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A low frequency rotational energy harvesting system

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Abstract. This paper presents a rotary power scavenging unit comprised of two systems of flexible beams connected by two masses which are joined by means of a spring, considering a PZT (QP16N, Midé Corporation) piezoelectric sheet mounted on one of the beams. The energy harvesting (EH) system is mounted rigidly on a rotating hub. The gravitational force on the masses causes sustained oscillatory motion in the flexible beams as long as there is rotary motion. The intention is to use the EH system in the wireless autonomous monitoring of wind turbines under different wind conditions. Specifically, the development is oriented to monitor the dynamic state of the blades of a wind generator of 30 KW which rotates between 50 and 150 rpm. The paper shows a complete set of experimental results on three devices, modifying the amount of beams in the frame supporting the system. The results show an acceptable sustained voltage generation for the expected range, in the three proposed cases. Therefore, it is possible to use this system for generating energy in a low-frequency rotating environment. As an alternative, the system can be easily adapted to include an array of piezoelectric sheets to each of the beams, to provide more power generation.

1. Introduction

It is still a remained challenge to design energy harvesting (EH) systems for real applications. This means a scavenging mechanism capable of working at low frequencies (<100 Hz) and low accelerations (<1g). Most of previously large amount of work on EH systems were developed for harvesting energy in vibrating environments [1, 2]. However, a major shortcoming is the high selectivity in the frequency range where the generation is significant, since most of them work at resonance [3]. Energy harvesting from rotational motion is one of the alternatives to this problem when rotational kinetic energy is available (rotating machines, shafts, wheels, tires). It is demonstrated that under a proper design, the resonant frequency of the harvester can match the frequency of the rotation over a wide frequency range [4]. Khameneifar et al. [5] modelled and analyzed an EH system comprising a cantilever beam with a tip mass, on which a PZT is mounted. All the system is fixed on a rotating hub. Then, mechanical vibrations are generated by the gravitational force while the hub is in rotary motion. They demonstrated that the device could be used as a power generator to provide enough energy for charging batteries of wireless sensors in rotating mechanisms. Hsu et al [6] presented a self-frequency tuning EH system for rotational motion, consisting on a cantilever beam mounted on a rotating axis similar to the configuration of ref. [5]. However, a more complete FEM formulation is considered in this case, since it takes into account shear deformation, piezoelectric plate, and the centrifugal force in the beam harvester. Their

results show a relatively good power generation but fails to predict a precise voltage peak generation. More recent, Guan and Liao [7] reported a generation about 80-800 μW on a rotating prototype cantilever piezoelectric beam. The system is aimed at introducing a rotational EH system, which can generate a high output voltage at low speeds.
This paper presents an innovative design of a piezoelectric EH system which represents an alternative to the most common cantilevered beam systems to generate energy on a rotating environment. The system can be adapted to add/eliminate beams in the device to explore its dynamics with the aim to maximize voltage generation. Numerical modelling and experimental data sustain the validity of the projected mechanism.

2. Design and Modelling

The proposed EH system comprises two systems of flexible aluminum beams connected by two masses jointed by a spring with a PZT (QP16N, Mide Corporation) piezoelectric sheet mounted on one of the beams. The device is placed rigidly on a rotating hub, at some distance of the axis of rotation, which is parallel to the span of the system of beams (see figure 1).

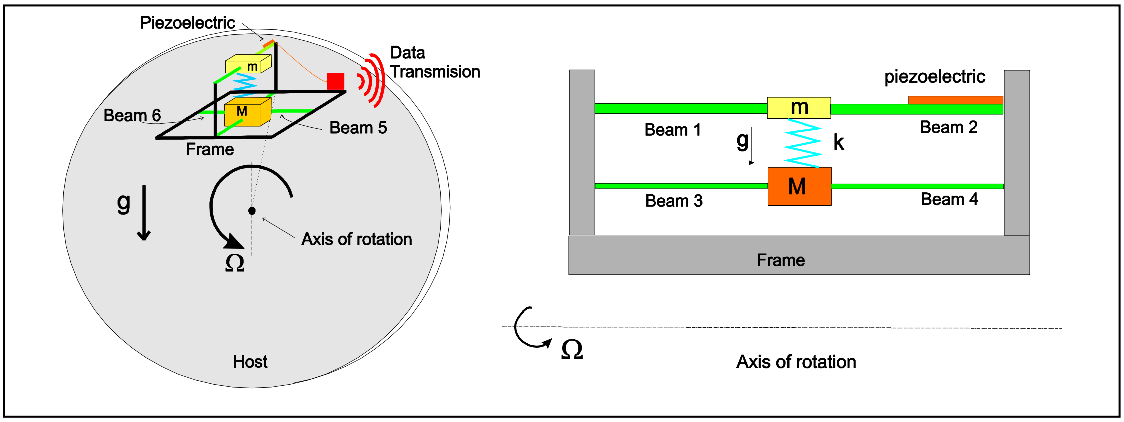

Figure 1: Schematic picture of the system comprising six beams and a piezoelectric sheet mounted over one of them. Front view (left) and lateral view (right).

Table 1. Parameters of beam structure and PZT element.

	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	Young`s modulus (GPa)	Coupling d_{31}(pm/V)	Capacitance (nF)	Permittivity
Beams 1-2	75	25	0.5	2700	70	-	-	-
Beams 3-6	75	18	0.5	2700	70	-	-	-
QP16N	45.9	20.57	0.25	2700	67	-190	90.78	1500 ε_0

The mathematical formulation of the problem is based on a finite element (FE) unidimensional description. In contrast with analytical models, the FE method allows to build complex geometrical models such as the proposed here. The main aspects of the present piezoelectric rotating beam formulation are as follows. The kinematics is based on Timoshenko's beam theory, the electrical potential is a linear interpolation through the piezoelectric's thickness and a linear constitutive model for the piezoelectric material is adopted in this primary approach to the problem. However, the authors recognize the failures of the linear model as has been suggested by other researchers [8] for similar levels of excitation. In this sense, future work will be conducted to consider this point.

The system is designed to test different arrange of beams in the device: two beams in different planes, four beams in different planes and six beams, which allow different possibilities of voltage generation (see fig 2). All three cases possesses one piezoelectric sheet attached to one of the beams. However, the prototype is thought to include an array of piezo elements to provide more power generation.

2.1 Mathematical formulation

As it has been stated before, a FE formulation is proposed to model the EH system of figure 1. This method provides a convenient approach for the discretization of a continuum in case of complex geometry. Regarding the FE construction, we build the elements in such a way that each beam has 2 nodes per element with 12 degrees of freedom (6 at each node=3 displacements + 3 rotations). The discrete matrix form of the dynamics governing equations can be written as:

$$\boldsymbol{M}\,\ddot{\boldsymbol{U}} + \boldsymbol{D}\,\dot{\boldsymbol{U}} + (\boldsymbol{K_M} + \boldsymbol{K_G} + \boldsymbol{K_R})\boldsymbol{U} + \boldsymbol{C_c}\dot{\boldsymbol{U}} - \boldsymbol{\Theta}\,\boldsymbol{V} = -\boldsymbol{F_E} \quad (1)$$

$$\boldsymbol{\Theta^T}\dot{\boldsymbol{U}} + \boldsymbol{C_P}\,\dot{\boldsymbol{V}} + \frac{\boldsymbol{V}}{R_E} = \boldsymbol{0} \quad (2)$$

where is $\boldsymbol{U}$ the nodal displacements and $\boldsymbol{M}, \boldsymbol{K_R}, \boldsymbol{D}, \boldsymbol{C_C},$ are the mass, rotation stiffness, damping and Coriolis force matrices respectively. Additionally $\boldsymbol{K_M}, \boldsymbol{K_G}, \boldsymbol{\Theta}, \boldsymbol{C_P}$ are the material, geometric stiffness, electromechanical and capacitance matrices respectively with R_E being the resistive load and $\boldsymbol{F_E}$ a vector representing the external forces which includes the acceleration due to gravity [10].

2.2 Numerical validation of FE with ABAQUS

A commercial software ABAQUS is used to validate the three dimensional piezoelectric rotating finite beam element. The results are shown in figure 2, for the material constants of table 1 and the other parameters are: k = 568 N/m, m=31.6 gr and M=76 gr. From the figure it is possible to observe an excellent agreement of both methods for the first frequency at a speed of rotation of 120 rpm (2 Hz). Superior natural frequencies also show a similar agreement, but they are not shown here for a matter of space availability.

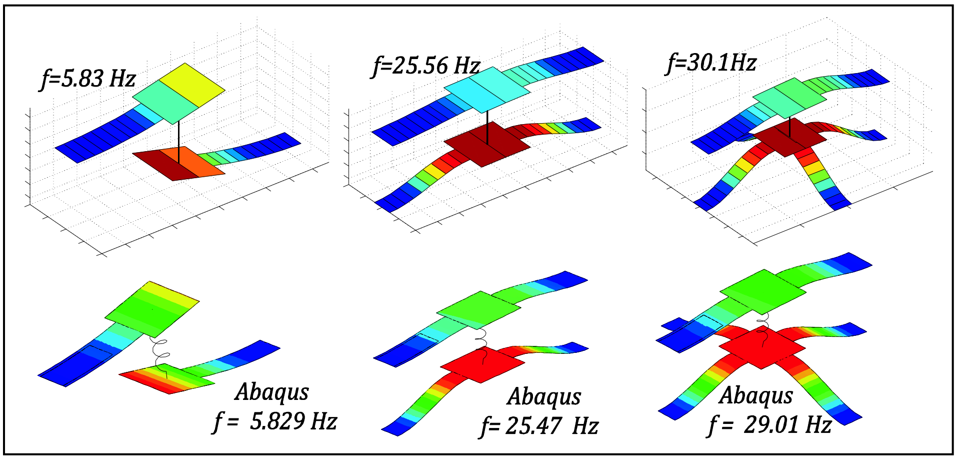

Figure 2. Comparison between the FE method developed here and the commercial software ABAQUS. First natural frequency for a speed of rotation of 120 rpm (2 Hz).

3. Experiments and Results

Experimental tests for the three proposed cases were performed in the following way. An electric motor with a variable speed controller provides the rotational motion of the system which was rigidly mounted

to the hub as observed in figure 3. Instead of using a more common slip-ring system which is a major shortcoming to properly acquire the voltage signal, an Arduino board with a Bluetooth connection was used instead, that sends the collected data to a pc at a rate of 100 samples/sec. A load resistor of 56 and 10Kohm was used in order to capture the voltage generation for different loads. However, the data acquisition system presents a maximum possible read of 5 volts (Arduino setting) which restricts the load selection to limited values.
The experimental voltage generation is presented in figure 4 for the desired frequency range (50-150 rpm). From the analysis of the results, a common feature of all three cases can be pointed out. There is a region between 0.8-3 Hz where the generation increases and then the voltage drops up for increasing values of frequency.

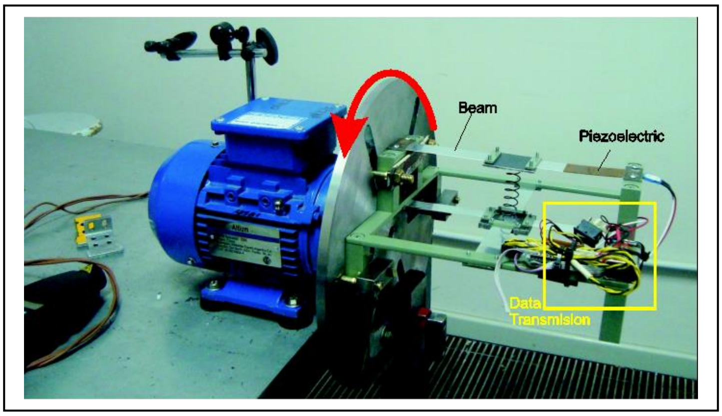

Figure 3. Photo of the experimental setup used in the experiments, the EH system is mounted over an electrical motor which induces the rotation of the system

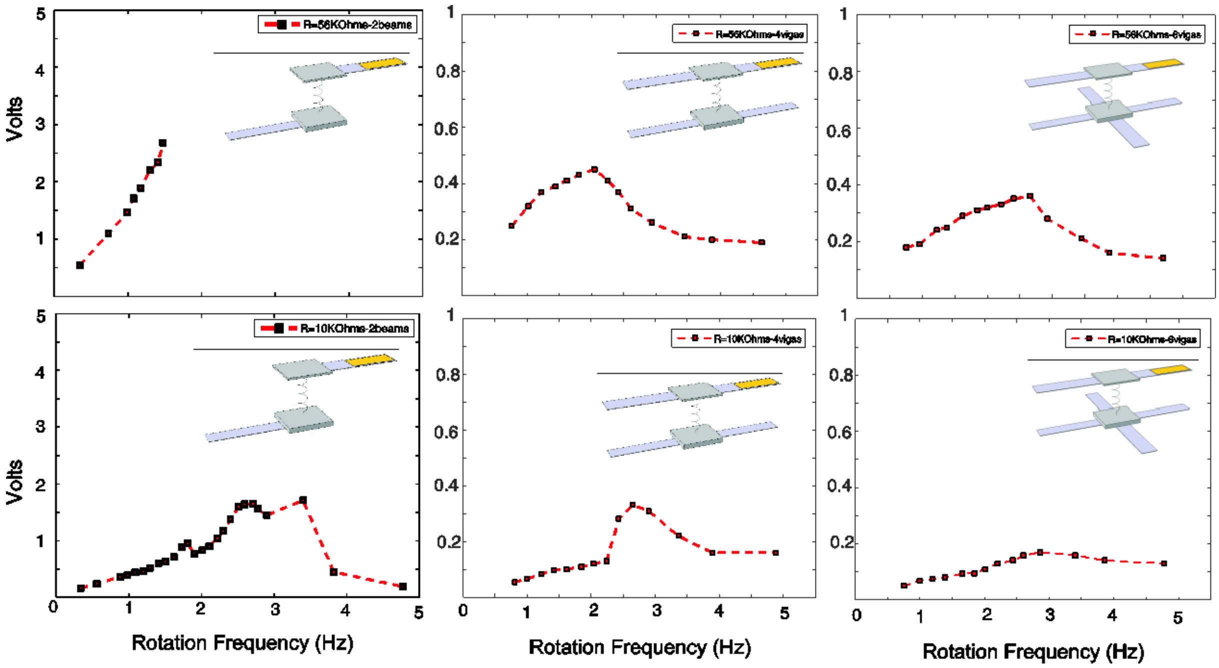

Figure 4. Influence of rotation speed on the voltage generation for the different proposed designs of EHs.

From the proposed cases, the one with two beams has the largest voltage generation. It is observed that for R=56 Kohm the generation exceeds the maximum limit of the data acquisition system (5 Volts) so the readings are cut in this point. FE predictions for this case are summarized in figure 5. There, it is possible to find the voltage generation as a function of speed of rotation, the natural frequency of beam system and the speed of rotation. An inspection of this figure reveals the important fact of a matching between the natural frequency of the system and rotation velocity for a certain frequency range due to the softening effect of the centrifugal force. It is expected that the voltage generation becomes maximum in this range. Compared with the experimental data, there exists a discrepancy in the frequency of maximum generation. This may be due to several omitted effects in the FE formulation: nonlinearities in the piezoelectric material [8], imperfect clamped boundary conditions of the beams, consideration of point masses and perfect bond of the spring, between others. Due to this limitation, FE predictions are presented only for the case of two beams. For the other two cases, no evidence of self-tuning is found in the desired driving frequency range. However, there exist an acceptable voltage generation despite of the fact that the system is in an off- resonance condition. Nevertheless, experimental data of a narrow frequency band where the generation raises, is found.

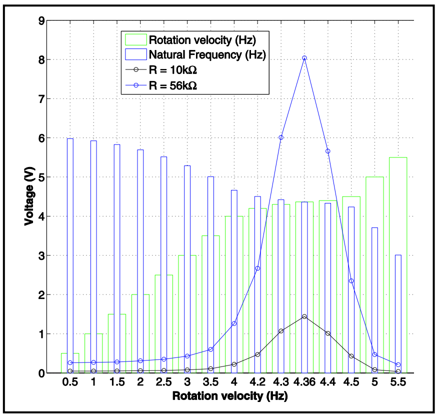

Figure 5. FE predictions of the generated voltage for the case of two beams. Variation of the natural frequency of the system as a function of speed of rotation.

4. Conclusions

This paper presents an alternative of a power scavenging system for a rotating environment comprising a set of beams, masses, spring and a piezoelectric sheet with different geometric configurations. The gravitational force causes sustained oscillatory motion in the flexible beams provided by the rotary motion. A FE beam model is proposed to describe the complex geometry of the system which was validated with available commercial FE software (ABAQUS). The experiments show an acceptable sustained voltage generation for the desired frequency range, in the three proposed cases. However, the case with two masses has a noticeable better voltage generation compared with the other two, principally due to a self-tuning effect, which was numerically confirmed. Future works will be conducted to improve the numerical model including the effect of the nonlinearity in the piezoelectric material, imperfect boundary conditions and large masses. The intention is also to study the generation when an array of piezoelectric sheets is added.

Acknowledgments

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