode TENG of type Dielectric-to-Dielectric

Width (μ m)	Maximum distance (μ m)	Optimum angle (°)	Maximum Energy(FJ)
100	20	61	7.5
200	30	73	37.7
300	20	75	46.5
400	50	78	150
500	50	69	140

The limitation of the maximum distance given in the above tables is because of the energy loss due to parasitic edge and fringing effects that decrease the efficiency of the charge transfer. [11]

VI. CONCLUSION

This paper presents a new motion mode for TENGs namely diagonal mode which offers new optimization capabilities based on motion angle. It also presents a new CAD tool that fasten the electrostatic simulation for TENGs replacing the slower COMSOL simulation by a factor of 300x. The diagonal mode has been studied on attached electrode TENG and the tool results is in good agreement with COMSOL results. The paper also offers design recommendation in the scope of the confined dimensions of the study which is of great importance to small biomedical and wearable electronics. Lastly, it paves the road for further investigation of diagonal mode for other TENG configurations and geometries.

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