ENERGY HARVESTING FROM ROTATING WHEELS USING PIEZOELECTRIC BEAMS UNDER MAGNETIC FORCES

By

Mohamed Ali Abdelmegeed Elhadidi

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
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In Mechanical Design and Production Engineering

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Energy Harvesting from Rotating Wheels Using Piezoelectric Beams Under Magnetic Forces

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Summary:

Energy harvesting from vibration are always based on reaching the resonant frequency by try to vibrate the harvester at its resonant frequency to maximize gained energy. Some systems have operation conditions that forces the designer to find a mechanism that maximizes harvested energy at off-resonant frequencies. The focus of the current work is to investigate the viability of a system that can supply a sensor mounted inside a car tire with sufficient power using energy harvesting principles of off-resonant frequency, as an example for the targeted sensors is a car tire air pressure sensor.

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NOMENCLATURE

c	Damping coefficient	$\mathrm{N} \cdot s/m$
C	Capacitance	F
d	Coupling matrix of piezoelectric material	C/N
d_{31}	Transverse piezoelectric constant in the 31 mode	C/N
d_{33}	Longitudinal piezoelectric constant in the 33 mode	C/N
E	Young's modulus	Pa
E_E	Experimental Young's modulus	Pa
E_N	Numerical Young's modulus	Pa
F	Magnetic force between magnets	N
f_c	Centrifugal force	N
F_m	Magnetic repulsion force from lookup tables	N
F_x	Force in x-direction	N
F_{C_x}	Centrifugal body load in x-direction	$\mathrm{N/m^3}$
F_{C_y}	Centrifugal body load in y-direction	$\mathrm{N/m^3}$
F_{R_x}	Rotation body load in x-direction	$\mathrm{N/m^3}$
F_{R_y}	Rotation body load in y-direction	$\mathrm{N/m^3}$
g	Gravitational acceleration	m/s^2
h	Beam height	mm
I	Moment of inertia	$\mathrm{m^4}$
k	Equivalent stiffness of the system	N/m
L	Beam length	mm
L_p	piezoelectric material length	mm
L_m	metal length, w beam width	mm
m_{eff}	Equivalent mass of beam and tip mass	Kg
m_b	Beam mass	Kg
m_t	Tip mass	Kg
P	Force on tip	N
Q_{Gen}	Generated charge	C
r	Hub radius	mm
s	Tip mass position from root	mm
S_E	Compliance matrix	1/Pa
s_{33}^E	Elastic compliance constant in the 33 mode for the piezoelectric	1/Pa
s_{11}^m	Metal compliance	1/Pa
s_{11}^E	Elastic compliance constant in the 11 mode for the piezoelectric	1/Pa
s_m	Elastic compliance constant for the substrate	1/Pa
s_p	piezoelectric material compliance	1/Pa
T	Time	S

t_m	metal thickness	M
t_p	piezoelectric material thickness	mm
u	Deformation in x-direction	mm
v	Deformation in y-direction	mm
V	Applied voltage	V
Vel	Car velocity	m/s
w	Bender width	mm
X	Position in x-direction	mm
Y	Position in y-direction	mm
ν	Poisson's ratio	1
ω_d	Driving frequency	rad/s
ρ	Density	$\mathrm{kg/m^3}$
δ	Tip deformation	mm
ω	Rotation frequency	rad/s
Ω	Rotational speed	$\mathrm{rad/s}$
ε_{33}^T	Permittivity of the piezoelectric at constant stress	1
η	Compliance (Young's modulus) ratio	1
λ_1	Length ratio (piezoelectric layer length over Middle elastic layer length)	1
Δ	Magnet gap	mm
α	Mass damping parameter	1/s
β	Stiffness damping parameter	s
ξ	Thickness ratio (middle elastic layer over piezoelectric layer)	1

ABSTRACT

Energy harvesting from vibration are always based on reaching the resonant frequency by try to vibrate the harvester at its resonant frequency to maximize gained energy. Some systems have operation conditions that forces the designer to find a mechanism that maximizes harvested energy at off-resonant frequencies. This work is concerned with the concept of extracting energy from rotating wheels. The use of bistable harvesters to extract energy is investigated. The proposed harvester consists of a piezoelectric cantilever beam that is mounted on a rigid rotating hub. This beam carries a tip mass and a permanent magnet. The tip mass is applied to assist the beam to oscillate due to gravity as the beam rotates. Magnetic repulsion forces from an opposite magnet cause the beam to possess two stable equilibrium positions.

Rotation of the beam in a vertical plane under both gravity and magnetic forces allow for greater bending strains to be applied on the piezoelectric device, thereby generating enhanced levels of energy output. A single degree of freedom system and a finite element model were developed to study the system dynamics. Used Finite element model was verified by comparing its results with previously published work.

An effort is made to select the design parameters to enable the harvester to exhibit large-amplitude oscillations across a range of rotational speeds for enhanced energy harvesting. Findings of the present work are verified experimentally. Experimental results are measured in output voltage and mechanical strain. Results were measured in different domains time-domain and frequency-domain. The results indicate that enhanced levels of power output are obtained for rotational speeds up to 5 Hz, which is commensurate with the average speeds in city traffic. Findings of the present work indicate the viability of designing self-powered sensors that can be mounted within automotive tires, such as tire pressure sensors.

CHAPTER 1 : INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

The concept of extracting energy from a rotating wheel has attracted attention in the energy harvesting community for its various uses. A potential application in the automotive industry is the design of self-powered tire pressure monitoring systems. These systems typically consist of a battery-powered wireless sensor that is placed inside the tire cavity and a remote receiver that collects the sensor data, such as pressure, temperature and acceleration. Concerns over replacement and disposal costs of batteries have recently spurred interest in the concept of harvesting energy from the tire itself due to the ubiquity of kinetic energy in a rotating wheel. Energy can be extracted in a number of ways from a rolling tire. For a review of energy harvesting technologies from rotating wheels, the reader is referred to the work of Bowen and Arafa [1]. One of the promising designs is the use of inertial harvesters that are mounted onto the wheel rim and make use of the wheel's rotation as an essentially inexhaustible source of mechanical energy to tap into. In these designs, the wheel's rotation is utilized to induce cyclic bending in a piezoelectric cantilever beam, thereby generating power.

A challenge in the design of energy harvesting benders is to ensure adequate power generation across low range of excitation frequencies. Insight into the pertinent literature reveals that two main approaches have been adopted to address this issue. The first approach relies on widening the bandwidth of an essentially passive device, i.e. one whose design parameters are fixed. This is normally accomplished by designing harvesters that exhibit favorable dynamics to cope with variable-frequency excitation environments. Examples of these solutions include the use of nonlinear dynamics [2], designs having multiple oscillators [3] and structures exhibiting multiple resonance frequencies to harvest energy from a wide band of frequencies. Efforts to match the rotational speed with the resonance frequency have also been proposed [4] to achieve a self-tuning design. The second approach relies on actively tuning the resonance frequency of a harvester, in response to the forcing environment, in order to attain resonance constantly. In this context, systems with manually [4] and automatically [5] adjustable natural frequencies have been proposed to improve the performance.

This has spurred interest in the design of passive bistable devices for broadband operation. These systems usually consist of some elastic structure that exhibits a snap-through behavior, in which it rapidly deforms from one stable equilibrium state to another upon the application of an external excitation. Such inter-well oscillations occur with large amplitudes, which makes them ideal for power generation across a broad-frequency bandwidth. Bistable behavior can be triggered in a number of ways, including the use of buckled structures [6], magnetic forces [7] and bistable composite laminates [8]. For a