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Similarity and duality of electromagnetic and piezoelectric vibration energy harvesters

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ABSTRACT

A frequency analysis has been conducted to study vibration energy harvesting performance and characteristics of a single degree of freedom vibration energy harvester connected to a single load resistor based on the Laplace transfer method and physical models of a voltage source. The performance and characteristics of electromagnetic and piezoelectric harvesters have been analysed and compared. The main research outcome is the disclosure of similarity and duality of electromagnetic and piezoelectric harvesters for both the energy harvesting efficiency and the normalised resonant harvested power using only two dimensionless characteristic parameters: the normalised resistance and the normalised force factor. The dimensionless resonant harvested power and energy harvesting efficiency analysis allows for a parameter study and optimization of the ambient vibration energy harvesters from macro- to nano-scales and for evaluation of the vibration energy harvester performance regardless of the size and type.

1. Introduction

Harvesting energy from the environment is an attractive alternative to battery-operated systems, especially for long-term, low-power consuming and self-sustaining electronic systems. The electromagnetic and piezoelectric vibration energy harvesters have been intensively studied in the literatures where various piezoelectric vibration energy harvesters or electromagnetic vibration energy harvesters were connected to a single load resistor [1,2,4,6–10,13,14,17,20,21,23,25,26,28–30,34,36,41,43,45], as a simplified and usual view in considering a linear circuit is to replace the extraction circuit by its equivalent linear input resistance [43]. The power output has been optimised [2,3,5,7–9,11–13,15–19,22–28,29–35,36–38,41–45] and has been normalised in dimensionless forms [1,12,13,19,21,26,27,31–34,36,41,42,45].

Most research papers have discussed some optimizations of harvested power of the electromagnetic or piezoelectric vibration energy harvesters while limited works have been conducted to compare the power harvesting performance of the electromagnetic and the piezoelectric vibration energy harvesters [25,29] and to normalise resonant harvested power and energy harvesting efficiency for dimensionless analyses [1,12,13,19,21,26,27,31–34,36,42,45].

Williams and Yates [43] analysed the damping dissipated power of a single degree of freedom vibration energy harvester. However, the effects of the force factor of the piezoelectric material and external electric load resistance on the harvested

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Nomenclature

A	Piezoelectric material insert surface area
B	Magnetic field constant
D	Short circuit mechanical damping of the single degree of freedom system
C_0	Blocking capacity of the piezoelectric material insert
e	2.718281828
e_{33}	Piezoelectric constant
F	Excitation force
F_M	Amplitude of the excitation force
$\|F\|$	Amplitude of the excitation force
f_n	Natural frequency
H	Thickness of the piezoelectric material insert disk thickness
i	Square root of -1
I	Current in the circuit
K	Short circuit stiffness of the single degree of freedom (SDOF) system
L_e	Self-inductance of the coil
M	Oscillator mass of the single degree of freedom system
P_h	Harvested power
P_{in}	Input power
$\frac{P_h}{(M^2\|\ddot{y}\|^2/D)}$	Dimensionless resonant harvested power
$\frac{P_{h\ max}}{(M^2\|\ddot{y}\|^2/D)}$	Peak dimensionless resonant harvested power
s	Laplace variable
T	Period of the excitation force signal
V	Output voltage of the SDOF system
V_M	Output voltage amplitude of the SDOF system
$\|V\|$	Modulus or amplitude of the output voltage
y	Base excitation displacement
$\dot{y}$	Base excitation velocity
$\ddot{y}$	Base excitation acceleration
Y_M	Base excitation displacement amplitude
z	Relative displacement of the mass with respect to the base
$\dot{z}$	Relative velocity of the mass with respect to the base
$\ddot{z}$	Relative acceleration of the mass with respect to the base
$\|z\|$	Amplitude of the relative displacement
Z_M	Relative displacement amplitude of the mass with respect to the base
α	Force factor of the piezoelectric material insert or Equivalent force factor of the electromagnetic transducers
α_N	Normalised force factor
η	Resonant energy harvesting efficiency
η_{max}	Maximum resonant energy harvesting efficiency
ω	Excitation frequency
π	3.1415927

Subscripts

0	Rectified or blocking capacity of the piezoelectric material insert
33	Piezoelectric working mode having the same direction of loading and electric poles
C	Damping dissipated
h	Harvested energy
in	Input
M	Amplitude or before the inversion process
max	Maximum value
m	after the inversion process
N	Normalised

Superscripts

-1	Inverse
S	Clamped
*	Complex conjugale
‾	Time average
.	The first differential
..	The second differential

Special function

< >	Time averaged
| |	Modulus or absolute value

Abbreviations

SDOF	Single degree of freedom

power and the vibration energy harvesting efficiency were not studied. Stephen [34] normalised resonant harvested power using the maximum input power and expressed the normalised power in dimensionless frequency and damping ratio though the energy harvesting efficiency was not normalised and optimised. Stephen did not compare the power harvesting performance difference between the electromagnetic and the piezoelectric harvesters. Shu et al. [31,32] compared and optimised the resonant harvested power of a vibration energy harvester connected with standard and parallel "synchronous switch harvesting on inductor" (SSHI) interface circuits where the oscillator displacement was divided by the static displacement for the normalisation. Wickenheiser et al. [42] studied and optimised the harvested power of a vibration energy harvester connected with a standard interface circuit where the voltage and tip displacement were divided by their short-circuit amplitudes for the normalisation. Poulin et al. [25] compared electromagnetic and piezoelectric harvesters for their duality and similarity using the equivalent circuit and impedance method. It was shown that the equivalent circuits of the electromagnetic and piezoelectric harvesters had an obvious similarity and their power graphs had the same trend. Their equivalent impedances were in a complete duality. However, similarity and duality of the resonant harvested power and energy harvesting efficiency have not been studied, the resonant harvested power and energy harvesting efficiency of