Energy Conversion and Management 152 (2017) 166–175

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An out-of-plane rotational energy harvesting system for low frequency environments

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ARTICLE INFO

Keywords:
Low frequency
Rotational energy haversting device
Wind turbines

ABSTRACT

We present a novel design of a rotational power scavenging system as an alternative to cantilever beams attached to a hub. The device is meant to provide energy to wireless autonomous monitoring systems in low frequency environments such as wind turbines of 30 kW with rotational speeds of between 50 and 150 rpm. These characteristics define the bandwidth of the rotational energy harvesting system (REH) and its physical dimensions. A versatile geometric configuration with two elastic beams and two heavy masses joined by a spring is proposed. A piezoelectric sheet is mounted on the primary beam while the REH is placed on a rotating hub with the gravitational force acting as a periodic source. This kind of double-beam system offers the possibility to modify the vibration characteristics of the harvester for achieving high power density. An analytical framework using the Lagrangian formulation is derived to describe the motion of the system and the voltage output as a function of rotation speed. Several sets of experiments were performed to characterize the system and to validate the assumed hypothesis. In the experimental setup, a wireless data acquisition system based on Arduino technology was implemented to avoid slip-ring mechanisms. The results show very good agreement between the theoretical and experimental tests. Moreover, the output power of a simple harvesting circuit, which serves as an energy storage device, yields values ranging 26–105 μW over the whole frequency range. This allows us to use the proposed device for the designed purpose, taking into account the power requirements of commercially available wireless transmitter systems.

1. Introduction

The condition monitoring of structures and rotating machines is highly desirable to improve the health, safety and failure predictability of civil and industrial systems. In this sense, data transmission and sensors are essential elements. Between wired and wireless communication systems, wireless sensing is more appropriate for sensory data acquisition in applications involving rotary motion. The design of piezoelectric energy scavenging systems for low frequencies (< 100 Hz) and low accelerations (< 1 g) are subjects of current research efforts, mainly because the amplitude of environmental vibration sources is below 0.3 g (or 3 m/s^2) and 30 Hz [1,2].

Vibrating energy harvesting (VEH) systems have been developed largely in this sense, considering different mechanical designs, fields of application and transduction mechanisms [3–6]. Other mechanisms used in energy harvesting include solar [7], thermal [8], electromagnetic [2] and triboelectric devices for exploiting renewable energy sources as well [9]. However, energy harvesting from rotational motion has been much less investigated in the literature even though there is a large subset of civil or industrial scenarios where rotational kinetic energy is available, for example gas and wind turbines, rotating machines, car tires, wheels, shafts, fans, among others. Thus, powering condition-monitoring systems with rotational energy harvesters sounds promising and attainable.

There are several facts that make harvesting energy from rotations distinct from harvesting energy from vibrations. Firstly, if the harvesting device is properly oriented, Earth's gravity can act as a source of periodic excitation with the frequency of the rotational speed. Secondly, the centrifugal force, which grows with the square of the rotational speed, induces large constant body forces, while the system is rotating. These issues may represent singular benefits to the mechanical designer to improve energy harvest and adapt a mechanism to scavenge energy in low frequency and low acceleration environments. For example, a passive tuning scheme can be implemented with the centrifugal force acting as an axial force that can change the stiffness of a cantilever beam piezoelectric system. This type of approach has been successfully used by Leland and Wright [10] and Eichhorn et al. [11], who applied a compressive axial preload to a vibration energy scavenger to adjust its resonance frequency.

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http://dx.doi.org/10.1016/j.enconman.2017.09.042
Received 19 June 2017; Received in revised form 28 August 2017; Accepted 16 September 2017

Nomenclature

w	transverse elastic displacements (m)
u	axial elastic displacements (m)
t	time (s)
e_x	unit vector in the x direction
e_z	unit vector in the z direction
H_n	Heaviside function
ϕ_j	j^{th} normalized mode shapes functions
q_j	j^{th} mode of the generalized coordinate
K_j	j^{th} modal stiffness
χ_j	j^{th} equivalent "modal" radius
Γ_j	j^{th} modal excitation
ω_j	j^{th} modal natural frequency (rad/s)
ξ_j	j^{th} modal damping
ϑ_j	j^{th} piezoelectric coupling of mode
$\dot{\theta} = \Omega$	rotating frequency (rad/s)
R	position of an infinitesimal segment on the beam in the rotating coordinates (m)
r	distance from the axis of rotation to the beams (m)
r_1	distance from the axis of rotation to the beam#1 (m)
r_2	distance from the axis of rotation to the beam#2 (m)
d_1	offset distance of the tip mass#1 (m)
d_2	offset distance of the tip mass#2 (m)
M_1	heavy mass#1 (kg)
M_2	heavy mass#2 (kg)
I_{T1}	moment of inertia of the tip mass#1 (m^4)
I_{T2}	moment of inertia of the tip mass#2 (m^4)
k	linear spring stiffness (N/m)
n	number of beam sections (n = 1, 2 and 3)
L_n	length of each section (m)
EI_n	flexural beam rigidity for each section (N m^2)
ρA_n	area density for each section (kg/m)
t_n	thickness of each beam's section (m)
b_n	width of each beam's section (m)
c	linear damping coefficient (Ns/m)
g	gravity (m/seg^2)
C_p	internal capacitance of the piezoceramic (nF)
v	voltage drop in the piezoelectric (V)
V_{oc}	open-circuit voltage (V)
J_p	electromechanical coupling coefficient (Npm/V)
d_{31}	piezoelectric constant (pm/V)
R	resistive load (Ohm)
P	power (W)
t_p	piezoelectric thickness (m)
b_p	piezoelectric width (m)
a	distance from the neutral axis to the bottom piezoelectric layer (m)
E_p	piezoelectric Young's modulus (N/m^2)
V	voltage amplitude (V)

A common practice in the design of VEH devices to maximize power is matching the resonant frequency of the harvester to the excitation frequency. This approach appears to be applicable also to rotational devices. However, a main drawback of this methodology is that the physical dimensions of the devices (especially at low frequencies) are such that it is impossible to fit them given the size and weight limitations of practical applications. In rotating devices such as car-tires, wheels or shafts, the reduced availability of space is crucial and determines the actual design of the harvesting device. In the following paragraphs, a brief survey of the literature on rotational energy harvesting (REH) devices is presented. Manla et al. [12] proposed a system of power generation from rotating vehicle wheels using a piezoelectric generator and a ball bearing. The system is designed to be a tire pressure monitoring system (TPMS). The ball impacts the piezoelectric transducer inside a tube by means of the centrifugal force. Experiments showed that the device can produce 4 mW of electrical power at 800 rpm in a volume of 2 cm^3. They also demonstrated that increasing both the tube length and the mass of the ball bearing increases the output power. Also Zheng et al. [13] developed a TPMS based on a novel asymmetric air-spaced piezoelectric cantilever. They reported that the device has several desirable advantages. Firstly, the voltage generated is increased due to the much larger distance between the piezo layers and the neutral plane; and secondly, the asymmetric structure makes the device more robust since the piezo layer is operating in the compression mode. The prototype was capable of generating 47 μW with a 21.6 gr. proof mass at a driving speed of 80 km/h. More recently, Roundy and Tola [14] presented an energy harvester using the dynamics of an offset pendulum along with a nonlinear bistable restoring spring to improve the operational bandwidth of the system. Depending on the speed of the rotating environment, the system can act as a bistable oscillator, a monostable stiffening oscillator, or linear oscillator. Simulation and experimental tests showed that the prototype generator is capable of directly powering an RF transmission system every 60 s or less over a speed range of 10–155 km/h. With the aim to powering a TPMS, Manla et al. [15] developed an off-axis piezoelectric device consisting of pre-stresses piezoelectric beams and a magnet, which is capable of generating energy in a large range of rotational speeds due to the implementation of a levitating magnet that generates nonlinear magnetic over a wide range of centrifugal forces. The prototype occupies a volume of approximately 17.74 cm^3 and generates an output power ranging from 0.2 to 3.5 μW when the rotating speed changes from 180 rpm to 330 rpm.

A passive self-tuning REH device was presented by Gu and Livermore [16]. Their harvester comprises a radially oriented beam mounted at a distance r from the axis of rotation. As the rotational speed varies, the corresponding tension due to centrifugal force on the beam adjusts the beam's resonant frequency so that the harvester always works at or near its resonant frequency. In this way, and under a proper design, the resonant frequency of the harvester can match the frequency of the rotation over a wide frequency range, significantly improving its performance compared with an untuned REH. The same authors also presented an impact-based REH that also works as a self-tuning device with an optimized design [17]. The system comprises two beams: a rigid piezoelectric generating beam and a narrow, flexible driving beam with a tip mass at the end. The mass impacts the generating beam repeatedly under the influence of gravity to drive generation, while the centrifugal force from the rotation modifies the resonant frequency of the flexible driving beam and the frequency response of the harvester. Thus the generation is improved due to the self-tuning mechanism. As a result, the system is capable of generating a power density of 30.8 μW/cm^3 over a wide frequency range. Khameneifar et al. [18,19] proposed and tested a REH system consisting of a rotating piezoelectric cantilever beam with a tip mass mounted on a hub. The gravitational force generates mechanical excitation while the hub is in rotary motion. Expressions for the optimum load resistance and maximum power were obtained and experimentally validated using PDVF and PZT transducers. A maximum power of 6.4 mW at a rotational speed of 1320 rpm been achieved with a 0.25 cm^3 PZT device. This is about 44 times higher than when a PVDF film is used. Thus, their proposal could be used as a power generator for a wireless communication system. For low frequency (< 1 Hz) and low size (< 10 cm), a hybrid electromagnetic-tribolectric nanogenerator consisting of four units of freestanding triboelectric nano generators (TENG) and four electromagnetic generators (EMG) [9] can be used as a self-powered sensor for road traffic monitoring. With an optimization of the geometry of the electromagnetic component and with the combination of