A Nonresonant Triboelectric-electromagnetic Energy Harvester via a Vibro-impact Mechanism for Low-frequency Multi-directional Excitations

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Abstract: A majority of current studies about non-resonant energy harvesters for low-frequency energy are based on pure experiment without theoretical modelling. In this work, a novel hybrid triboelectric-electromagnetic harvester in form of a rolling magnet inside a casing is proposed for scavenging low-frequency energy from multi-directional excitations, which includes a number of sub triboelectric energy harvesters (sub-TEHs) and two sub electromagnetic energy harvesters (sub-EEHs). Both the mechanical model and electrical model are established for a horizontal excitation, a rocking excitation and a vertical excitation. A velocity-dependent coefficient of restitution for impact and an impact-velocity-dependent charge density are obtained via experiment, which improve the theoretical model and result in better agreement between theoretical and experimental results. Structural response and electric outputs under different types of external excitations are investigated theoretically.

It is found that the harvester has a good sensitivity to small-angle ultra-low-frequency rocking excitations, which is beneficial to low-frequency energy harvesting. When tested on a shake table at 4 Hz, a sub-TEH and a sub-EEH can generate peak powers of 212.1 µW and 57.8 mW, respectively. An electronic clock is able to work continuously when powered by the harvester shaken by hand. The harvester is also tested inside a handbag carried by a walking human for biomechanical energy and on a floating structure for wave energy, which exbibits good performance. This work presents a novel design with a capability of harvesting low-frequency energy under different external excitations, which contributes to the development and applications of triboelectric and electromagnetic energy harvesting.

Keywords: hybrid energy harvester; friction; vibro-impact; low-frequency; multi-directional excitation

# 1. Introduction

In the last a few decades, renewable energy markets have grown rapidly, accompanied by a great upsurge of research in the field of large-scale power generation, such as solar energy [1], wind energy [2] and hydroelectric power [3], which have been significant sources of global energy supply. Recently, with the explosive development and increasingly wide utilization of Internet of Things (IoT), wearable devices, wireless sensor networks (WSN), implantable medical devices and microelectromechanical systems (MEMS), there has been a strong demand for new and efficient power supplies for those devices [4–6], as conventional power sources, such as batteries, are faced with inevitable problems related to limited lifespan, regular replacement or charging, and harmful effect on environment. Fortunately, owing to the development of integrated circuits, the power requirements of a number of devices have been reduced to a low level with a magnitude of a few µW [7]. Therefore, small-scale energy harvesting targeting for those low-power electronics has begun to attract more and more research interests.

Among a variety of ambient energy sources, vibration, as a common phenomenon in ambient environment, is an ideal and sufficient energy source for small-scale energy harvesting, such as walking humans or animals, working machinery, waves and wind flows, which usually range in acceleration amplitudes of 0.01 ̶ 1 g and frequencies of 1 ̶ 200 Hz [8]. Generally, there are mainly three types of vibration-based energy harvesters, namely, piezoelectric energy harvesters (PEHs), electromagnetic energy harvesters (EEHs) and triboelectric energy harvesters (TEHs). Compared with PEHs [9–11] and EEHs [12–14] which have been studied extensively, TEHs are relatively new and have gained increasing attention since the first triboelectric nanogenerator (TENG) was reported by Wang’s group in 2012 [15]. The power generation of TEHs relies on a conjunction of triboelectrification and electrostatic induction, which take place between two distinct surfaces with different triboelectric polarities when brought into physical contact with each other [16]. A large number of conventional materials can be utilized for TEHs [17], which are characterized by light weight, mechanical flexibility and low cost. This applicability to a variety of materials is one of the advantages of TEHs, which enables different potential applications with suitable materials to adapt to operation conditions.

Power enhancement is always a popular topic in the field of energy harvesting. The performance of TEHs highly depends on the surface charge on triboelectric materials. Thus, an effective and direct way to enhance the performance of TEHs is to improve the surface charge density on the triboelectric films through material science. Some chemical compositions, such as ZnO [18,19], BiWO6 [20], Ti3C2Tx [21], α-Fe2O3 [22], AgSbS2 [23], thiolate ligands [24], graphene oxide [25], cellulose nanofibrils [26], are employed to synthesize functionalized materials to enhance electric polarity of triboelectric materials. Besides the materials, an integrated-self-charge-pumping system based on a floating layer structure and a charge pump is also able to significantly enhance the surface charge density [27]. For TEHs in contact-separation mode and sliding mode, the effective contact area is crucial for power generation. Theoretically, a larger contact area can bring about higher output power. In this regard, in the field of surface technology, nano arrays [28–31] and nanowires [32] are introduced on the interface of triboelectric films to increase the effective contact area in micro/nanoscale. A striking characteristic of TEHs is high internal impendence, which also limits the performance and applications. A needle-to-needle booster consisting of a pair of opposite needles enclosed in an inert atmosphere was reported to reduce the impendence of TEHs when wired in series, which was proved to be able to improve the maximum power by 330.76% [33]. All those strategies for power boosting are from the perspective of material, interface and electrical design. Actually, for TEHs, the power generation is closely associated with the relative displacement between the contact surfaces. For linear TEHs [34,35], their maximum power is usually limited by their natural frequencies as the harvesting systems with liner stiffness have the maximum displacement at the natural frequencies. In order to improve the frequency response and harvesting efficiency, nonlinearity is employed in energy harvesting to broaden the frequency bandwidth, which has been studied extensively in EEHs [36–39] and PEHs [40–43] in the last decades. In recent years, with more and more researcher working in efficient TEHs, different types of TEHs using mechanical [44–47] and magnetic [48–51] bistability have also been proposed and investigated, which have been proved to be able to achieve much higher output power than linear systems at low frequencies [52].

Due to the electrostatic induction mechanism and the nature of the conductor-to-dielectric or dielectric-to-dielectric interface, TEHs behave as low current sources with parallel internal impedance, which typically have high open-circuit voltages (~ 1 ̶ 1000 V) and low short-circuit currents (~ 1 ̶ 1000 µA) [53]. In order to improve the output current, a feasible way is to integrate a number of sub-harvesters in a single design and synchronize their outputs [54]. Another approach is to integrate TEHs with other types of energy harvesters, such as EEHs, to form a hybrid harvester. EEHs usually behave as low voltage sources with low series internal impedance resulting from the electromagnetic induction mechanism and the high conductivity of the coils, which have low open-circuit voltages (~ 1 ̶ 1000 mV) and high short-circuit currents (~ 1 ̶ 1000 mA) [53]. Therefore, a hybridization of TEHs and EEHs can take advantage of their complementary features. Specifically, TEHs have a high output voltage and EEHs have a high output current. When combined, they more likely meet the requirement of particular applications. Furthermore, the hybridization of TEHs and EEHs can be used to broaden the operating bandwidth of the harvester due to the high efficiency of TEHs at low frequencies and high performance of EEHs at high frequencies. Many designs of hybrid triboelectric-electromagnetic energy harvesters have been proposed for general vibration energy [55], wave energy [56] and wind energy [57]. Most of these investigations are pure experiments under simple operation conditions.

For harvesting low-frequency energy, non-resonant TEHs [58], EEHs [59] and hybrid triboelectric-electromagnetic energy harvesters [56,60–67] have been proposed. Compared with resonant energy harvesters which depend on displacement amplification at resonance in a narrow bandwidth, non-resonant harvesters are able to expand the operation bandwidth [68] as non-resonant systems have no nature frequency. Therefore, even under low-frequency excitations, non-resonant energy harvesters still have a considerable efficiency. However, due to the lack of vibration amplification, non-resonant energy harvesters usually require a large amplitude excitation, which limits their application for small-amplitude excitations. Fortunately, low-frequency vibrations are usually accompanied by large amplitudes, such as human motions and wave motions. Usually, non-resonant TEHs take the form of a movable mass inside a container. The structural response of the movable mass directly affects the performance of the harvesters. Currently, most existing studies about non-resonant energy harvesters are based on pure experiment. The modelling and theoretical investigations of their dynamic behaviours and electric outputs are fragmented. Furthermore, impact is a common phenomenon in many non-resonant energy harvesters, which may even be a dominant factor of the electric outputs, especially for some designs consisting of contact-separation TEHs [61,62]. However, the modelling of impact in those non-resonant energy harvesting systems has not been studied.

In this work, a novel hybrid triboelectric-electromagnetic energy harvester is developed for harvesting low-frequency energy under multiple operation conditions, which is a nonresonant vibro-impact system in the form of a free-rolling magnet inside a casing. Two coils and several TEHs in contact-separation mode are located in the two internal side cells and ends of the casing, respectively. Under external excitations, the rolling magnet moves forwards and backwards and impacts at the ends of the casing, resulting in the changing of the magnetic flux inside the coils and possible contact-separation between the films of the TEHs. Consequently, electricity can be generated from the coils and TEHs. A theoretical model including the mechanical model and electrical model is established for different excitations. Numerical simulations are carried out to explore the structural dynamics and electric performance. A velocity-dependent coefficient of restitution for impact and a velocity-dependent charge density for TEHs are obtained based on testing results. Experimental validation is conducted on a shake table. The proposed harvester is also tested on a shaking hand, inside a handbag carried by a walking human and on a floating structure successively, which exhibits great potential and good performance in harvesting different kinds of energy at low frequencies. This work aims to present an efficient harvester for scavenging low-frequency energy with a capability to adapt to different external excitations, and develop a theoretical model for both mechanical and electrical systems, and carry out investigations from the perspective of structural vibration and electric performance, which helps to provide a guideline for structure design and real application. The novel contributions of this work are summarised as follows:

(1) In light of the facts that a majority of studies about non-resonant TEHs (including hybrid TEHs) are purely experimental, and there is a serious lack of theoretical studies, a comprehensive theoretical model combining both mechanical and electrical systems based on different types of excitations is established in this work. An algorithm for implementation of the trapezium integration rule and the second-order backward difference scheme (TR-BDF2) is employed for solving the non-smooth mechanical system and the stiff electrical system.

(2) The modelling of impact in most non-resonant TEHs has rarely been investigated. In this work, a velocity-dependent coefficient of restitution for the mechanical system is obtained, and an impact-velocity-dependent charge density for the electrical system is identified. They contribute to improving the theoretical model for a better agreement with the experiment results.

(3) The configuration of the harvester enables the roller in the harvesting casing to impact at the two ends with large displacement and velocity under ultra-low-frequency rocking excitation with small rocking angles, which is beneficial to low-frequency energy harvesting.

# 2. Prototype design

In this work, a novel hybrid triboelectric-electromagnetic energy harvester consisting of several sub-harvesters is developed for scavenging low-frequency energy, shown in Fig. 1 (a). The harvester includes a casing and a roller made of neodymium magnet. There are tiny gaps between the top of the roller and the top wall of the casing, and between the side surfaces of the roller and the walls of two side symmetric cells (which form a narrow channel inside the casing). Consequently, the roller is able to roll freely in the casing. A number of identical sub-TEHs in contact-separation mode can be stacked and glued at each end of the casing. And two coils each sit inside the two side cells, referred to as the sub-EEHs.

Fig. 1 (b) shows the configuration of a single sub-TEH, which consists of two metal films attached on two substrates. One of the metal films is covered by a dielectric film. In this work, the metal films are made from a double-side conductive adhesive copper tape, and the dielectric film is made from ethylene propylene (FEP) membrane. The substrates and films are lightweight, the masses of which are negligible. The two metal films work as electrodes, whose substrates are connected by a pair of elastic components (elastic connections). External compressive forces acting on the substrates may push the single metal film into contact with the dielectric film on another metal film. The elastic connections provide restoring force to separate the single metal film and the dielectric film with the decrease or disappearance of the compressive forces.

The proposed harvester is a non-resonant vibro-impact system, which can be utilized to harvest different kinds of energy under low frequencies for a variety of applications, for example, to power structure monitoring sensors when fixed on vibrating structures. It also has potential to scavenge biomechanical energy from humans or animals for health monitoring sensors or animal trackers. Besides, it can be attached to a floating structure to harvest wave energy for environment monitoring sensors.

The electricity generation of the proposed harvester relies on two parts. One part is the triboelectric energy harvesters in contact-separation mode at the two ends, and the other part is the coils inside the two side cells. The working mechanism of the harvester is illustrated in Fig. 1 (c) and (d). At each end, only one sub-TEH is shown here. For the electromagnetic energy harvesting, when the roller (magnet) travels backwards and forwards in the casing, as illustrated in Fig.1 (c), according to Faraday’s law of induction, a change of magnetic flux inside the coils induces a voltage, which can be used to power an electric load. For the triboelectric energy harvesting, at the original state, no charge is generated or induced, with no electric potential difference between the two electrodes. When the single metal film is brought into contact with the dielectric film due to the compressive force from the roller (Fig.1 (d)-I), the triboelectric effect means that electrons are injected from the single metal film into the dielectric film because of their opposite electric polarities, resulting in net negative charges in the dielectric film and net positive charges in the single metal film, respectively. Once the roller leaves the ends and the single metal film is separated from the dielectric film due to the restoring force from the elastic connections, a potential difference is then established between the two electrodes under the open circuit condition due to the opposite triboelectric charges. When a load is wired with the two electrodes, electrons are driven to flow through the load between the electrodes (Fig.1 (d)-II). With a further separation between the single metal films and the dielectric film, the potential difference keeps increasing and the current continues to flow through the load until an electric balance is established (Fig.1 (d)-III). Once the roller comes back and the electrodes get close to each other, an opposite current is generated through the external load (Fig.1 (d)-IV). As a consequence, an alternating current is generated through the external load circuit during vibration.



Figure 1. Prototype design. a) configuration of the harvester. b) structure of the sub-TEHs. c) working mechanism of the sub-EEHs. d) working mechanism of the sub-TEHs

# 3. Theoretical models

## 3.1. Mechanical model

A structural dynamics model is developed for investigating the dynamic response of the harvester, which is applicable to horizontal excitation, rocking excitation or a combination of the horizontal excitation, the rocking excitation and vertical excitation. It is assumed that in this model, there is no relative slip between the roller and the floor of the casing. It is also assumed that all the sub-harvesters are identical and all the elastic connections are simplified as linear springs with the same stiffness. The substrates of the sub-harvesters are treated as rigid plates, whose masses are negligible.

For establishing a general model, a complex excitation is applied on the harvester, which includes three parts, a horizontal excitation , a vertical excitation and a rocking excitation , as shown in Fig. 2 (a). All of them are time-dependent functions. In order to describe the motion of the roller, a global coordinate system *X*G*Y*G*Z*G is established, whose origin *O*G is at the rotation centre of the harvester prior to excitation. Besides, a local coordinate system *X*L*Y*L*Z*L is attached with the harvester shell, whose origin *O*L is set at the geometric centre of the casing.



Figure 2. Schematic of the harvester. a) multi-directional excitations applied on the harvester. b) different numbers of sub-TEHs integrated in the harvester. c) vibro-impact process. d) parameters for the harvester configuration.

Under the horizontal excitation , the vertical excitation and the rocking excitation , the harvester travels from position A to position B, and the absolute displacements for the centre of the casing *O*L along *X*G-axis and *Z*G-axis in the global coordinate system can be expressed as

The relative displacement between the centre of the roller and the centre of the casing is written as , then one can get the absolute displacements for the centre of the roller along *X*G-axis and *Z*G-axis in the global coordinate system

The number of the sub-TEHs *n* at each end can be designed flexibly, as shown in Fig. 2 (b), which depends on the dimension of the harvester casing and power requirement of real applications. Fig. 2 (c) illustrates the vibro-impact process. Every sub-harvester has the same simplified stiffness and initial gap between the FEP film and the single copper film in a sub-TEH. Coils are not included here at first. Therefore, as shown in Fig. 2 (d), before the roller comes into contact with the sub-harvesters at the ends (Fig. 2 (c) - I), namely when , the governing equation of motion for the roller can be written as

Here, is the moment of inertia for the roller about its centre, and denotes rotational angle of the roller about its centre. Based on the assumption that pure rolling takes place between the roller and the shell, the rotational angle satisfies .

Via mathematical transformation, the governing equation of motion before the roller contacts with the sub-TEHs can be rewritten as

When the coils are placed in the side cells, an electromotive force is induced on the roller from each cell. Accordingly, an additional electric damping is introduced into Eq. (8). The mechanical damping is also considered. Then the final governing equation is rewritten as follows

in which can be expressed as

Here, and denote the coil resistance and load resistance for the electromagnetic energy harvester, respectively. represents the transduction factor, which usually can be treated as a constant [69,70].

When the roller begins to push the sub-TEHs (Fig. 2 (c) - II), namely when , due to the introduced spring force from the elastic connections, the motion of the roller is now governed by

in which is the force provided by the elastic connections, which can be expressed as

When the roller continues to move toward the ends after it contacts the sub-TEHs, impact may happen when a sub-TEHs at either end is compressed fully (Fig. 2 (c) - III, ). During an impact event, the instantaneous coefficient of restitution is employed to reflect the velocity change of the roller, which can be described by

where and donate the translational velocity of the roller just before and just after impact.

The horizontal excitation , the vertical excitation and the rocking excitation are functions of time, which depend on the real external vibration sources. For numerical simulations, these excitations are limited to prescribed harmonic motion expressed as

## 3.2. Electrical model

### 3.2.1 Electromagnetic energy harvesting

An EEH contains two core parts, namely the magnet and the induction coil. When the EEH is subjected to external excitations, according to Faraday’s law of induction, the relative displacement between the magnets and the coil induces a voltage, which can power an electric load in the external circuit. The mechanical domain is linked to the electrical domain by the transduction factor . The induced voltage can be obtained by [71]

A load resistor is connected to the EEH. Based on Kirchhoff’s voltage law, the sum of the voltages around any closed loop is zero. Then the electrical differential equation for a sub-EEH in this design can be described as follows

in which is the inductance of the coil and denotes the current in the circuit.

### 3.2.2 Triboelectric energy harvesting

Any TEH can be approximately modelled by a series connection of a variable capacitor and a voltage source [16]. In this section, an electrical dynamics model is developed which contains an equivalent capacitance and an open-circuit voltage. Both of them are determined by the gap between the contact surfaces of a TEH. The most significant theoretical equation for the real-time power generation of a TEH is the relationship among the voltage between the electrodes, the amount of transferred charges and the relative displacement.

As all the sub-TEHs are identical, the equivalent capacitance and the open-circuit voltage for those sub-TEHs at right end and left end can be expressed as

in which and are equivalent capacitance for the sub-TEHs at the right end and left end, respectively. and are the open-circuit voltage for the sub-TEHs at the right end and left end, respectively. is absolute dielectric permittivity of classical vacuum (8.854×10-12). denotes contact area between the FEP film and the single copper film. is the surface charge density. is the effective thickness of the FEP film, in which and denote the thickness and relative permittivity of the FEP film. and are the gaps between the FEP films and the single copper films in the sub-TEHs at the right end and left end, respectively, written as

For assessing the electrical output performance of the sub-TEHs, it is assumed that each sub harvester is wired with a load resistor . Then, for every sub-TEH at the right end, the voltage across the load resistor can be written as

in which is the amount of charge transferred in each sub-TEH at the right end.

Similarly, for every sub-TEH at the left end, the voltage across the load resistor can be written as

Applying Ohm’s law, substituting and , one can get the electric differential equations for the sub-TEHs at the right end and left end as

## 3.3 Computational algorithm and procedure

In the electrical system of the proposed harvester, as the order of magnitude of (absolute dielectric permittivity of classical vacuum) is of -12 and the load resistance can vary in a wide range in the electric differential equations for the sub-TEHs (Eq. (23) and Eq. (23)), Eq. (23) and Eq. (24) are stiff. Some traditional numerical methods, such as the fourth-order Runge-Kutta method (RK4), cannot be used to solve stiff differential equations. Therefore, the ode23tb solver provided in MATLAB based on an implementation of the trapezium integration rule and the second-order backward difference formula (TR-BDF2) is employed, which is suitable for solving stiff systems.

Besides, due to the modelling of impact, the mechanical model is non-smooth. During operation, the rolling magnet will get into contact with the sub-TEHs, and compress them. Impact events take place when the sub-TEHs are fully compressed. In addition, under low-frequency rocking excitation, the rolling magnet may stick with the casing at the left or right end for a while in each cycle. Therefore, the critical conditions for the contact, impact and stick are checked at each time step to see if those events have occurred, and the transition time instants for those events are captured. The corresponding computation flow chart can be seen in Appendix B.

# 4. Theoretical and experimental investigations

## 4.1 Fabrication of the prototype

For each sub-TEH, acrylic (PMMA) sheets (length:35mm, width:30 mm, thickness:1 mm) serve as substrates. Each sub-TEH includes two acrylic sheets, one of which is covered by a double-side conductive adhesive copper tape with a thickness of 30 μm. And the other acrylic sheet is covered by the coper tape and a fluorinated ethylene propylene (FEP) film with a thickness of 30 μm. The two substrates are connected by two pieces of polyvinyl chloride (PVC) sheet at two sides, working as the elastic connections, whose stiffness is measured to be about 10 N/m.

Two spools are firstly 3D-printed, then the copper wire with a diameter of 0.35 mm is wound on each of the two spools to produce two coils with nearly the same configuration. A multimeter is utilized to measure the resistance and inductance of the coils, which are 19.8 Ω and 11.6 mH. A neodymium magnet (diameter: 40 mm, thickness:10 mm) is utilized as the roller. A casing (80 mm × 40 mm × 44 mm) and a top cap are produced by 3D printing. The coils are placed in the two side cells inside the casing, and the sub-TEHs are glued at the two internal ends of the casing.

## 4.2 Measurement of coefficient of restitution during impact

The proposed harvester is a vibro-impact system, in which impact events take place between the roller and the casing at the two ends. In order to model the impact in this work, the instantaneous coefficient of restitution is measured and employed. As the power generation of the sub-TEHs relies on the contact between the single copper film and the FEP film resulting from the impact, the coefficient of restitution is a crucial factor for both the structural response and electric output.

A test rig is built to measure the coefficient of restitution for impact, as shown in Fig. 3 (a) and (b). A guide way is connected to the left end of the casing, where the roller is located initially. A sub-TEH is fixed at the right end of the casing. During measurement, the roller is pushed quickly toward right with different initial velocity, which then impacts with the sub-TEH at the right end of the casing. A PSV 500 scanning vibrometer is utilized to measure the velocity of the roller, as illustrated in Fig. 3 (c). The speed of the roller increases from zero due to the pushing by hand, which gradually decreases after being realised. When an impact event occurs, the velocity of roller experiences change of direction and magnitude instantaneously. According to the velocity just before impact and the velocity just after impact, the coefficient of restitution can be obtained based on Eq. (13). The coefficient of restitution can be usually treated as a constant [52]. However, for the proposed harvester, as the electric output from the triboelectric energy harvesters is directly determined by the contact-separation between the surfaces of the single copper film and the FEP film, impact under different velocities may affect the electrical behaviour. Therefore, the coefficient of restitution is measured under a number of different impact velocities, as shown in Fig. 3 (d). The data is then processed in Origin 2021 for curve fitting. The fitted curve for the coefficient of restitution versus impact velocity is expressed as



Figure 3. Test rig for the coefficient of restitution during impact. a) scanning vibrometer. b) test rig for impact. c) velocity of the roller before and after an impact. d) coefficient of restitution versus impact velocity.

## 4.3 Experiment setup

As described in section 3.1, the harvester is responsive to horizontal excitation, rocking excitation or a combination of the horizontal excitation, rocking excitation and vertical excitation. For the convenience of validation, a reduced model is firstly investigated, which only includes the horizontal excitation. And only one sub-TEH is utilized at each end. The experiment system for horizontal vibration energy harvesting is shown in Fig. 4. A BK Precision 4052 function generator and an APS 125 power amplifier are used to drive the APS 113 shake table. As the roller is a strong magnet, which can be affected by some steel components and the internal magnetic field of the shake table, the harvester is fixed on a wooden plate attached to the shake table to isolate the harvester from the shake table. A KISTLER 8690C50 accelerometer is fixed on the shake table, used to monitor its vibration amplitude. The signal of the accelerometer and the output voltages of the harvester across the load resistors are processed by an NI-9234 data acquisition module and LabVIEW 2021. In consideration of the fact that the sub-TEHs have a high internal impedance and the sub-EEHs have a low impedance, in order to obtain the maximal power, the load resistors of the sub-TEHs and the sub-EEHs are selected based on impedance matching result. That means when measuring the output voltage of the hybrid harvester, the sub-EEH is connected to a small resistor and the sub-TEH is wired with a large resistor. One of the striking characteristics of triboelectric energy harvesting is high output voltage. It is noted that the measuring range of the data acquisition module is from -5 V to +5 V, which may be lower than the voltage across the load resistor of the sub-TEH. Therefore, the load resistor of the sub-TEH actually consists of several resistors connected in series, which serve as a potential divider. The voltage across one of the resistors is fed into the data acquisition module. Then the final output voltage across the entire load resistor can be obtained via mathematical conversion in LabVIEW 2021.



Figure 4. Experiment system for horizontal vibration energy harvesting.

## 4.4 Results and analysis

For measuring the output voltage of the sub-EEH under horizontal excitation, a load resistor is connected with one of the coils, as shown in Fig.5 (a). According to the theory of impedance matching, the optimum load resistance should be equal to the coil resistance. As mentioned in section 4.1, the resistance of the coil is measured to be 19.8 Ω. Therefore, a resistor of 20 Ω is used as the load resistor for the sub-EEH during experiment. The excitation amplitude is 20 mm here. The measured output voltage of the single sub-EEH is shown in Fig. 5 (b). The peak voltage increases from 0.26 V at 1 Hz to 1.08 V at 4 Hz. Fig. 5 (c) illustrates the root-mean-square (RMS) output voltage and peak power of the sub-EEH under different excitation frequencies. As observed, the RMS voltage increases linearly from 0.085 V to 0.36 V when the excitation frequency increases from 1 Hz to 4 Hz. The corresponding peak power rises from 3.4 mW to 57.8 mW. At low frequencies, the effect of the coil induction can be neglected [72]. From Eq. (15) and (16), it can be seen that the voltage across the load resistor for the sub-EEH has a linear relationship with the velocity of the roller. For the nonresonant vibro-impact system, the RMS velocity increases linearly with the frequency at a certain excitation amplitude, which explains the linear relationship between the RMS voltage of the sub-EEH and the excitation frequencies. In numerical simulation, when the transduction factor is set to 1.9, the theoretical result fits best with the measured results. It should be pointed out that due to the nonresonant dynamics, the performance of the harvester is not limited by the frequency bandwidth, which is different from most vibration-based harvesters of other types whose maximum power usually appears within the frequency bandwidth.

During measuring the output voltage of the sub-TEHs, as illustrated in Fig. 5 (d), several resistors in series are wired with a sub-TEH, as explained at the end of section 4.3. The peak power with different load resistance is measured at *f*=2 Hz and *A*=0.02 m, as shown in Fig. 5 (e). A surface charge density of 15 µC/m2 is used here. The experimental result indicates that a sub-TEH has the highest peak power of 134.3μW when the load resistance is about 990 kΩ. The theoretical result also shows good agreement with the experimental data. With the optimum load resistance, the output voltage of the sub-TEH is measured under different excitation frequencies at *A*=0.02 m, as illustrated in Fig. 5 (f). As observed, when the excitation frequency increases from 1 Hz to 4 Hz, the amplitude of the output voltage also increases from 5.5 V to 14.5 V. For triboelectric energy harvesting, the durability of the device depends on the property of the triboelectric films and the configuration of the harvesters. In order to test the durability of the sub-TEH, the output voltage is measured on the shake table at 2 Hz after a number of cycles, as shown in Fig. 5 (g). After 2400 cycles, the output voltage still stays at the same level, which exhibits the stable performance of the sub-TEHs.

In the electrical modelling in section 3.2, a constant surface charge density is employed for the theoretical model of triboelectric energy harvesting. However, in actual experiment, it is found that the theoretical output voltage could not agree well with the measured voltage at different frequencies when using a constant surface charge density. As the power generation of the sub-TEHs depends on the impact, it is reasonable to believe that the surface charge density is affected by the impact. A similar test rig shown in Fig. 3 in section 4.2 is utilized to measure the output voltage under different impact velocities, and meanwhile the surface charge density is estimated in numerical simulation to fit the magnitude of the measured output voltage. The estimated surface density under different impact velocities is illustrated in Fig. 5 (h). A curve fitting result between the estimated surface charge density and impact velocity is obtained via Origin 2021, whose function is shown as follow.



Figure 5. Experimental investigations. a) measurement circuit for a sub-EEH. b) measure voltage of a sub-EEH. c) peak power and comparison of measured voltage and theoretical voltage of a sub-EEH. d) measurement circuit for the a sub-TEH. e) peak power of a sub-THE under different load resistances. f) measure voltage of a sub-THE. g) measured voltage of a sub-TEH after a number of cycles. h) estimated surface charge density. i) comparison of the theoretical and experimental peak voltage of a sub-THE. j) DC voltage with different capacitors. k) DC voltage under different excitation frequencies with a capacitor of 3.3 μF. l) 74 LEDs powered by the hybrid harvester.

It can be seen that the surface charge density increases with the rise of impact velocity when the impact velocity is approximately lower than 0.4 m/s. Due to the weak impact resulting from the low impact velocity, the interface of the sub-TEHs does not have full contact. The increased impact velocity further enhances the contact area (in microscale) between the single copper film and the FEP film, resulting in a higher surface charge density macroscopically. When the impact velocity is higher than 0.4 m/s, the surface charge density nearly keeps the same level. Because a relatively strong impact brings about a good contact between the single copper film and the FEP film, a further increase of the impact velocity will not significantly increase the contact area any more. A similar phenomenon about the impact-velocity-dependent charge density is also found in other studies [47,73]. Based on the experimental result, the original theoretical model for triboelectric energy harvesting is improved with the modified charge density. Fig. 5 (i) illustrates the measured voltage and the theoretical voltage using a constant charge density (15 μC/m2) and the modified charge density under different excitation frequencies, and the measured peak power is also shown here, which increases from 30.5 µW at 1 Hz to 212.1 µW at 4Hz. The theoretical model with the constant charge density gives a much higher prediction of the output voltage under lower frequencies and a lower prediction under higher frequencies. Compared with the result corresponding to the constant charge density, the result corresponding to the modified charge density has closer agreement with the experimental data.

The outputs of the hybrid energy harvester are AC voltages, which should be converted into DC voltage for powering potential electronic devices. With this in mind, each sub-harvester (sub-EEH and sub-TEH) is wired with a rectifier, then connected in parallel. The rectified voltage is fed in to a capacitor for testing charging performance of the harvester. A handheld digital oscilloscope (HANMATEK HO52) with a high impedance probe is employed to measure the DC voltage across the capacitor. The DC voltage with different capacitors (0.22 μF, 1 μF, 3.3 μF and 22 μF) at *f*=2 Hz and *A*=0.02 m is shown in Fig. 5 (j), which is a function of time. It can be seen that the charging speed decreases with the increase of the capacitance. A DC voltage of 6.6 V can be obtained with a capacitor of 0.22 μF, which decreases to 1.2 V when a capacitor of 22 μF is utilized. Fig. 5 (k) illustrates the DC voltage with capacitor of 3.3 μF under different excitation frequencies. Note that the DC voltage is improved with the increase of the frequency. The hybrid harvester with the rectifier circuit is used to power a number of light-emitting diodes (LEDs, rated voltage: 1.9 to 2.1 V) connected in series, as shown in Fig. 5 (l). During experiment, 74 LEDs are lit and shining at 3 Hz.

Besides the horizontal excitation, the proposed harvester is also able to work under rocking excitation or a combination of the horizontal excitation, rocking excitation and vertical excitation. Numerical simulations are carried out for further investigating the behaviours of the harvester under the different external excitations. Three cases are studied, namely, case 1: =0.02 m, =0, =0, *R*=0; case 2: =0, =0, = rad, *R*=0; case 3: =0.02 m, =0.02 m, = rad, *R*=0.2 m; which correspond to the horizontal excitation, rocking excitation and the combination of the horizontal excitation, rocking excitation and vertical excitation. Fig. 6 (a) and (b) illustrate the relative displacement and phase portrait of the roller at two different frequencies (0.5 and 1.5 Hz) under horizontal excitation. At 0.5 Hz (Fig. 6 (a)), no impact takes place due to the low excitation frequency, which means the sub-TEHs at the two ends do not make contribution to the entire output power as the sub-TEHs will not work without impact. Under horizontal excitation, the harvester requires higher frequencies such as 1.5 Hz shown in Fig. 6 (b), which help to bring about impact events. Under the rocking excitation (case 2), at 0.5 Hz as shown in Fig. 6 (c), the roller is able to impact with the ends and stick at the ends for a while before it goes backward. With the increase of excitation frequency, impact still happens with the disappearance of sticking, as illustrate in Fig. 6 (d). Under the combined excitation (case 3), the dynamic behaviours are similar with that under rocking excitation, as shown in Fig. 6 (e) and (f), where impact events take place at both low and high frequencies. The results above indicate that for the nonresonant harvester in this work, it is more suitable to harvest ultra-low-frequency energy under the rocking excitation or the combined excitation which includes rocking excitation. The harvester still can work under the horizontal excitation but requires higher excitation frequencies for the occurrence of impact.

According to the experimental results, it can be seen that the impact velocity affects the surface charge density of the sub-TEH. And the output voltage of the sub-EEH has a linear relationship with the velocity of the roller. Therefore, further comparisons of the impact velocity, the velocity of the roller and the corresponding output voltages of the sub-TEHs and the sub-EEHs at different excitation amplitudes with an ultra-low frequency (0.5 Hz) are carried out. As the dynamic behaviours under the rocking excitation and the combined excitation are similar, and in order to simplify the comparison, only the horizontal excitation and rocking excitation are involved here. Fig. 6 (g) illustrates the average impact velocity and RMS velocity of the roller under horizontal excitation. As observed, when the excitation amplitude is lower than 0.02 m, the average impact velocity is zero, which means no impact takes place. When the amplitude exceeds 0.02 m, impact events occur, and the impact velocity increases with the increase of the amplitude. As a result, the output voltage of the sub-TEH is zero when the amplitude of the horizontal excitation is smaller than 0.02 m, which increases when the amplitude is larger than 0.02 m due to the increase of impact velocity, as shown in Fig. 6 (h). The RMS velocity of the roller experiences a sharp rise at =0.02 m because of the occurrence of impact, resulting in a dramatic increase of the output voltage of the sub-EEH. Under the rocking excitation, the impact velocity and the RMS velocity of the roller are shown in Fig. 6 (i). Different from the results under the horizontal excitation, impact events take place even when the rocking angle is quite small, such as 2°. Consequently, the sub-TEH can work under small rocking angles with ultra-low frequencies, as shown in Fig. 6 (j). The results above indicate that the harvester has a high sensitivity to ultra-low-frequency and small-angle rocking excitation, which is conducive to low-frequency energy harvesting. For example, when the rocking angle and frequency are 13° and 0.5 Hz, the peak voltages of a sub-TEH and a sub-EEH are 7.6 V and 0.28 V (as shown in Fig. 6 (j)), and the corresponding powers are 58.3 µW and 3.9 mW. Under such a low frequency, the power of the proposed harvester is even higher than that of many reported harvesters [59,66,74].



Figure 6. Theoretical investigations about structural response and electrical outputs under different types of excitation. a) (b) response of the roller under the horizontal excitation at 0.5 and 1.5 Hz. c) (d) response of the roller under the rocking excitation at 0.5 and 1.5 Hz. e) (f) response of the roller under the combined excitation at 0.5 and 1.5 Hz. g) average impact velocity and RMS velocity of the roller versus excitation amplitude under the horizontal excitation at 0.5 Hz. h) peak voltages of a sub-TEH and a sub-EEH versus excitation amplitude under the horizontal excitation at 0.5 Hz. i) average impact velocity and RMS velocity of the roller versus rocking angle under the rocking excitation at 0.5 Hz. j) peak voltages of a sub-TEH and a sub-EEH versus rocking angle under the rocking excitation at 0.5 Hz.

# 5. Potential applications under different operation conditions

The proposed harvester is able to work under multi-directional excitations, namely horizontal excitation, rocking excitation or a combination of the horizontal excitation, the rocking excitation and the vertical excitation. The horizontal excitation is common among some vibrating structures, such as vehicles. The harvester can harvest horizontal vibration energy for powering structure monitoring sensors. The demonstration of the harvester working under horizontal excitation has been conducted via a shake table, as presented in section 4.

The swinging motion of arms or legs of humans or animals is a common form of rocking excitation. Under this kind of excitation, the harvester is able to scavenge biomechanical energy for health monitoring or animal tracking. Fig. 7 (a) illustrates the harvester shaken by hand. At each end of the harvester casing, there are two sub-TEHs piled together. So totally 4 sub-TEHs are used here. Fig. 7 (b) and (c) shows the output voltages of a sub-TEH with a load resistor of 990 kΩ and a sub-EEH with a load resistor of 20 Ω. A sub-TEH can achieve a peak power of 236.5 µW and a sub-EEH has a peak power of 23.1 mW. A capacitor of 47 µF is utilized in the rectifier circuit and an electronic clock is employed as the load, as shown in Fig. 7 (d) and (e). The harvester is able to power the electronic clock for continuous working under hand shaking. A video about the harvester powering the clock can be seen in the Supplementary material of this paper. For further demonstrating the potential applications of the harvester, the harvester is placed in a handbag with a walking human with a walking velocity of about 0.45 m/s (a rocking frequency of about 1 Hz), as shown in Fig. 7 (f) to (h). The sub-TEH can generate a peak power of 48.1 µW while the sub-EEH provides a peak power of 6.1 mW.



Figure 7. Demonstration of the harvester for biomechanical energy harvesting. a) the harvester on a hand. b) c) output voltages of a sub-TEH and a sub-EEH during hand shaking. d) circuit for powering the electronic clock. e) the electronic clock powered by the harvester when shaken by hands. f) the harvester in a handbag. g) h) output voltages of a sub-TEH and a sub-EEH when the harvester is placed in a handbag with a walking human with a walking velocity of about 0.45 m/s.

The combination of the horizontal excitation, the rocking excitation and the vertical excitation often occurs on floating structures on waves, which enable the proposed harvester to scavenge wave energy, as shown in Fig. 8 (a). In order to test the performance of the harvester for harvesting wave energy in laboratory, a test rig is built as shown in Fig. 8 (b) and (c). A tank is filled with water, in which there is a lightweight cuboid block floating at the center of the water surface. The floating block is connected to the bottom of the tank with a wire, like a mooring system. The proposed harvester is placed on the top of the floating block. A gyroscope sensor (WT901BLEC) is employed to record the pitch motion of the floating block. In order to create waves, one end of a L-shaped structure is fixed on the shake table, and a plate is bolted at the other end, serving as a wave paddle. A demonstration of the harvester to light a number of LEDs under wave excitations to form a word “UoL” (a commonly-used short form for the University of Liverpool) is shown in Fig. 8 (c). The performance of the harvester on waves is further investigated under two wave conditions, where an excitation amplitude of 0.01 m and 0.03 m at 2 Hz are applied on the wave paddle.

The excitation amplitude of 0.01m results in weak waves and small response of the floating block, whose pitch angle (with an average peak value of 7.8°) is shown in Fig. 8 (d). Consequently, impact events do not occur frequently, and the output voltage of the sub-TEH and sub-EEH are relatively low, as shown in Fig. 8 (e) and (f). When the excitation amplitude is 0.03 m, strong waves are generated, resulting in large response of the floating block. Its pitch angle is measured to be about 11.8°, as shown in Fig. 8 (g). Under this condition, a sub-TEH can produce a pick voltage of 8.96 V and a sub-EEH can generate a peak voltage of 0.34 V, as shown in Fig. 8 (h) and (i). The corresponding peak powers for a sub-TEH and a sub-EEH are 81.1 µW and 5.8 mW. With the capability of scavenging wave energy and modular design, a number of the harvesters can be easily integrated in buoys or form large-scale arrays on floating structures to power wireless sensors for monitoring the water quality, temperature, humidity or other environmental indices, as shown in Fig. 8 (j).



Figure 8. Demonstration of the harvester for wave energy harvesting. a) schematic of the working process for wave energy. b) schematic of the test rig. c) test rig during experiment. d) e) f) pitch angle of the harvester casing, output voltages of a sub-TEH and a sub-EEH when the excitation amplitude is 0.01 m. g) h) i) pitch angle of the harvester casing, output voltages of a sub-TEH and a sub-EEH when the excitation amplitude is 0.02 m. j) potential application of the harvester.

# 6. Discussions

The theoretical investigations and experiments presented above have shown the capability of the hybrid harvester for scavenging low-frequency energy under the horizontal excitation (vibration of the shake table), rocking excitation (motion of swinging arms) and combined excitation (motion of floating structures). Different from some non-resonant harvesters with a cycloid or circular path, the proposed harvester has a straight path for the roller, which makes the roller sensitive to small-angle rocking excitation. As illustrated in Fig. 6, even a small rocking angle under ultra-low frequencies can bring about a large displacement and a high velocity of the roller, and result in impact events taking place at the two ends of the harvesting casing, which is conducive to harvesting ultra-low-frequency energy. A comparison is made between the proposed harvester and some hybrid triboelectric-electromagnetic energy harvesters reported recently, as shown in Table. 1. Although the proposed harvester is not the most efficient one, it exhibits outstanding performance, compared with most of the reported harvesters.

Table 1. Comparison between the proposed harvester and some reported hybrid triboelectric-electromagnetic energy harvesters for low frequencies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Triboelectric layers | Dimension | Working conditions | Power of TEH | Power of EEH | Ref. |
| Kapton and paper | diameter: 20 mm; length :50 mm | 2 Hz | 1 μW | 4 mW | [75] |
| PTFE with nanowires and Al | unknown | 100 rpm | 90.7 μW | 0.08 mW | [76] |
|  |  |  |  |  |  |
| silicone and Cu (processed by a spin-coating  technique | length :190 mm;  width: 50mm;  height: > 20 mm | 2 Hz | 800 µW | 9 mW | [67] |
| FEP and Cu | diameter: 65 mm; length :55 mm | 500 rpm | 1.05 mW | 58.3 mW | [77] |
| Al layer synthesized by Ti3C2Tx MXene Nanosheets and PTFE | major diameter: 65 mm;  minor diameter: 45 mm | 3 Hz | unknown | 106 and 44.8 mW | [65] |
| PTFE nanowires and NdFeB | diameter: 13 mm; length :120 mm | 5 Hz | 57 µW | 144 mW | [64] |
| FEP and Cu | 80×55×50 mm | 15.5 Hz | 130 µW | 0.08 mW | [78] |
| PVB nanowire/PDMS  and nylon | 36×36×30 mm | 22.5 Hz | 100 µW | 2.8 mW | [66] |
| silicone wafers and Al | 100×88×43 mm | 2.4 Hz | 80 µW | 14.9 mW | [78] |
| FEP and Al | diameter: 95 mm; length :100 mm | 263 rpm | 14.4 μW | 15.6 mW | [79] |
| PTFE and Cu | width: 100 mm;  height: 167 mm | 2.5 Hz | 15.21 μW | 1.23 mW | [74] |
| microstructure PDMS and Al | 65×26×18 mm | Hand shaking | 88 μW | 11.5 mW | [80] |
| FEP and Cu | 80×40×40 mm | |  |  | | --- | --- | | Horizontal excitation | 4 Hz | | 3 Hz | | 2 Hz |   Hand shaking  Arm swinging  Wave excitation | 212.1 µW  206.7 µW  114.8 µW  236.5 µW  48.1 µW  81.1 µW | 57.8 mW  27.4 mW  11.6 mW  23.1 mW  6.1 mW  5.8 mW | This work |

# 7. Conclusions

This work presents a hybrid triboelectric-electromagnetic energy harvester (TEH-EEH) including two sub-EEHs and a number of sub-TEHs in contact-separation mode, which is able to scavenge low-frequency energy under different types of external excitations. Both the mechanical model and the electrical model of the harvester are established. A velocity-dependent coefficient of restitution is obtained based on experiment of impact events in the nonresonant vibro-impact harvesting system. The surface charge density of the triboelectric films is found to increase with the increase of impact velocity within a range and then remain nearly the same when the impact velocity exceeds a certain value. Accordingly, an impact-velocity-dependent charge density is identified based on the experimental results, which contributes to improving the theoretical model of the sub-TEH and bring about closer agreement between the theoretical and experimental results of electrical outputs. The dynamic behaviours of the proposed harvester under the different excitations are studied numerically. The comparison of the structural response and electric outputs under horizontal excitation and rocking excitation indicates that the harvester has a better performance under the rocking excitation at ultra-low frequencies. When being shaken by hand, the harvester is able to power an electronic clock to work continuously. A sub-TEH and a sub-EEH can generate a peak power of 48.1 µW and 6.1 mW, respectively, when the hybrid harvester is placed in a handbag carried by a walking human. A demonstration shows that the powers of a sub-TEH and a sub-EEH can reach 81.1 µW and 5.8 mW when the harvester is attached on a floating block under water wave excitations. This work introduces a new design of a hybrid triboelectric and electromagnetic energy harvester for scavenging low-frequency energy under different operation conditions, which is expected to pave the way toward the practical applications with low cost for wearable electronics and self-power sensors widely used in monitoring human or structure health and environment.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that have appeared to influence the work reported in this paper.

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# Appendix A

The mathematical derivation of Eq. (8) from the previous equations is shown as follows.

Substituting Eq. (3) and Eq. (4) respectively into Eq. (5) and Eq. (6) yields

Eq. () and Eq. () are multiplied respectively by and on both the left-hand and right-hand sides, then they become

By adding Eq. () with Eq. (), the following equation can be obtained

By substituting Eq. (7), and into Eq. (), Eq. () can be rewritten as

# Appendix B



Figure S1. Computational flow chart.

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