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ScienceDirect

Procedia Engineering 144 (2016) 635 – 644

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Vibration Problems, ICOVP 2015

Dynamic analysis of piezoelectric based energy harvester under periodic excitation

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Abstract

In the present work, a vertical cantilever beam fixed with a torsional spring at one end and a tip mass at free end is analyzed as an energy harvester using piezoelectric patch for super-harmonic resonance condition. This model is non-linear dynamical system; it is exhibit super-harmonic resonances that can activate large amplitude motions at fraction integers of the fundamental frequency of the system. Such resonances offer a unique and untapped opportunity for harnessing vibratory energy from excitation sources with low frequency components. The nonlinear temporal differential equation of motion having periodic excitation is solved by using method of multiple scales. The closed form expressions for super-harmonic resonance condition are determined. The generated voltage is estimated for a wide range of system parameters.

Peer-review under responsibility of the organizing committee of ICOVP 2015

Keywords: Energy harvesting, Piezoelectric, Non-linear dynamics, Method of multiple scales.

1. Introduction

While recent technology advances in designing and manufacturing small electronics have made low-cost and low-power consumption sensor network in reality, their actual development has been severely restricted by power requirements. Today, sensors used for many field application like health monitoring of structure and machines requires sub-milliwatt power levels to function. However, such system still functions by a conventional battery which have many limitations like fixed storage capacity, low energy density and require regular replacement or recharging.

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Peer-review under responsibility of the organizing committee of ICOVP 2015
doi:10.1016/j.proeng.2016.05.057

To overcome the shortcomings of battery technology and advancement in electronics, vibration energy harvesting techniques become a focal research area in recent years. Unused periodic vibration generated by various resources can be used for generating electricity. This electricity can be stored in the storage devices e.g. batteries and capacitors. These devices can be used to operate health monitoring sensors, pace makers, spinal stimulators, wireless sensor, micro-electromechanical systems, etc. because milliwatt power is required for functioning above devices [1].

A common energy harvesting device uses a piezoelectric patch on a cantilever beam with a tip mass [2]. In this type of works, piezoelectric patches are attached to the beam near the clamped end and external excitation is applied at base of the beam to produce the vibration. This vibration produces large strains near the clamped end, and strain to the patch. Vibration energy harvester based on linear vibration have limited efficiency and effectiveness as they are based on the principle of resonant interactions between the fundamental frequency of the harvester and the frequency of excitation, and further operate only in a small region of frequency spectra where the excitation frequency is very close to the natural frequency of the oscillator [3]. Therefore, most of the resonance energy harvesting device is designed for known input vibration excitation forms.

The issue of frequency matching becomes more prevalent when one realizes that most energy harvesting devices are operating under unknown or random excitations, and in such situations, harvesters with a broad band or adaptive response seem to be beneficial. An alternative approach to maximize the harvested energy is to purposefully introduce stiffness-type nonlinearities into the harvester's design so as to extend its effective bandwidth. The presence of the nonlinearity extends a wider range of frequencies between the environmental excitation and the harvester [4].

Due to purposefully inclusion of nonlinearity in the system has exhibit many resonance conditions like super-harmonic, sub-harmonic and internal resonances that can activate large amplitude motions at different integers of the fundamental frequency of the harvester. In the present work, super-harmonic resonance condition exploits for a base excited cantilever beam with piezoelectric patch at its fixed end. This system is important when the excitation frequency is low because at low frequency other transductions like electrostatic and electromagnetic based energy harvesting is difficult to arrest due to small physical dimensions of the devices.

2. Mathematical model of energy harvester

A rectangular cross section cantilever beam of length *L*, tip mass M_t, under base excitation ($z(t) = z_0 \cos\Omega t$) is considered for study as shown in Fig. 1. Piezoelectric patch of length L_c and torsional spring of stiffness K_t are also attached to base of beam. Euler-Bernoulli beam equation is used for mathematical modelling. The transverse and axial displacements at the tip mass are *v* and *u*, respectively, and *s* represents the distance along the neutral axis of the beam.

Consider an arbitrary point on the beam, *P*, at a distance *s* from the base. This point undergoes a rigid body translation due to the base excitation and further displacement due to the beam elastic deformation, which is given by transverse displacement v_p and axial displacement u_p. Let ϕ_p denotes the rotation of the beam at a distance *s* from the base and hence, the rotation at the tip mass is $\phi_p = \phi_p(L_t, t)$, measured at the mass centre. These are function of length of the beam s and time *t*.

When external excitation frequency is far away from harvester excitation the effect of the excitation will be small unless its amplitude is hard; that is external forcing term same order with linear term. The governing equation of motions (Derivation is given in the appendix) [4].