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Nonlinear Kinetic Energy Harvesting

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Abstract

Harvesting of kinetic energy present in the form of random vibrations is an interesting option due to the almost universal presence of this kind of motion. Traditional generators based on piezoelectric effect are built with linear oscillators made by a piezoelectric beam and a mass used to tune the resonance frequency on the predominant frequency of the vibrations spectrum. However, in most cases the ambient random vibrations have their energy distributed over a wide spectrum of frequencies, being rich especially at low frequency. Furthermore frequency tuning is not always possible due to geometrical/dynamical constraints. In this work we present a different method based on the exploitation of the nonlinear dynamical features of bistable oscillator. The experimental results and the digital simulations show that nonlinear harvester (e.g. bistable oscillators) can overcome some of the most severe limitations of generators based on linear dynamics.

1. Nonlinear harvester

A kinetic energy harvester is a device capable to convert the environmental vibrations into electrical power. The standard transduction methods for vibration to electricity conversion are piezoelectric, capacitive and inductive. In this work we will focus our attention on the piezoelectric method. The equation of motion and the piezoelectric coupling of a cantilever can be described by the following set of equations:

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - KvV + \xi(t) \tag{1}$$

$$\dot{V} = K_c\dot{x} - \frac{1}{\tau p}V \tag{2}$$

where x represent the displacement of the cantilever tip, $U(x)$ is the potential energy function of the cantilever with equivalent mass m. The term $-yx$ accounts for the energy dissipation and $-K_vV(t)$ accounts for energy transferred to the electric load R_L. The external vibration force is represented by the term $\xi(t)$. The time constant of the piezoelectric dynamics, τ_p, is related to the piezoelectric capacitance C and to the resistive load R_L by $\tau_p = R_LC$. K_c is the coupling constant between the displacement x and the generated voltage V of the piezoelectric element. Traditional energy harvester are based on linear oscillator (e.g. piezoelectric beam) tuned on the prevalent frequency of the vibrations spectrum. However this approach presents some limitations with common environmental vibrations, in fact most of the kinetic energy present on the environment is spread in a wide frequency range with the prevalence of low frequency components (Fig. 1a). To overcome to the limitation of this approach we will consider energy harvester based on nonlinear dynamics [1,2].

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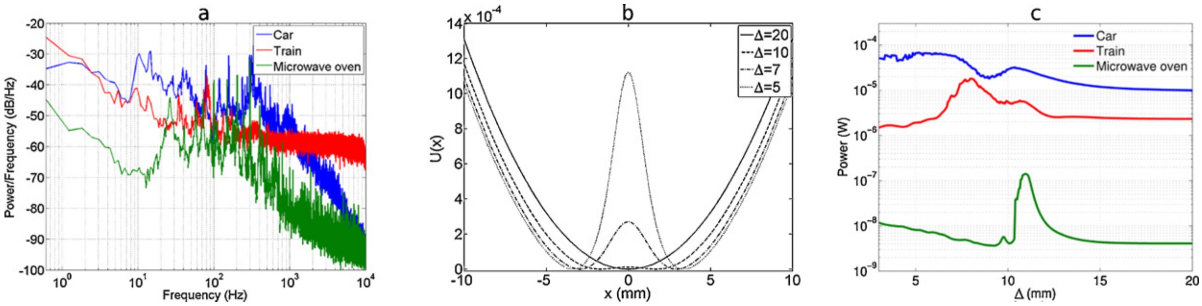

Figure 1. a) Power spectral densities in dB/Hz of the three environmental noise. b) Bistable harvester potential function, *U(x)*. On decreasing Δ the potential changes from monostable to bistable. c) Simulation results of the cantilever piezoelectric oscillator mean electric power as a function of the parameter Δ for the three different vibrations.

The harvester considered is a piezoelectric cantilever with a magnetic mass on the tip and another one placed at a certain distance Δ with opposite magnetization. The cantilever is subjected to both elastic restoring force and anti-spring force due to magnetic repulsion as described in [3].

The potential of this system can be represented by the following equation:

$$U(x) = \frac{1}{2}kx^2 + \frac{\mu_0}{2\pi}\frac{M_1 M_2}{(x^2 + \Delta^2)^{3/2}} \tag{3}$$

where k is the spring constant, μ_0 is the vacuum permeability, M_i are the effective magnetic moments and Δ is the relative distance between magnets[3,4]. When distance Δ is large the cantilever behaves like a linear oscillator. This situation accounts well for the traditional piezoelectric vibration-to-electric energy converters. Decreasing Δ the dynamics became nonlinear and the potential became bistable (Fig. 1b).

In Fig. 1c we computed the power by measuring the voltage drop V over a resistive load, under the influence of three different environmental noises (car, train and microwave oven). The electrical power is plotted as a function of the magnet distance Δ. In all the three cases the power increases rapidly from the linear configuration (large magnet distance) up to a maximum value and then decreases when the magnets become closer and closer. Specifically three different regimes can be identified:Large magnet distance. The cantilever dynamics is characterized by quasi-linear oscillations. This condition accounts for the usual performances of a linear piezoelectric generator.Small magnet distance. The potential energy is bistable with a very pronounced barrier between the two wells. In this condition and for a given amount of noise, the cantilever swing is almost exclusively confined within one well and the dynamics is characterized once again by quasi-linear oscillations around the minimum of the confining well.In between of the two previous cases, there is a range of distances where the power reaches a maximum value. In this condition the cantilever dynamics is highly nonlinear and the swing reaches its largest amplitude with noise assisted jumps between the two wells.

2. Conclusions

In conclusion we have discussed a vibration harvesting method based on the exploitation of the dynamical features of stochastic bistable oscillators employed here to model nonlinear piezoelectric harvesters subjected to wide spectrum vibrations. Such a method is shown to outperform standard linear oscillators in three real-world cases. This behaviour is not limited to the few specific cases presented here but can be generalized to a vast class of vibration signals where the vibration spectrum is spread in a wide frequency range. This method can be applied also to micro and nano-mechanical resonators where noise driven dynamics are considered as a promising option.

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