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Energy harvesting using parametric resonant system due to time-varying damping

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ABSTRACT

In this paper, the problem of energy harvesting is considered using an electromechanical oscillator. The energy harvester is modelled as a spring-mass-damper, in which the dissipated energy in the damper can be stored rather than wasted. Previous research provided the optimum damping parameter, to harvest maximum amount of energy, taking into account the stroke limit of the device. However, the amount of the maximum harvested energy is limited to a single frequency in which the device is tuned. Active and semi-active strategies have been suggested, which increases the performance of the harvester. Recently, nonlinear damping in the form of cubic damping has been proposed to extend the dynamic range of the harvester. In this paper, a periodic time-varying damper is introduced, which results in a parametrically excited system. When the frequency of the periodic time-varying damper is twice the excitation frequency, the system internal energy increases proportionally to the energy already stored in the system. Thus, for certain parametric damping values, the system can become unstable. This phenomenon can be exploited for energy harvesting. The transition curves, which separate the stable and unstable dynamics are derived, both analytically using harmonic balance method, and numerically using time simulations. The design of the harvester is such that its response is close to the transition curves of the Floquet diagram, leading to stable but resonant system. The performance of the parametric harvester is compared with the nonparametric one. It is demonstrated that performances and the frequency bandwidth in which the energy can be harvested can be both increased using time-varying damping.

1. Introduction

Semi-active or active control is achieved by altering a system parameter, such as damping or stiffness, in real-time to enhance the performance of the system through vibration isolation or energy harvesting [1]. Semi-active control has the advantages of showing good vibration control performance while maintaining the advantages of passive methods such as simplicity and low cost implementation. Active control, on the other hand, can provide better performances, at the cost of a more complex implementation and the requirement for an external source of energy.

Energy harvesting from the ambient vibration has also attracted significant attention in recent years [2]. Some interesting applications include low-power electronics, wireless sensors [3], electrostatic MEMS vibration energy harvester [4]

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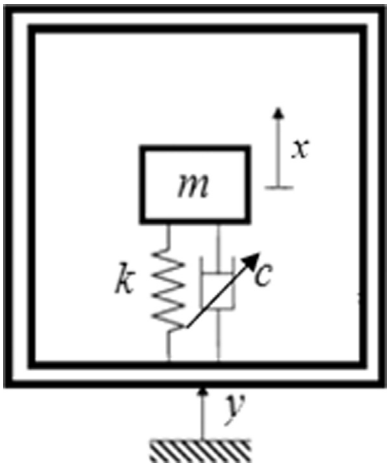

Fig. 1. Single degree-of-freedom base excited system with semi-active damper.

and large-scale energy harvesters [5]. In many applications, the vibration amplitude is too low to be harvested efficiently. Hence, methods have been proposed to improve the energy harvesting rate by both mechanical and electrical approaches [6,7]. In order to increase the frequency range and the dynamic range of the excitation amplitude over which the vibration energy harvester operates, various nonlinear arrangements have been suggested, particularly using nonlinear springs [8,9], which have been previously used for vibration isolation [10,11]. Recently, semi-active strategies [12] have been used and nonlinear damping in the form of cubic damping has been introduced to extend the dynamic range of an energy harvester [13]. In the semi-active control paper [12], the damping consisted of a series of harmonics of the excitation frequency. An optimisation algorithm was then carried out to maximise the amount of average harvested power at a particular frequency subject to the constraints on the limit values of the coefficients of the series. The optimum solution converged to a form of parametric damping $c_0[1-\cos(2\omega_n t)]$ and all the other coefficients became zero, without investigating the dynamics of such systems. In this paper a periodic time-varying damper will be considered as parametric excitation to exploit parametric amplification of the electromechanical oscillator for energy harvesting. The parametric excitation can increases the amplitude of motion and consequently can harvest more power, allowing a more effective flow of energy between the energy source and the system itself.

2. Theory of energy harvesting

A single degree-of-freedom system (spring-mass-damper) shown in Fig. 1 is considered, which is subjected to a base excitation, where m is the mass, k is the suspension stiffness, c is an active damper, x is the mass displacement and y is the base displacement. The system is harmonically excited at frequency ω and the amplitude Y. The time-varying damping coefficient is assumed to harvest useful energy. Firstly, no mechanical dissipation are taken into account, while in Section 5 dissipation are introduced.

The governing dynamic equation can be written as:

$$m\ddot{x}+c(t)(\dot{x}-\dot{y})+k(x-y)=0. \tag{1}$$

For harmonic base excitation

$$y=Y\cos(\omega t), \tag{2}$$

the fundamental component of the relative displacement is assumed to be

$$z=A\cos(\omega t)+B\sin(\omega t). \tag{3}$$

The dynamic Eq. (1) can be rewritten as:

$$m\ddot{z}+c(t)\dot{z}+kz=-m\ddot{y}=m\omega^2 Y\cos(\omega t) \tag{4}$$

The periodic time-varying damper is assumed to have the form of

$$c(t)=c_0+c_p\cos(\Omega t) \tag{5}$$

where c_0 is a constant part, c_p is the parametric damping and Ω is the parametric excitation frequency.

Substituting Eq. (3) and its derivatives and using trigonometry relations it results

$$\begin{aligned}&-m\omega^2 A\cos\omega t-m\omega^2 B\sin\omega t-c_0\omega A\sin\omega t+c_0\omega B\cos\omega t\\&\quad+c_p\cos\Omega t(-A\omega\sin\omega t+B\omega\cos\omega t)+kA\cos\omega t+kB\sin\omega t=m\omega^2 Y\cos(\omega t)\end{aligned} \tag{6}$$