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NONLINEAR MEMS MECHANISM FOR ENERGY HARVESTING FROM MECHANICAL VIBRATIONS

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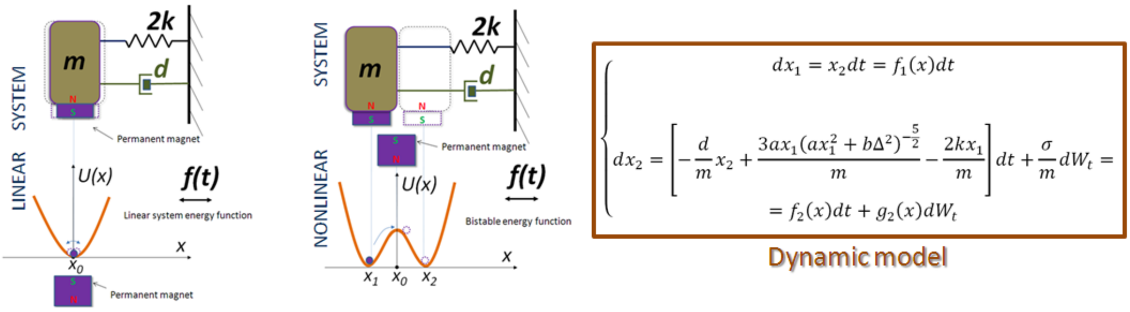
Abstract

Energy harvesting materials, renewable power sources, scavenging techniques and autonomous sensor nodes that save energy from the environment, have emerged as a prominent research area and in continuous development. The interest to save energy from the environment is highly felt in small and also integrated scale: self powered integrated systems, autonomous MEMS transducers, batteryless sensor node, self-powered sensors, smart systems [1], represent a set of devices that adopt the harvested energy to sustain or to supply an electronic device. Different kinds of energy can be harvested from renewable natural sources, such as: sunlight power, thermal gradients, wind, rain, tides, acoustic, and mechanical vibrations. In particular the last one represents an available source and presents a significant energy amount. It is present in nature as earth's vibration, seismic vibrations, naturally noise source and different energy converters can be adopted such as: piezoelectric, electromagnetic, and electrostatic transducers. A classical approach is represented by a mechanically resonant device that is, suitably, matched to the single tone vibration of the source. However, in the vast majority of cases the ambient mechanical vibrations come in a vast variety of forms and having the energy distributed over a wide spectrum of frequencies, typically distributed in a bandwidth of few thousands of Hz. Several ways for optimization have been explored, concerning the increment of the converted and extracted energies, and the transduction mechanisms [2]. A different approach is presented here: it is based on the exploitation of the properties of "nonresonant" MEMS oscillators characterized by a nonlinear dynamic response. For these oscillators, it is not possible to define a transfer function, and thus a properly defined resonant frequency, even if the power spectral density can show one or more well defined peeks. Furthermore a wider spectrum is predicted for the nonlinear system with respect to the linear oscillator. The nonlinear behaviour has been previously demonstrated on macro cantilever prototypes [3, 4]. The figure 1 shows the bistable mechanism applied in a U-shaped MEMS device and the dynamic model assumed as a nonlinear pendulum governed by a double well nonlinearity [3, 4]:



$$\begin{cases} dx_1 = x_2dt = f_1(x)dt \\ dx_2 = \left[-\frac{d}{m}x_2 + \frac{3ax_1(ax_1^2 + b\Delta^2)^{-\frac{5}{2}}}{m} - \frac{2kx_1}{m}\right]dt + \frac{\sigma}{m}dW_t = \\ = f_2(x)dt + g_2(x)dW_t \end{cases}$$

Figure1: Bistable MEMS mechanism, on the left: high distance between the two magnets implies a linear behaviour and the parabolic function describes the energy. Furthermore two equilibrium states x_1 and x_2 will appear when the mass spring damper system is subjected to the effect of the neighbor external magnet; x_0 represents an unstable condition (on the right). The term $2k$ represents the contribution of the two parallel springs, d is the damper and m the mass at the tip of the cantilever. In red, the dynamic model is presented.

Where Δ is the distance between the two magnets (the first deposited onto the cantilever surface and the second, in the external part of the system, and maintained fixed); a and b represent constants correlated to the physical parameters of the systems. In presence of a stochastic source, $f(t)$ assumes non periodic oscillations, so the dynamic can be described through a stochastic differential equation. The system of equations is composed by two 1st order Itô's equations with two drift terms, $f_1(x)$ and $f_2(x)$: the first represents the velocity of the cantilever tip, the latter is function of the damping (d), the elastic constant (k) and an additive nonlinear term. Only one diffusion term is included in the system $g_2(x)$, that is function of the vibrations amplitude (σ, standard deviation of the source) and the mass (m) of the nonlinear oscillator; x_1 is the displacement of the cantilever tip, and t is the time. The previously model has been simulated by using MATLAB® SDE (Stochastic Differential Equation) Toolbox. The Euler-Maruyama method has been used with vibration source (gaussian white noise) having a standard deviation (σ) of 20 µN. The figure 2a shows the simulation result of an U-shaped cantilever device having an elastic constant of 12 kg/s^2 and based on two parallel cantilever beams having a length of 2500 µm and width of 700 µm, connected at their free extremity by a 'linking arm' (3400 µm x 700 µm, the thickness is 15 µm). A resonance spike has been detected at Δ=0.933 mm. The integrated system has been also realized by using the BESOI technology [5] (figure2d). The principle has been experimentally validated by using an external permanent magnet stack and a translator system, in order to modulate the distance between the two magnets, a shaker has been used to stimulate the structure, an active Wheatstone bridge has been used as conditioning circuit and a LabVIEW™ routine has been performed to filter and to drive the shaker using a GPIB communication. A resonance condition has been experimentally verified that represents the maximum value of the beam displacement and a bistable condition with a low energy barrier. Coherence as respect the simulation results has been detected (Δ=0.94 mm). Figure 2c shows the output signal of the bridge when a distance of 0.94 mm between the two magnets occurs, while figure 2b shows the output spectrum evaluated through the measure campaign: a wider spectrum compared to the linear case appears for the nonlinear system, so more energy can be saved adopting a bistable dynamic. The proposed mechanism validated for a MEMS device, evinces an improvement of the performance with respect to a linear oscillator. The obtained results confirm the nonlinear principle applied to a MEMS device, moreover they represent a major advance with respect to the state of the art in the integrated energy harvesting area; in fact the device that has been designed, realized and validated can be highly efficient for scavenging energy from a large range of vibration sources having different nature and therefore different spectral content. As a future trend a PZT material and magnetic stack deposition will be performed.

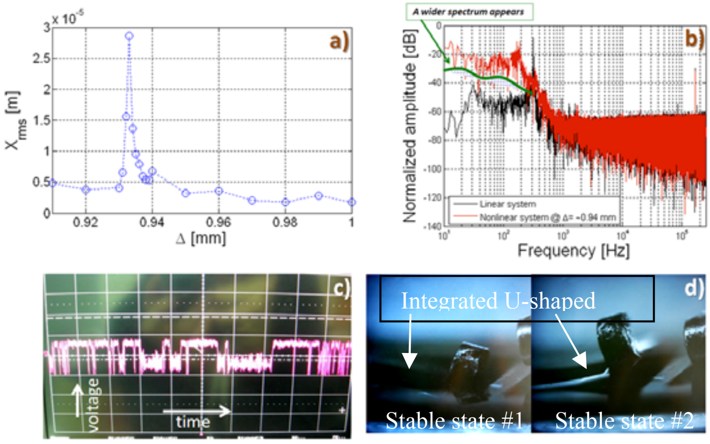


Figure2: a) Simulation result: displacement of the U-shaped device (AC component), excited by gaussian vibrations having standard deviation (σ) of 20 µN. Experimental results: b) Output spectrum in the linear case (black) and in the nonlinear case (red). A wide spectrum appears in presence of a bistable energy function, c) scope picture of the Wheatstone bridge output at Δ=0.94 mm and σ=20 µN. d) Microscope picture of the U-shaped device realized with the permanent magnet deposited at the tip; in front, the tunable magnetic stack: on the left the first stable state; on the right, second stable state.

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