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Coupling loss factor of linear vibration energy harvesting systems in a framework of statistical energy analysis

Xu Wang

School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora East, Vic 3083, Australia

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ABSTRACT

This paper establishes coupling loss factor of linear vibration energy harvesting systems in a framework of statistical energy analysis under parameter variations and random excitations. The new contributions of this paper are to define the numerical ranges of the dimensionless force factor for the weak, moderate and strong coupling and to study the connections of dimensionless force factor, coupling loss factor, coupling quotient, critical coupling strength, electro-mechanical coupling factor, damping loss factor and modal densities in linear vibration energy harvesting systems. The motivation of this paper is to enable statistical energy analysis of linear vibration energy harvesting systems for reliable performance predictions and design optimisation under parameter variations of materials and manufacturing processes and random ambient environmental excitations.

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 is 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 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 harvesting 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 harvesting 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 and 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 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.

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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
$\frac{P_h}{\left(M^2\frac{\lvert\ddot{y}\rvert^2}{C}\right)}$	mean dimensionless resonant 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_M^2	dimensionless 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 conjugate
—	time average
.	the first differential
..	the second differential

Special function

< >	time and spatial averaged
| |	modulus or absolute value

Abbreviations

sdof	single degree of freedom

Electro-mechanical coupling factor k_e^2 of the electromagnetic and piezoelectric vibration energy harvesters was defined in [1,2,5,7–11,15,19,22–24,27], which is a numerical measure of the conversion efficiency between electrical and vibration energy. According to the literatures, the electro-mechanical coupling factor k_e^2 of piezoelectric materials is equal to squared piezoelectric coefficient of the piezoelectric disk divided by the product of the free stress permittivity and short-circuited elastic rigidity of the piezoelectric disk. The electro-mechanical coupling factor is also equal to the squared force factor divided by the product of the short-circuited stiffness and the capacitance of the piezoelectric disk. Shu and Lien [16–18] defined critical coupling strength k_e^2/ξ, as the squared electro-mechanical coupling factor k_e^2 divided by the mechanical damping ratio ξ. They believed that when the critical coupling strength is much less than one, the harvester system is uncoupled or weakly coupled. When the critical coupling strength is larger than 1 and less than 10, the harvester system is moderately coupled. When the critical coupling strength is larger than 10, the harvester system is strongly coupled. As previous researches on vibration energy harvesting analysis have never been conducted in the framework of statistical energy analysis, coupling loss factor has never been defined for vibration energy harvesting analysis. The coupling loss factor