Multibeam energy harvester for rotational low-frequencies

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Abstract. The mechanical vibration induced by rotation speed is gaining interest in the last years. Comparing to other mechanical vibration sources, the excitation by rotational speed from low power wind turbines is really a challenge since the vibration frequency is lower than 10 Hz and it generates accelerations higher than 1 g. In this paper, a rotating piezoelectric energy harvester is designed and analysed. In order to achieve the best electrical power performance, the prototype is designed to have low natural frequencies varying the hub positions and dimensions of the multi-beams, decreasing the crossing-frequency (natural frequency/rotation speed) and finding the optimal electrical load resistance. The dynamic behaviour of the harvester is simulated using a nonlinear one-dimensional finite element formulation. The rotating piezoelectric beam is formulated by means of a geometrically nonlinear finite element with six mechanical degrees of freedom and one electrical degree of freedom per node. The simulations are performed from 1 to 4.5 Hz (60 – 270 rpm) rotation speeds. A performance assessment is done investigating the influence of the hub positions, crossing-frequencies, electrical resistance and rotation speeds over the voltage and power generation. Regarding harvester’s performance, promising results are obtained since the output power 3.72 mW @ 3.61 Hz. In this sense, this article provides a prototype at low rotational frequency capable to scavenge energy from low power wind turbines.

1. Introduction

Sensing electronic devices in wind turbines are known for their small size and low power consumption. The most commonly used sensors are ultrasonic wind sensors, weather, pressure, humidity temperature and temperature transmitters. Mostly, electrochemical batteries are the best choice today to powering these sensors or electronic devices. Despite the advantages of batteries such as low cost, high energy density and small size, they have disadvantages such as low durability, inconveniences to recharging and environmental pollution. On the other hand, the evolution of alternative energy sources to powering electronic devices with low power consumption is gaining interest in the science community. In the last decade, one source of alternative energy is the energy harvesting from mechanical vibrations under base acceleration excitation [1],[2]. Between them, mechanical vibration induced by rotation speed has drawn much attention in the last years [3],[4]. In comparison with to other mechanical vibration sources, rotational excitation from low power wind turbines is really a challenge since the vibration frequency is lower than 10 Hz and the accelerations are higher than 1 g.
In this paper, a rotational piezoelectric energy harvester comprising of multi-beams is designed and analyzed. In order to obtain the maximum power [5], the prototype is designed to have low natural frequencies near the rotation speeds, varying the hub positions (R) and the dimensions of the multi-beams. The dynamic behavior of the harvester is simulated using a nonlinear one-dimensional finite element formulation developed by Ramírez, et al [6]. The rotating piezoelectric beam is formulated by means of a geometrically nonlinear finite element with six mechanical degrees of freedom and one electrical degree of freedom per node. The simulations are performed from 1 to 4.5 Hz (60 – 270 rpm) rotation speeds at three hub positions (R). A performance assessment of the influence of the hub distance (R) on the crossing-frequencies is investigated. For the selected dimensions, the crossing-frequency phenomenon is induced by the softening effect [7], which yields a natural frequency near the rotational frequencies. The effect of rotation speeds and electrical load resistance over the voltage and power generation are assessed. Finally, the study of the results obtained concludes that the proposed design is a promising prototype to scavenge energy from low power wind turbines.

2. Design and modelling
The proposed harvester consists of multiple beams with attached masses and a MFC 2814 P2 piezoelectric sheet (fabricated by NASA and commercialized by Smart Material Corporation) mounted on one of the multiple beams. The material properties of the harvester are show in table 1. The prototype is mounted on a rigid plate that has the possibility to adjust the hub position (R) with respect to axis of rotation (see figure 1). Likewise, the rigid plate rotates at a constant angular velocity \( \Omega \).

![Figure 1. Schematic of the rotating energy harvester prototype.](image)

| Material     | Aluminium | MFC 2814 P2 | Steel |
|--------------|-----------|-------------|-------|
| E₁           | 67 GPa    | 30.3 GPa    | 210 GPa|
| E₂           | 67 GPa    | 15.85 GPa   | 210 GPa|
| Density      | 2700 kg/m³| 5440 kg/m³  | 7850 kg/m³|
| Piezoelectric constant \( d_{31} \) | -2.1 E+2 pm/V | | |
| Capacitance  | 30.78 nF  | | |

2.1. Finite element formulation
A one-dimensional finite element is used for modeling three-dimensional rotational energy harvesters [6]. The rotating piezoelectric beam is formulated by means of a geometrically nonlinear finite element with six mechanical degrees of freedom and one electrical degree of freedom per node. The electromechanical equations of motion in matrix form are:

\[
K_T \ddot{U} + D \dot{V}_C + C_e \ddot{V}_C + M \ddot{\tilde{a}}_G - \Theta \ddot{V} = F_E
\]

\[
\Theta^T \ddot{U} + C_p \dot{V} + Q_E = 0
\]

where \( \dot{V} \) and \( \ddot{U} \) are the nodal voltage and displacement vectors. \( \dot{V}_C \) and \( \ddot{\tilde{a}}_G \) are the nodal velocity and acceleration vectors. \( F_E \) and \( Q_E \) are the mechanical and electrical loads. \( K_T \) is the total stiffness
matrix which includes the material, geometric, and rotation stiffness, $D$ is the damping matrix. $\Theta, C_P$ are the electromechanical and capacitance matrices, respectively.

3. Numerical results and discussion

3.1. Natural frequencies of vibration

One of the key points of the harvester design in this case is to obtain low natural frequencies to achieve the resonance phenomenon at low rotational speeds. All the simulations of the rotating system are performed at constant angular velocity from $1 - 4.5$ Hz (60 to 270 rpm) for three hub positions, $R = -0.03$ m, $R = 0$ m and $R = +0.03$ m as shown in figure 2. The study of the harvester starts with the modal analysis; this requires designing specific dimensions of the beams and the tip masses of the harvester to obtain a low natural frequency. After this process, the first natural frequency of the non-rotating system is 4.7 Hz. Additionally, the influence of the hub distance ($R$) on the crossing-frequency phenomenon, which yields a natural frequency near the rotational speeds, is evaluated. The results show that the natural frequency decreases as the rotational speed increase for all three cases of $R$. The decrement of the natural frequencies is due to the softening effect of the rotating structure, i.e. the contribution of negative stiffness [7]. The values of the crossing-frequency are: 3.61 Hz at $R = -0.03$ m, 3.30 Hz at $R = 0$ m and 3.53 Hz at $R = +0.03$ m.

![Figure 2](image)

**Figure 2.** The schematic of three positions of the harvester (a) $R=-0.03$, (b) $R=0$ and (c) $R=+0.03$ m.

3.2. Energy harvester performance

The harvester prototype is excited by rotational speed from 1 to 4.5 Hz (60 – 270 rpm) for all three $R$ varying the load resistances values: 10, 100, 330 and 1000 kΩ. The voltage generated is shown in figures 3-5. Clearly, it can be seen that the maximum voltage is generated when the resonance phenomenon is reached and above this value, the voltage generation decreases. It is important to note that increasing the rotation speeds higher than 4.5 Hz (270 rpm), the voltage generation starts to increase due to the resonance of the second bending mode. However, going beyond this frequency, the stress limits of the whole structure of the harvester are exceeded.

![Figure 3](image)

**Figure 3.** Voltage vs. rotation velocity ($R = -0.03$ m).

![Figure 4](image)

**Figure 4.** Voltage vs. rotation velocity ($R = 0$ m).

![Figure 5](image)

**Figure 5.** Voltage vs. rotation velocity ($R = +0.03$ m).
In figure 3, the maximum voltage is generated at 3.61 Hz, where the resonance phenomenon is reached. The maximum voltages for different load resistance values are: 0.92 V – 10 kΩ, 8.80 V – 100 kΩ, 26.36 V – 330 kΩ and 61.70 V – 1000 kΩ. Similarly, figures 4-5 show the maximum voltages generated as a function of rotation speed are: 0.40 V – 10 kΩ, 3.82 V – 100 kΩ, 11.35 V – 330 kΩ and 26.59 V – 1000 kΩ at R = 0 m and 0.88 V – 10 kΩ, 8.49 V – 100 kΩ, 25.20 V – 330 kΩ and 59.01 V – 1000 kΩ at R = +0.03 m. A summary of the maximum voltage and power generation as a function of rotational speed from 1 to 4.5 Hz (60 – 270 rpm) for all hub distances are illustrated in figures 6 and 7, respectively.

![Figure 6](image1.png) ![Figure 7](image2.png)

**Figure 6.** Maximum voltage generation as a function of R.

**Figure 7.** Maximum electrical power as a function of R.

As it can be observe in this last figure that the best configuration of the prototype is for R = -0.03 m (Ω = 3.61 Hz – 216 rpm, 61.7 V) which gives a value of electrical power $P = V^2/1 \, \text{MΩ} = 3.72 \, \text{mW}$.

### 4. Conclusions

This paper presents a novel low frequency rotating energy harvester. The rotating piezoelectric beam is formulated by means of a geometrically nonlinear finite element with six mechanical degrees of freedom and one electrical degree of freedom per node. In order to design the harvester, the simulations are performed from 1 to 4.5 Hz (60 – 270 rpm) rotation speeds. Several design features of the prototype such as the hub position (R), the tip masses and dimensions of the multi-beams are considered to achieve the crossing-frequency phenomenon as lower as possible. Regarding the harvester performance, promising results are obtained with a power of 3.72 mW at 3.61 Hz for R = -0.03 m. With this generation this prototype is good candidate to harvest energy from low power wind turbines.

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