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Coupling analysis of linear vibration energy harvesting systems

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ABSTRACT

This paper has disclosed the relationship of vibration energy harvester performance with dimensionless force factor. Numerical ranges of the dimensionless force factor have been defined for cases of weak, moderate and strong coupling. The relationships of coupling loss factor, dimensionless force factor, critical coupling strength, coupling quotient, electro-mechanical coupling factor, damping loss factor and modal densities have been established in linear vibration energy harvester systems. The new contribution of this paper is to determine a frequency range where the vibration energy harvesting systems are in a weak coupling and the statistical energy analysis is applicable.

1. Introduction

Conversion of vibration energy in structure, machine or vehicle into electric energy will improve reliability, comfort and energy utilisation efficiency, which contributes to environmental sustainability. However, most of the vibration energy harvesting researches focused on the resonant analysis of the harvesters of specially designed materials or structures with single frequency harmonic excitation. The resonant analysis is often conducted by deterministic approach. In reality, ambient environment excitation is often random such as the excitation generated from the road surface to moving vehicles. The deterministic analysis is not sustainable. This is because the resonant harvested power and energy harvesting efficiency are much overestimated, when the excitation frequency is deviated from the resonant frequency.

Ambient environment vibrations or excitations are random, and they could be of a low or mid or high frequency. As a matter of fact, some of the piezoelectric vibration energy harvesters work more efficiently in the middle and high frequency than in the low frequency [21,26]. In the middle or high frequency, the established methods are not able to reliably predict the vibration energy harvesting performances of a series of vibration energy harvester systems of the same design. This is due to the system parameter variations which are caused by variations in materials and manufacturing processes. In this case, statistical energy analysis (SEA) of vibration energy harvester systems needs to be developed. SEA is a framework of study with primary variables of energy for the systems being studied from populations of similar design construction having known distributions of dynamic parameters. The procedures for SEA are: model development, parameter evaluation and calculation of response. The motivation of adopting the SEA framework is to avoid repeatedly re-simulating a system with

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Nomenclature

A	Piezoelectric material insert surface area;
B	Magnetic field constant;
C	Short circuit mechanical damping of the single degree of freedom system;
C_0	Blocking capacity of the piezoelectric material insert;
E_E	Mean energy of the electrical subsystem;
E_M	Mean energy of the mechanical subsystem;
e	2.718281828;
e_{33}	Piezoelectric constant;
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;
k_e	The electro-mechanical coupling factor or electro-mechanical coupling coefficient;
L_e	Self-inductance of the coil;
M	Oscillator mass of the single degree of freedom system;
P_h	Mean harvested power;
P_{in}	Mean input power;
$\frac{P_h}{\left(\frac{M^2\lvert\ddot{y}\rvert^2}{C}\right)}$	Dimensionless resonant mean harvested power;
s	Laplace variable;
V	Output voltage of the SDOF system;
V_M	Output voltage amplitude of the SDOF system;
$\lvert V\rvert$	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;
$\lvert z\rvert$	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 electro-magnetic device/transducer;
α_N	Normalised force factor;
ν_{ME}^2	The coupling quotient from the mechanical to the electrical subsystems;
η	Resonant energy harvesting efficiency;
η_M	Damping loss factor of mechanical subsystem, or mechanical damping loss factor;
η_E	Damping loss factor of electrical subsystem, or electrical damping loss factor;
η_{ME}	Coupling loss factor from the mechanical to the electrical subsystems;
ω	Excitation frequency;
π	3.1415927;

Subscripts

0	Blocking capacity of the piezoelectric material insert;
33	Piezoelectric working mode having the same direction of loading and electric poles;
M	Mechanical subsystem;
E	Electrical subsystem;
h	Harvested energy;
in	Input;
N	Normalised;

Superscripts

-1	Inverse;
*	Complex conjugale;
$\overline{}$	Time average;
$\dot{}$	The first differential
$\ddot{}$	The second differential

Special function

< >	Time and spatial averaged
| |	Modulus or absolute value

Abbreviations

SDOF	Single degree of freedom

varied parameter adjustments, as variations of materials and manufacturing processes always exist even for vibration energy harvesters of the same design. This manuscript focuses on establishing coupling loss factor which enables statistical energy analysis of linear piezoelectric and electromagnetic vibration energy harvesters. The models and results developed in this manuscript are only applicable to linear piezoelectric and electromagnetic vibration energy harvester systems. As most of electrostatic and magnetoelectric vibration energy harvester systems are nonlinear as reported in [27–29], therefore, the models and results are not suitable to the nonlinear electrostatic and magnetoelectric vibration energy harvester systems. However, the nonlinear term or coefficient may be introduced into the analysis which will expand the statistical energy analysis method or model developed in this manuscript to the nonlinear systems which will be our future work.

Electro-mechanical coupling factor k_e^2 of the electromagnetic and piezoelectric vibration energy harvesters was defined in [1,2,5–11,15,19,22–24], which is a numerical measure of the conversion efficiency between electrical and vibration energy. Electro-mechanical coupling factor k_e^2 of piezoelectric materials is equal to squared piezoelectric coefficient of the piezo-electric disk divided by the product of the free stress permittivity and short-circuited elastic rigidity of the piezoelectric disk