Wind energy harvesting from a conventional turbine structure with an embedded vibro-impact dielectric elastomer generator

Citation for published version:

Digital Object Identifier (DOI):
10.1016/j.jsv.2020.115616

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
Journal of Sound and Vibration

Publisher Rights Statement:
© 2020 Elsevier Ltd.

General rights
Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Wind energy harvesting from a conventional turbine structure with an embedded vibro-impact dielectric elastomer generator

C L Zhang¹,², Z H Lai¹*, M Q Li³, D Yurchenko⁴

¹ Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, People’s Republic of China
² School of Mechatronics Engineering, Nanchang University, Nanchang 330031, People’s Republic of China
³ Department of Mathematics, Nanchang University, Nanchang 330031, People’s Republic of China
⁴ Institute of Mechanical, Process & Energy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, UK

* Corresponding author: Z H Lai, E-mail: laizh@szu.edu.cn

Abstract: In this paper, a novel wind energy harvester is proposed and studied. The wind energy harvester consists of a conventional two-blade horizontal wind turbine and a vibro-impact (VI) dielectric elastomer generator (DEG) embedded symmetrically at the end of a rotating shaft. The wind energy is harvested by the VI DEG due to the rotational motion of the turbine’s blades and the shaft. The dynamic model of the proposed system under wind-induced rotations is established theoretically, and the energy harvesting (EH) process of the VI DEG is introduced with the system output voltage and power being derived. The impact-based rotational energy harvesting process of the system is validated experimentally by measuring the output voltages of a single-sided impact (SSI) DEG under different impact velocities, and by measuring the ball’s impact moments under rotational excitations, thus demonstrating the feasibility of the impact-based EH of DE material. Furthermore, the dynamical and electrical behaviors of the system under different wind speeds are fully studied through numerical simulations. The influences of the wind speed, tip speed ratio and the distance between dielectric elastomer membranes (DEM) on the system EH performance are further discussed. It is found that the proposed wind energy harvester can work effectively in a range of small wind speed and produce a relatively high output power as large as 0.7125 mW under a wind speed of 3.99 m s⁻¹. The tip speed ratio, distance between two DEMs can be selected as the adjusting parameter to produce optimal EH performance under different wind speeds, thus providing an effective solution for the design and improvement of the proposed system under different wind environments.

Keywords: Wind energy harvesting; Vibro-impact; Dielectric elastomer generator; Two-blade turbine
1 Introduction

With the rapid development of the Internet of Things and artificial intelligence technologies, many small-scale electrical devices emerged, such as various cameras and tachometers. These devices play important roles in our daily life. However, all these devices faced an issue of quickly-depleting electrical energy supplies. In many circumstances, the cost of wired electricity is high, and the battery replacement is often a difficult and costly routine. Therefore, harvesting energy from surrounding environments to power these devices has promising potentials. Environmental energy that can be harvested mainly includes wind, solar, wave and tidal energies. Among all these green energy sources, wind energy has attracted extensive attention from researchers because it is abundant and easy to be harvested [1].

Wind energy harvesting devices that can convert wind energy into electrical one have been intensively studied in the past decade [2]. These devices cover various scales from the conventional large-scale wind turbines to small- and micro-scale wind energy harvesters [3], which have been successfully applied in many application such as wireless network [4], automotive [5] and other sectors. To date, the majority of investigations on wind energy harvesters has been focused on the electromagnetic (EM) [2, 6] and piezoelectricity (PE) generators [7, 8]. Typical EM generators based on electromagnetic induction are mainly focused on the larger-scale wind energy due to its structural characteristics. In contrast, the small-scale EM generators have low generation efficiency under a small magnetic field at low frequency [9], which limits their applicability in wind energy harvesting from small-scale devices. Compare with EM generators, PE generators, which are able to operate under a lower frequency and produce a relatively high power output, are considered as the promising candidates [10-14]. Therefore, the majority of investigations on the small-scale wind energy harvesters mainly has been focused on PE-based structures. Since then, PE prototypes have been established to harvest wind-induced vibrational energy including vortex [15, 16], galloping [17, 18], and flutter [19, 20]. However, these devices can only generate a relatively small amount of energy, thus restricting their application potentials and making them less versatile than desired. Therefore, in order to improve the performance of the wind energy harvesters, it is necessary to keep searching for more suitable alternative solutions.

In recent years, a type of a novel electrostatic (ES) energy harvester based on dielectric elastomers (DE) materials have received widespread attentions due to their high energy density, large deformation, good electromechanical conversion efficiency and moderate or low cost, etc. [21-23]. DE materials are a type of electro-active polymers [22], which have shown their application potentials in actuators [24], humanlike robots [25], stretchable electronics [26], sensors [27], and energy harvesters.

The DE-based energy harvesters, which are also termed as DE generators (DEGs), can convert mechanical energy into electrical one under an input voltage and the capacitance variances resulting from external excitations. The first DEG was proposed by Pelrine et al. back in 2001 [28]. Furthermore, Suo et al [29] established the DE theory based on thermodynamics and continuum mechanics. Following their works, many studies related to DEGs have been published. The basic material properties of the dielectric elastomer membrane (DEM) and failure mechanisms, including material rupture, loss of tension, electrical breakdown, and electromechanical instability, were established [30] and a detailed
model that describes the four cycling phases of DE-based energy conversion was developed in [31]. These research results have laid the foundation for further investigations in DEGs. Up to now, several DEGs for energy harvesting (EH) have been developed such as the ocean wave generator [32], wind energy harvester [33], and contact-type generator [34], etc. The investigations found that the highest power density that has been achieved in a DEG experimentally is $3.8 \, \mu Wmm^{-3}$ [35], which is higher than those in EM ($2.21 \, \mu Wmm^{-3}$) [36], and PE ($0.375 \, \mu W mm^{-3}$) [37] generators.

Although many achievements have been made in the DEGs, these investigations mainly focused on DE materials and simple energy harvesting structures. For example, a vibro-impact (VI) DEG system, which can be used in energy harvesting from external vibrations, has been proposed by the authors previously [38, 39]. The research results have shown that the proposed VI DEG can achieve a high electrical power. However, the energy harvesting schemes for specific application scenarios, such as wind energy harvesting, are still limited so that DEGs have not achieved desirable results. In order to utilize the proposed VI DEG for energy harvesting in practical vibrational environments, a wind energy harvester with this VI DEG embedded into a bluff body was further proposed by the authors [33]. Research results showed that this scheme is suitable for energy harvesting from a high wind speed range, while it cannot work effectively under a low-speed wind. Therefore, it is necessary to further propose new DEG schemes that can harvest energy from low-speed wind environments.

In this paper, a novel wind energy harvester with a VI DEG embedded into a two-blade turbine is proposed to harvest wind-induced rotational energy from low-speed wind environments. The structure and energy harvesting mechanism of the proposed wind energy harvester is introduced in Section 2. The impact-based rotational energy harvesting process of DE material is validated in Section 3. In Section 4, the dynamical and electrical outputs of the proposed system under different wind speeds are studied through numerical simulations. In Section 5, the influences of the wind speed, the tip speed ratio and the distances between two DEMs on the system EH performance are discussed. Conclusions are drawn in Section 6.

2 Model analysis

2.1 Model introduction

In order to take advantage of the VI DEG in practical energy harvesting from sustainable sources such as wind energy, a novel wind energy harvester is proposed and studied in this paper, as shown in Fig. 1 (a). It can be seen that the system comprises a small two-blade turbine (including a base, two blades, a bearing and a rotating shaft) converting wind energy to rotational motions, and a VI DEG embedded symmetrically at the end of the rotating shaft. The VI DEG [33], whose structures and dimensions are shown in Fig. 1 (b), comprises a hollow cylinder with inner radius $R_0$, an inner ball of mass $m$ and radius $r_b$, rolling/sliding freely inside the cylinder and two pre-stretched circular DEMs with effective radius $R_0$ at both ends of the cylinder. The length of the DEG is denoted as $l$ and the distance between two membranes can be written as $d = l - 2w$, where $w$ is the width of the four identical cylindrical frames to connect the membranes with the cylinder.

For the convenience of further analysis, a Cartesian absolute coordinate system $xy-o$ is
introduced as follows: the coordinate origin locates at the center point of the turbine; \( x \)-axis indicates the rightward horizontal direction; \( y \)-axis indicates the upward perpendicular orientation, as shown in Fig. 1(a). Moreover, as to the rotational VI DEG, a relative coordinate system is introduced. The origin of the relative coordinate system for the inner ball coincides with that of the cylinder and is set in the center of the cylinder. In addition, a \( z \)-axis is defined along the axis of the VI DEG for both the cylinder and the inner ball, as shown in Fig. 1(b). It should be pointed out that, as an axis of the relative coordinate system, \( z \)-axis rotates with the rotations of the VI DEG. The initial positive direction of \( z \)-axis coincides with that of \( x \)-axis.

![Diagram](image)

**Fig. 1.** (a) The schematic diagram of the proposed wind energy harvester and (b) the structures and dimensions of the embedded VI DEG.

The proposed wind energy harvester works as follows. When the wind passes over the turbine, the turbine blades rotate accordingly, thus motivating the inner ball to move between two DEMs under the action of gravity and centrifugal force and impact both DEMs intermittently. Electrical energy can be harvested at each impact based on the mechanical-electrical energy conversion properties of the DE materials [28].

### 2.2 System dynamical analysis

In this section, the system dynamical behaviors under wind environments are analyzed. Here, we assume that the wind passes over the turbine perpendicularly, as shown in Fig. 1(a).

Without loss of generality, the turbine is assumed to rotate counterclockwise when it is subjected to the continuous wind, and the angular speed of turbine is \( \omega \) (rads\(^{-1}\)). Moreover, according to [40], the functional relationship between \( \omega \) and the wind speed \( u \) (ms\(^{-1}\)) and can be written as

\[
\omega = ku / R
\]

where \( k \) is the tip speed ratio, whose value ranges from 0 to 18 depended on the structure of the turbine [40]. In this paper, the value of \( k \) is selected as 1.4 for the used non-taper turbine blade structure. It should be noted that the starting threshold of wind velocity for the turbine is not considered in this paper.

As to the inner ball, its displacement in terms of the rotational \( z \)-direction is defined as \( z(t) \). Thus, the velocity \( v(t) \) and acceleration \( a(t) \) of the ball in terms of \( z \)-direction can be written as
\[ v(t) = \dot{z}(t), \quad a(t) = \ddot{z}(t) \]  

The friction between the ball and the slot is quite small and therefore it is ignored. Thus, the motion of the ball is influenced by the gravity component and the centrifugal force \( F_c \) during the rotations of the system. However, the directions of these two forces in terms of the \( z \)-direction rely on the ball’s position and the rotational angle of the system, which is given by \( \theta = \omega t = kut/R \), thus making them complicated to be analyzed. In order to calculate the resultant force on the ball accurately for further analysis, the force application on the ball with the considerations of the system rotational angle and the ball’s position are fully presented in Fig. 2, where cases I, II, III and IV represent the system conditions of the VI DEG under different rotational angles.

![Fig. 2. The force diagram of the ball under different position and system rotational angle](image)

Based on Fig. 2, it is easy to obtain the resultants force on the ball (in terms of the \( z \)-direction) in different cases, which are summarized in Table 1, where \( F(t) \) indicates the resultant of the ball against time \( t \).

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
<th>Resultant Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>I:</td>
<td>( 2k\pi \leq \theta &lt; 2k\pi + \pi / 2 )</td>
<td>[ F(t) = m\omega^2 z(t) - mg\sin(\theta) ] [ F(t) = -m\omega^2 z(t) - mg\sin(\theta) ]</td>
</tr>
<tr>
<td>II:</td>
<td>( 2k\pi + \pi / 2 \leq \theta &lt; 2k\pi + \pi )</td>
<td>[ F(t) = m\omega^2 z(t) - mg\sin(\theta) ] [ F(t) = -m\omega^2 z(t) - mg\sin(\theta) ]</td>
</tr>
<tr>
<td>III:</td>
<td>( 2k\pi + \pi \leq \theta &lt; 2k\pi + 3\pi / 2 )</td>
<td>[ F(t) = m\omega^2 z(t) + mg\sin(\theta) ] [ F(t) = -m\omega^2 z(t) + mg\sin(\theta) ]</td>
</tr>
<tr>
<td>IV:</td>
<td>( 2k\pi + 3\pi / 2 \leq \theta &lt; 2k\pi + 2\pi )</td>
<td>[ F(t) = m\omega^2 z(t) + mg\sin(\theta) ] [ F(t) = -m\omega^2 z(t) + mg\sin(\theta) ]</td>
</tr>
</tbody>
</table>

Considering that \( \sin(\theta) \geq 0 \) when \( 2k\pi \leq \theta < 2k\pi + \pi \) and \( \sin(\theta) \leq 0 \) \( (\sin(\theta) = -\sin(\theta)) \) when \( 2k\pi \leq \theta < 2k\pi + \pi \), the resultants of the ball under any rotational angles and positions can be written as:

\[ F(t) = m\omega^2 z(t) - mg\sin(\theta) \]  

(3)

According to Eq. (3), the acceleration of the ball can be written as
\[ \ddot{z}(t) = F(t) / m = \omega^2 z(t) - g \sin(\theta) \]  

(4)

Thus, the governing equation of the ball within the cylinder between two membranes can be written as

\[ \ddot{z}(t) = (ku / R)^2 z(t) - g \sin(kut / R) \]  

(5)

Furthermore, by defining \( s = d - 2r_b \) as the largest distance the ball can travel between two membranes, the conditions that impacts occur are easy to be obtained:

\[
\begin{align*}
\dot{z}(t) &= s / 2, \ v(t) > 0, \text{the ball impacts DEM 1} \\
\dot{z}(t) &= -s / 2, \ v(t) < 0, \text{the ball impacts DEM 2}
\end{align*}
\]  

(6)

At each impact, the velocities of the ball is governed by

\[ v_+ = -rv_- \]  

(7)

where \( r(0 < r < 1) \) is the coefficient of restitution (COR) of the DEM under the ball’s impacts; \( v_- \) and \( v_+ \) represent the velocities of the ball just before and after each impact. \( v_- \) can be calculated by the governing equation of the ball (Eq. (5)). Therefore, \( v_+ \) can be obtained if the value of \( r \) at each impact is given.

2.3 System electrical analysis

At each impact, the membrane is deformed and the largest areas \( A \) and smallest thickness \( h \) of the DEM can be obtained [39]:

\[
\begin{align*}
A &= 2\pi r_b^2 (1 - \cos \alpha) + \frac{\pi(R_b^2 - (r_b \sin \alpha)^2)}{\cos \alpha} \\
h &= \frac{\pi R_b^2 h_b}{A}
\end{align*}
\]  

(8)

where \( h_b \) is the initial thickness of the membrane, and the values of \( \cos \alpha \) and \( \sin \alpha \) are given by:

\[
\begin{align*}
\cos \alpha &= \frac{r_b (r_b - \delta) + R_b \sqrt{R_b^2 + \delta^2 - 2\delta r_b}}{R_b^2 + (r_b - \delta)^2} \\
\sin \alpha &= \sqrt{1 - \cos^2 \alpha}
\end{align*}
\]  

(9)

where \( \delta \) is the largest deflection of the membrane at each impact, which can be ascertained via experiments or theoretical calculation [33].

In addition, the maximum and minimal capacitance of the membrane at each impact can be calculated as:

\[
\begin{align*}
C_{\text{max}} &= \frac{\varepsilon_0 \varepsilon_r \text{Vol}}{h^2} \\
C_{\text{min}} &= \frac{\varepsilon_0 \varepsilon_r \text{Vol}}{h_0^2}
\end{align*}
\]  

(10)

where \( \varepsilon_0 = 8.854 \times 10^{-12} \) Fm\(^{-1} \) is the vacuum permittivity; \( \text{Vol} = \pi R_b^2 h_b \) is the constant volume of the membrane due to the incompressibility of the DE material; \( \varepsilon_r \) is the relative permittivity of the DE material which can be calculated according to [41]:

\[ \varepsilon_r = \varepsilon(T, \lambda) = a\lambda^2 + b / T + c \]  

(11)
where $T$ and $\lambda$ are the environment temperature and the DEM’s pre-stretched ratio, respectively; $a=-0.053$, $b=638$ K and $c=3.024$ are empirical constants.

Finally, by connecting the VI DEG to an energy harvesting circuit with a so-called “triangular” energy harvesting scheme [38], the output voltage $U_{out}$ at each impact can be calculated as:

$$U_{out} = \frac{C_{max} + C_T}{C_{min} + C_T} U_{in}$$  \hspace{1cm} (12)

where $C_T$ is the capacitance of the transfer capacitor of the circuit and $U_{in}$ is the constant input voltage. It was reported that most electrical energy can be harvested through this circuit when $C_T = 1.2 C_{min}$ [42].

The electrical energy gain at each impact can be obtained:

$$E = \frac{1}{2} U_{in} U_{out} (C_{max} - C_{min})$$  \hspace{1cm} (13)

Moreover, when a steady-state vibrations are considered, i.e., impacts will occur during a long time, the total energy $E_{total}$ harvested from the VI DEG and the generated output power $P$ can be calculated as:

$$\begin{align*}
E_{total} &= \sum_{i=1}^{n} E_i \\
P &= \frac{E_{total}}{t_2 - t_1}
\end{align*}$$  \hspace{1cm} (14)

where $n$ is the number of impacts during the time interval and $E_i$ is the harvested energy at $i^{th}$ impact; $t_1$ and $t_2$ are the start time and end time for calculation, respectively.

3. Experimental validation

3.1 Output voltage measurement experiment

In Section 2.3, the system output voltage at one impact is analyzed. The impact-based EH process of DE material is validated in this section using an output voltage measurement experiment for a single-sided impact (SSI) DEG.

The scheme of the SSI DEG is shown in Fig. 3, along with its fabrication process. The DEM specimens for experiments were fabricated using the VHB 4910 membranes (3M Corporation) with initial radius $R_{raw} = 20$ mm and thickness $h_{raw} = 1$ mm. The raw membranes were first pre-stretched radially by $\lambda$ times in order to improve their stiffness and respond speed. Hence, the thickness of the DEM became $h_0 = h_{raw} / \lambda^2$. The pre-stretched DEMs were then clamped using two identical home-made annular frames of inner radius $R_0 = 6$ mm. Two copper sheets were mounted between the DEMs and the frames to conduct charges. Next, the pre-stretched DEMs were coated with graphene electrodes (Tan Feng Technology). Finally, the obtained DEM specimens were installed in one end of a cylinder, thus obtaining a SSI DEG similar to the VI DEG.

The SSI DEG is helpful to study the dynamical and electrical responses of the VI DEG at one impact. Based on this SSI DEG, an output voltage measurement experiment was designed, as shown in Fig. 4, and the schematic diagram of this experiment is presented in Fig. 5. One
can see that this system consisted of a SSI DEG, an high-voltage power supply (BOHER 71030P) providing direct-current input voltage for the DEG, a diode preventing the charges flowing back, a voltage dividing circuit, and a multi-meter used to measure the output voltage of the SSI DEG. In Fig. 5, $U_{in}$ indicates the constant input voltage; the resistances $R_1 = 1 \times 10^9$ $\Omega$ and $R_2 = 1 \times 10^6$ $\Omega$. Thus, the output voltage of the SSI DEG can be calculated as $U_{out} = 1000U_{R_2}$, where $U_{R_2}$ is the measured voltages across $R_2 = 1 \times 10^6$ $\Omega$ when the SSI DEG generates higher output voltage.

![Fig. 3. The fabraction process of the singel-side impact DEG](image3)

![Fig. 4. The setup of the output voltage measurement experiment based on the SSI DEG](image4)

![Fig. 5. The schematic diagram of the output voltage measurement experiment system](image5)

Based on the proposed output voltage measurement system, the output voltages of the SSI DEG under different impact velocities $v = \sqrt{2gH}$ were measured and recorded, where $H$ represents the dropping height of the ball, which can be changed by changing the length of the cylinder. In the conducted experiments, the dropping heights $H$ of the ball were chosen as 50mm, 100mm, 150mm and 200mm, respectively. With the input voltage $U_i = 2000$ V and the pre-stretched ratio $\lambda = 3$, the measured output voltages of the SSI DEG under different impact velocities are presented in Fig. 6. It is noted that in order to obtain measurement results with adequate accuracy, the tests for each impact velocity were carried out at least ten times, thus obtaining the average output voltage. The error-bars indicating the maximum and minimum output voltages for each impact velocities were presented as well. It
can be seen from Fig. 6 that the output voltages are higher than the input voltages, thus verifying the effectiveness of the impact-based energy harvesting of DE materials. Although the measured values of the output voltages are lower than the theoretical ones, which is inevitable due to the leakage of the charges, the energy dissipation from the energy harvesting circuit, and not compliant electrodes, etc., it can be seen that the output voltage increases with the increase of the impact velocity from both experimental and theoretical results. Therefore, the feasibility of the theoretical approach in analyzing the influences of the impact velocity and other parameters can be verified.

It should be noted that, using the same SSI DEG shown in Fig. 3, $r$ and $\delta$ have been demonstrated as functions of the impact velocity through experiments [33].

**3.2 Impact measurement experiments**

In our previous work [33], we have shown that the value of $r$ is decided by the dimensional parameters and the material properties of the DEM, and the impact velocity between the ball and the DEM. Its calculation approach can be obtained through experiments using the proposed SSI DEG shown in Fig. 4. Thus, the dynamical behavior of the VI DEG subjected to the rotational excitations can be analyzed. In this subsection, an impact measurement setup is designed to measure the ball’s impact moments under rotational excitations, thus further providing an experimental verification for the system dynamical analysis.

The experimental setup is shown in Fig. 7(a), and the detailed drawing is shown in Fig. 7(b). It can be seen that the impact measurement system consisted of a VI DEG connected to a speed control motor (3IK15RGN-C), which can supply a rotational excitation to the VI DEG, a speed control unit that can control the speed of the motor, a laser displacement sensor (Panasonic HG-C1100) that rotates following the VI DEG used to measure the impacts between the ball and one DEM, a data acquisition card (USB DAQ-289) used to record the displacement data, and a voltage adapter used to power the laser displacement sensor. It should be pointed out that the laser displacement can only measure the deflection of the measured DEM 1, as shown in Fig. 7(b). Thus, when the displacement curve of DEM 1 strayed from its steady value, the time points were recorded as the impact moments.
Fig. 7. The setup of the impact measurement experiment used to measure the ball’s impact moments under rotational excitations.

In the conducted tests, the dimensional parameters of the VI DEG were \( l = 40 \) mm, \( d = 30 \) mm, \( r_b = 5 \) mm, \( R_o = 6 \) mm, and \( \lambda = 3 \). The rotational speed of the motor is 60 rpm (\( \omega = 2\pi \) rad/s). Thus, the ball’s displacement against time can be obtained through theoretical analysis combining the calculation approach of \( r \) obtained in [33]. The theoretical curve of the ball’s displacement containing two cycles is plotted in Fig. 8, where one can see that impacts occur when \( z_m(t) = \pm 0.01 \) m. Moreover, the impact moments recorded through experiments are plotted in Fig. 8 as well. It can be seen that the impact points of the experimental data have a good agreement with those of the simulated curve, thus verifying the theoretical dynamics analysis approach of the VI DEG subjected to rotational excitations.

![Graph of theoretical and experimental data](image)

**Fig. 8.** The simulated curve of the ball against time and the experimental curve of the DEM against time.

4. **Numerical simulations**

Based on the theoretical analyses presented in Section 2 and the experimental validation shown in Section 3, it is practical to calculate the harvested energy and output power under a given wind speed. However, it is difficult to obtain the system response analytically due to its highly nonlinear nature. Therefore, the fourth-order Runge-Kutta algorithm is adopted in this paper to solve the governing equations of motion. In this section, the dynamic behaviors of the VI DEG under given wind speeds are studied through numerical simulations, and the electrical outputs of the DEG system are presented as well.
In the numerical simulations, the values of the parameters are presented in Table 2 unless otherwise stated. Moreover, the initial position and velocity of the ball are set as \( z(0) = 0 \) m and \( \dot{z}(0) = 0 \) m/s.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>1.4</td>
<td>( r_b )</td>
<td>5 mm</td>
<td>( T )</td>
<td>25 °C</td>
<td>( R )</td>
<td>100 mm</td>
</tr>
<tr>
<td>( d )</td>
<td>30 mm</td>
<td>( \varepsilon_r )</td>
<td>4.69</td>
<td>( g )</td>
<td>9.8 ms(^{-2})</td>
<td>( h_c )</td>
<td>0.11 mm</td>
</tr>
<tr>
<td>( U_m )</td>
<td>2000 V</td>
<td>( R_0 )</td>
<td>6 mm</td>
<td>( w )</td>
<td>5 mm</td>
<td>( \lambda )</td>
<td>3</td>
</tr>
</tbody>
</table>

It should be noted that the calculation approaches of \( r \) and \( \delta \) for the presented parameters have been obtained through experiments [33]:

\[
\begin{align*}
  r &= 0.5989e^{-1.31v} + 0.2241 \\
  \delta &= -0.0069e^{-0.3498v} + 0.0083
\end{align*}
\]  

(15)

One can see from Eq.(12) that the system output voltage at each impact depends on the capacitance change of the DEM under the impact, which is determined by the largest deflection \( \delta \) of the membrane at the impact. Moreover, it can be found from Eq.(15) that \( \delta \) is dependent on the impact velocity \( v \). Therefore, in order to better understand the system electrical outputs including output voltages, harvested energy and system output power under different wind speeds, it is of great importance to analyze the dynamical behavior of the ball.

First, the case of a small wind speed \( u = 0.1 \) m/s is considered and the system dynamical and electrical outputs from 55 s to 65 s (indicating a stable state for the VI system) are presented in Fig. . The displacement and velocity of the ball in terms of the \( z \)-direction are plotted in Fig. (a, b), respectively, where the cases of different rotational angles are presented with different colors. It can be seen from Fig. (a, b) that the VI DEG is at case II between 55 s and 56.1 s, during which the displacement of the ball is equal to -0.01 m \((-s/2)\) and the velocity is equal to 0, indicating that the ball rotates under the contact of DEM 2 due to the coaction of the negative gravity component and the centrifugal force. The VI DEG changes to case III at 56.1 s, after which the gravity component becomes positive and increases gradually with the negative centrifugal force kept constant. When the absolute value of the gravity component is larger than that of the centrifugal force, the ball starts to depart from DEM 2 and moves along the positive \( z \)-direction under the larger gravity component until it impacts DEM 1. It should be noted that the ball impacts DEM 1 several times because both the gravity component and the centrifugal force are positive thus motivating the ball to impact DEM 1 again and again until its velocity is too small to depart from DEM 1. During case IV from 57.22 s to 58.34 s, the ball rotates under the contact of DEM 1. In the next case I, the ball starts to move to impact DEM 2 when the absolute value of the gravity component is larger than that of the centrifugal force. The VI DEG repeats this process and the ball impact both DEMs periodically, which can be seen from the closed phase trajectory of the ball from 50 s to 100 s, as shown in Fig. (c). Moreover, higher output voltages and electrical energies can be achieved at each impact, as shown in Fig. (d, e). The system output power can be calculated as 0.0567 mW under this wind speed.
Fig. 9. System responses under $u=0.1 \text{ m s}^{-1}$. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50~100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.

When the wind speed is increased to $u=0.5 \text{ m s}^{-1}$, the system dynamical and electrical responses are presented in Fig. , which is similar to Fig. . It can be seen that the output voltages become larger because the impact velocities are increased with a larger wind speed. The system output power is enhanced to 0.3097 mW.

Fig. 10. System responses under $u=0.5 \text{ m s}^{-1}$. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50~100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.

Situation changes when the wind speed is increased to $u=1 \text{ m s}^{-1}$, and the system responses are shown in Fig. . It can be seen from Fig. (c) that the ball’s motion presents a quasi-periodic state, and more details are presented in Fig. (a, b), where the displacement and velocity of the ball against time are plotted. It can be seen from Fig. (a) that at the first case II, the ball impact DEM 2 several times. After the VI DEG changes to case III, the gravity component of the ball becomes positive and larger. However, because the centrifugal force is larger due to a larger rotational speed, the ball passes over the central point of the VI DEG after a larger
rotational angle. Thus, the next impact with DEM 1 may occur even in case IV. Similar
impact conditions result in irregular output voltages and electrical energy gains of the system,
as shown in Fig. (d, e). The system output power under \( u = 1 \) m/s can be calculated as 0.2435 mW.

Fig. 11. System responses under \( u = 1 \) m/s. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50 ~ 100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.

Similarly, system responses under the wind speed \( u = 1.5 \) m/s are presented in Fig. It can be found from Fig. (a, b, c) that the ball moves periodically again. It can be explained that as rotational speed of the system continues to increase, the ball needs a larger rotational angle to pass over the centre so it cannot impact the DEMs in cases I and III, as shown in Fig. (a). Thus, regular output voltages and electrical energy gains can be observed in Fig. (d, e). The system output power under \( u = 1.5 \) m/s can be calculated as 0.2473 mW.

Fig. 12. System responses under \( u = 1.5 \) m/s. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50 ~ 100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.

Continuing to increase the wind speed to \( u = 2 \) m/s, the system responses from 59 s to 60 s are show in Fig. 7. It can be seen from Fig. 7(a, b, c) that the ball moves periodically.
However, one can see from Fig. 7(a) that at each cycle the ball impacts DEM 1 ones at case IV and impacts DEM 2 twice at case II, basically demonstrating the transition from 2:2 periodic motion to 2:1 period regime. Therefore, the curves of output voltage and electrical energy increment against time also present periodic patterns, as shown in Fig. 7(d, e). The system output power under $u = 2 \text{ ms}^{-1}$ can be calculated as 0.3011 mW.

![Fig. 7. System responses under $u = 2 \text{ ms}^{-1}$. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50 ~ 100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.](image)

However, when the wind speed is increase to $u = 2.5 \text{ ms}^{-1}$, no impacts occur and no electrical energy can be obtained at the stable state of the system, as shown in Fig. 8. It can be imagined that under a wind speed as large as $u = 2.5 \text{ ms}^{-1}$, the centrifugal force of the ball when it contacts either DEM is so large that the ball cannot depart from the DEM under its gravity for the selected length of the device. Therefore, the ball keeps contacting the DEM and its velocity in terms of the $z$-direction is always 0, as shown in Fig. 8(a, b).

![Fig. 8. System responses under $u = 2.5 \text{ ms}^{-1}$. (a) The movement displacement of the ball against time; (b) the velocity of the ball against time; (c) phase trajectories of the ball from 50 ~ 100 s; (d) the output voltage of the DEG against time; (e) the electric energy gain of the DEG against time.](image)

Thus, no higher output voltages and electrical energy gains can be obtained under this wind
speed, as shown in Fig. 8(d, e). It should be stressed that these results were obtained for the
given value of $k$ corresponding to a particular pitch angle. Obviously with the controlled
pitch angle, the velocity range which activates the energy harvesting can be changed.

5. Discussion

The dynamical and electrical behaviors of the proposed system under different wind speeds
are studied and explained in Section 4. It can be seen that the EH performance of the
proposed system is significantly affected by the wind speed. To better reveal this influence,
the EH performance under different wind speeds is studied in this section. Moreover, the
influence of the distance between two DEMs is further analyzed in this section.

5.1 EH performance under different wind speeds and tip speed ratios

It can be seen from Section 3 that the dynamical and electrical behaviours of the proposed
system are significantly affected by the wind speed. In order to further present the system EH
performances under different wind speeds, the system output power against wind speed ($0 \sim 5$
ms$^{-1}$) is plotted in Fig. 9. It should be noted that the blue dashed line represents the system
output power over $0 \sim 100$ s, and the red solid line represents that over $70 \sim 100$ s, which
indicates the stable operation state of the system. It can be seen that both curves almost
coincide with each other, indicating that the system can start to operate in its stable state
quickly.

When the wind speed increases from $0$ ms$^{-1}$ to as high as $5$ ms$^{-1}$, the power curves can be
roughly divided into four regions for different wind speeds. First, when the wind speed
increases from $0$ ms$^{-1}$ to $0.61$ ms$^{-1}$, the system output power is enhanced, which results from
more impacts and higher electrical gain at each impact, as shown in Fig. 9. Second,
when the wind speed increases from $0.61$ ms$^{-1}$ to $2.02$ ms$^{-1}$, the system output power
decreases first and then increases. The reason is that, when the wind speed increases within
this range, fewer impacts occur, but more electrical energy gain can be obtained at each
impact due to a larger impact velocity, as shown in the subplots in Fig. 9. These opposite
effects make the system output power higher when either the gravity component or the
centrifugal force is prominent ($u$ is small or large), but it gets lower when these two effects
offset each other. It can be observed that the highest output power (0.4748 mW) can be
achieved when $u=2.02$ ms$^{-1}$. Next, when the wind speed is higher than $2.02$ ms$^{-1}$, the output
power is rapidly decreased from 0.4748 mW to 0 mW because the ball can hardly pass over
the centre of the cylinder due to the dominant centrifugal force imposed by high wind speeds,
thus resulting in weak impacts and low output power. Finally, when the wind speed is greater
than $2.22$ ms$^{-1}$, no impacts occur and no electrical energy can be harvested from the VI DEG, as
shown in Fig. 8. It can be seen that the proposed system can work effectively during the
second wind speed range, which is about $0.61$ ms$^{-1}$ to $2.02$ ms$^{-1}$.

Moreover, it can be learnt from the theoretical analysis that the wind speed affects the
angular speed of turbine, thus deciding the system EH performance. Therefore, one can see
from Eq. (1) that the tip speed ratio $k$, which is decided by the structure of the turbine, has
the same influence on the system EH performance. Therefore, in practical wind energy
applications, the structure of the turbine can be appropriately designed to achieve a proper tip
speed ratio to match different wind speeds and produce optimal EH performance.
Fig. 9. System averaged output power against wind speed under $d=0.03$ m, $R=0.1$ m, $t=70 \sim 100$ s.

5.2 Influence of the distance between two DEMs on the system EH performance

The system parameters also have influences on the system EH performance. It can be seen from Eq. (6) that the impact conditions are affected by the distance between two DEMs ($d$), which can be easily adjusted for practical application. In this subsection, the influence of $d$ on the system output power is studied.

The system stable output power ($70 \sim 100$ s) against $d$ ($0.015 \sim 0.15$ m) is presented in Fig. 10, where the wind speed $u=1$ $\text{m s}^{-1}$. It can be seen that as the value of $d$ increases from 0.015 m to 0.15 m, the system output power curve can be divided into three regions: two-side impact region ($0.015 \sim 0.08752$ m), one-side impact region ($0.08752 \sim 0.1092$ m) and nonimpact region ($0.1092 \sim 0.15$ m). In the two-side impact region, in which the ball impact both DEMs regularly, the system output power keeps relatively stable as the value of $d$ increases. The reason is that a larger $d$ results in fewer impacts but higher impact velocity (also larger electrical energy gain) at each impact. The one-side impact region indicates the ball only impacts one DEM because the centrifugal force acting on the ball is so strong that it cannot pass over the central point of the VI DEG and impact the other DEM. In this region the system output power drops rapidly due to weaker impacts as the value of $d$ increases. While in the nonimpact region ($d > 0.1092$ m), the system output power is equal to 0 because the distance between two DEMs is so large that the ball moves from one side to another before it impacts either DEM.

In order to further reveal the combined effect of the wind speed and the distance between DEMs on the system EH performance, the system output power from $70 \sim 100$ s against different sets of $u$ and $d$ is plotted in Fig. 11. It can be seen that on one hand, as the distance between DEMs increases, the range of the effective wind speed becomes narrower; and vice versa. On the other hand, as the wind speed increases, the range of the effective operating distance between DEMs becomes narrower as well; and vice versa. It can be observed in Fig. 11 that the device can produce the largest output power $P=0.7125$ mW when $u=3.99$ $\text{ms}^{-1}$ and $d=15.27$ mm. In order to better observe the results, the system output powers ($70 \sim 100$ s) against the wind speed under different values of $d$ are plotted in Fig. 12(a), and those against $d$ under different wind speeds are plotted in Fig. 12(b). It can be seen from Fig. 12(a) that all
curves have the similar pattern shown in Fig. 9, but the effective wind speed range becomes narrower for a larger value of $d$. Moreover, it is can be seen from Fig. 12(b) that all curves show a similar pattern as that in Fig. 10, but the effective range of $d$ becomes narrower for larger values of wind speed. In practical applications, the distance between DEMs can be adjusted according to the wind speed to achieve an optimal EH performance for the proposed wind energy harvester.

**Fig. 10.** System averaged output power against the distance between two DEMs under $u=1$ m s$^{-1}$, $R=0.1$ m, $t=70$–100 s.

**Fig. 11.** System averaged output power over 70 – 100 s under different sets of wind speed and distance between two DEMs for $R=0.1$ m.
Fig. 12. System averaged output power from 70 ~ 100 s against (a) wind speed under different distances between two DEMs, (b) distance between two DEMs under different wind speeds for \( R=0.1 \) m.

5.3 Comparison with other unconventional wind energy harvesters

It can be seen from the results presented in Sections 5.1 and 5.2 that the proposed wind energy harvester can operate effectively under low-speed wind and generates a relatively high output power. In order to further evaluate the EH performance of this device, its effective operating wind speed range and maximal output power are compared to a PE-based wind energy harvester [43] and another DE-based wind energy harvester [33], as shown in Table 3.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Conversion Mechanism</th>
<th>Effective operating wind speed range (ms(^{-1}))</th>
<th>Optimal wind speed (ms(^{-1}))</th>
<th>Maximal output power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[43]</td>
<td>PE</td>
<td>2 ~ 10</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>[33]</td>
<td>DE</td>
<td>2.1 ~ 15.4</td>
<td>5</td>
<td>0.16</td>
</tr>
<tr>
<td>This work</td>
<td>DE</td>
<td>0 ~ 4.5</td>
<td>3.99</td>
<td>0.71</td>
</tr>
</tbody>
</table>

It can be seen from the comparison results shown in Table 3 that the PE-based wind energy harvester can work effectively during a wind speed range of 2 ~ 10 ms\(^{-1}\) and generate an output power as large as 0.3 mW under a relatively high wind speed value (10 ms\(^{-1}\)). The previous DE-based wind energy harvester can work effectively in a wider wind speed range, but it can only produce the lowest maximal output power (0.16 mW) among these three devices. The wind energy harvester proposed in this paper, which is suitable to work under wind speed from 0 ~ 4.5 ms\(^{-1}\), can produce the highest output power as larger as 0.7125 mW, indicating its superiority of wind energy harvesting from low-speed wind environments. Moreover, another advantage of this system is that one can also mount several VI DEGs to a rotational shaft connected to the wind turbine, thus further enhancing the wind energy harvesting performance of the proposed system.

6. Conclusions

In order to take advantage of the dielectric elastomer material in wind energy harvesting, a novel wind energy harvester with a vibro-impact (VI) dielectric elastomer generator (DEG) embedded into a two-blade turbine is proposed and studied in this paper. The system model is first proposed, and its wind energy harvesting mechanism is introduced by deriving its
dynamic governing equations of motion and electrical outputs (including output voltage, electrical energy gain and output power) under a given wind speed. Furthermore, the impact-based rotational energy harvesting process of the system was validated experimentally by measuring the output voltages of a single-sided impact (SSI) DEG and by measuring the ball’s impact moments under the rotational excitation. On this basis, the system dynamical and electrical outputs under different wind speeds are fully investigated through numerical simulations. It is found that the wind speed has a significant influence on the system outputs and further affects the system energy harvesting (EH) performance. The system can work effectively within a low wind speed range. Moreover, the influences of the tip speed ratio and the distance between two dielectric elastomer membranes are studied and the simulated results show that these two parameters can be adjusted to broaden the effective wind speed range and match different wind speeds to produce optimal EH performance. It is found that the proposed system can achieve the highest output power of 0.7125 mW under a wind speed of 3.99 ms⁻¹. The proposed system is compared with a PE-based wind energy harvester and a previously proposed DE-based wind energy harvester, and the superiority of the wind energy harvester proposed in this paper in low-speed wind energy harvesting is demonstrated. The device can also benefit from a pitch control system of the blades to adjust to different wind speeds.

Acknowledgement

This work was supported by National Natural Science Foundation of China (Grant No. 51905349), Natural Science Foundation of Guangdong Province (Grant No. 2020A1515011509), and Natural Science Foundation of Shenzhen University (Grant No. 2019036, 860-000002110264).

References


