ENERGY HARVESTING DEVICE WITH ENLARGED FREQUENCY BANDWIDTH BASED ON STOCHASTIC RESONANCE

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Abstract: Most of mechanical energy harvesters are based on linear oscillators. However, if the available vibration energy does not match their natural frequency, very few energy can be extracted. On the contrary, non-linear bistable oscillators present non-resonant large amplitude complex motions when excited with a sufficient intensity. Consequently, they can optimize energy harvesting. Using a stochastic resonant effect, it should be possible to improve the potentiality of this approach. An experimental device has been built and associated theoretical results are presented. It appears that the occurrence of large amplitude motions is increased and so the energy that can be harvested.

Keywords: Energy harvesting, bistable oscillator, stochastic resonance

INTRODUCTION

During the last decade, devices which can generate electrical power by exploiting ambient vibrational energy have been developed. Without the need for a battery it would be possible to power remote wireless sensors in automotive or aerospace applications. Most of these developments are based on linear oscillators (LO) (e.g. a cantilevered beam) with a more or less integrated electro-mechanical convertor (e.g. piezoelectric patches) used to transform the mechanical energy into a suitable electrical energy. If the natural frequency of the LO is tuned to the main frequency of the excitation spectrum, large displacements can occur. It eventually appears to be the only operating condition for this approach to be viable.

The extracted power of such devices is directly proportional to their inertial mass, one of the main challenges is their miniaturization, though. Under these conditions, the natural frequency increases and any tuning is virtually impossible since the usual main excitation frequency is about 100 Hz. Moreover, it can be inferred that as far as the mechanical energy spreads through a large spectrum, very few energy can be extracted by this strategy. Therefore, there is a need for large bandwidth harvesting devices [1, 2].

Several authors proposed to exploit the behaviour of non-linear bistable oscillators (NLBO) [3, 4]. The usual way of describing NLBO is to study their associated mechanical potential energy as shown in Fig. 1. Two stable as well as one instable equilibrium positions are the characteristic pattern of NLBO. When excited, they present complex motions oscillations. Indeed, in addition to simple oscillations in the vicinity of one of the two local stable equilibriums denoted ξ^- and ξ^+, there are also large movements that are jumps from one equilibrium to the other.

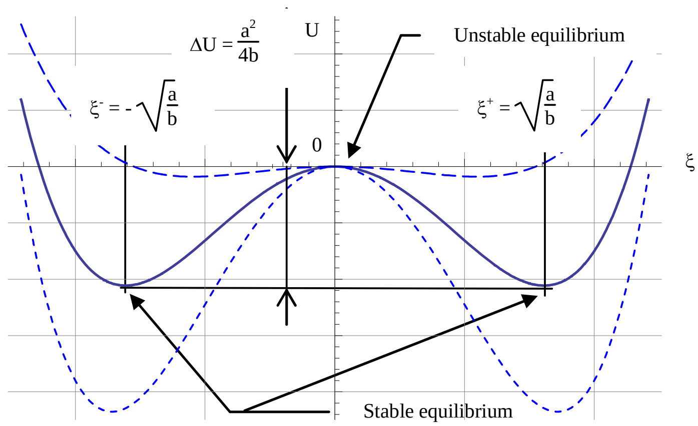

Fig. 1: Energetic potential U for a NLBO and modified energetic potential for SR.

It ensues that large displacement can be obtained from a NLBO when submitted to any excitation of sufficient intensity and thus can be used to optimize an energy harvesting device. Ramlan et al. [4] have suggested a theoretical limit of the benefit of NLBO compared to LO energy harvesters. The gain of the scavenged power is bounded by 4/π compared to a tuned LO. Moreover, this value can be greatly exceeded when the excitation frequency is lower than the LO's natural frequency.

Based on the behaviour of NLBO, we aim at improving the potentiality of this approach. To the extent that the larger the jumps, the higher the required excitation intensity, the latter could be one of the main limitations. Mc Innes et al. have theoretically demonstrated the benefit of the stochastic resonance (SR) phenomenon in an energy harvesting mechanism [5]. The SR can appear in a two-state-system, e.g. a

NLBO [6]. When the SR effect occurs, the position of the system jumps randomly from one state to the other. The traditional SR is used to amplify a weak signal by an appropriate amount of noise. In an opposite point of view this phenomenon could be used for energy harvesting if we suppose that the “noise” is provided by the environment excitation and a “weak signal” is added to a two-state-system.

This paper reports the development of an appropriate energy harvesting mechanism based on the effect of SR for enhanced bandwidth PowerMEMS utilization.

The work is separated in three steps. First, a simple model of a NLBO is described. The advantages of this structure compared to LO for energy harvesting are recalled. Second, the enhanced system by SR effect is discussed. Finally, an experimental device based on this model is presented.

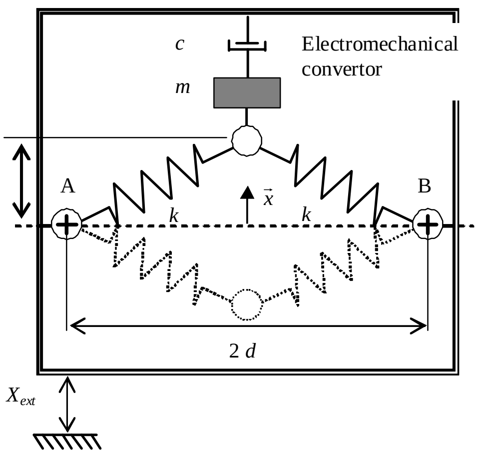

Fig. 2:Generic scheme of a mechanical NLBO.

THEORY

Energy harvesting with NLBO

Figure 2 shows the generic scheme of a NLBO and defines the main associated parameters and variables. We assume that the system is symmetrical. The Newton’s law applied to the inertial mass m leads to the dynamical equation:

$$m\ddot{x} + c\dot{x} + 2kx\left(1-\frac{L_0}{\sqrt{x^2+d^2}}\right) = FEx \quad (1)$$

In which L_0 is the free length of the springs, k their stiffness and $FEx = m\ddot{X}_{ext}$. To the extent that the length $d << L_0$, Eq. 1 is simplified then modified using the new variables $\xi = \sqrt{L_0/d^3}\,x$ and $\tau = t/\sqrt{m/k}$. We obtain:

$$\ddot{\xi} + \gamma\dot{\xi} + dU/d\xi = Q(\tau) \quad (2)$$

In which $Q(\tau)$ is a stochastic excitation and:

$$\gamma = c/\sqrt{km} \quad (3)$$
$$U = -a\,\xi^2/2 + b\,\xi^4/4 \quad (4)$$
$$a = -2\,(1 - L_0/d) \quad (5)$$
$$b = 1 \quad (6)$$

The energetic potential $U(\xi)$ (Fig. 1), related to Eq. 2 shows the characteristic two wells pattern of NLBO. If the intensity of the excitation $Q(\tau)$ is small, only small oscillations with frequency of about $\sqrt{2a}$ around one of the stable equilibrium occur. On the contrary, if the excitation is strong enough, the mass can jump across the central unstable position. An efficient implicit midpoint method has been used [7] to evaluate the response of the system when submitted to excitation. The results of numerical simulations using a stochastic excitation $Q(\tau) = \sigma\,\varepsilon(\tau)$ with Gaussian distribution, zero mean, unitary standard deviation, and exponential autocorrelation function with correlation time τ_c have been obtained. The non-dimensional position ξ of the mass m with respect to τ are plotted in Fig. 3. The complex behaviour obtained for sufficient intensity (case 2) is clearly observed.

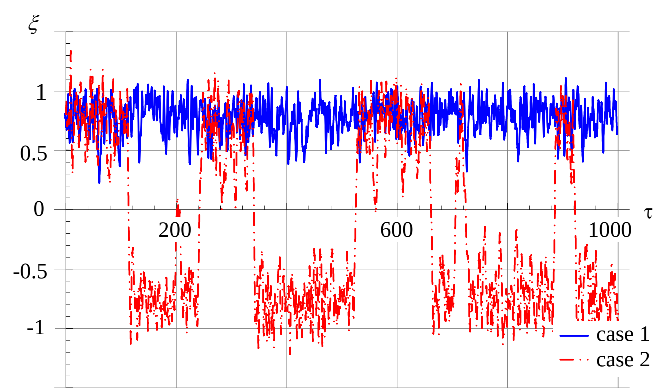

Fig. 3: displacement results for case 1: σ = 0.2, a =0.65, b= γ = 1, case 2: σ = 0.3, a =0.65, b= γ = 1.

The average resident time τ_{av} in a well can be approximately evaluated by the Kramers rate [6] as:

$$\tau_{avKR} = \frac{2\pi}{\sqrt{|U''(0)|\,U''(\sqrt{a/b})}}\,\frac{1}{\exp(-2\,\Delta U/\sigma^2)} \quad (7)$$

Average resident time has been calculated from the previous results and is in agreement with the theoretical value. Using the Kramers rate formula, for case 1 τ_{avKR1} = 1340 and for case 2 we have τ_{avKR2} = 71 compared to a simulated value of τ_{avE2} = 77.

Depending on the type of conversion, one may be interested in the displacement (e.g. piezoelectric conversion) or the energy dissipated at the damper $\underline{E}$ which can be representative of the available energy which is harvested eventually (e.g. electromagnetic conversion). For the displacement, the standard deviation SD_ξ of the position can be useful to compare the two cases: SD_ξ = 0.14 for case 1 and 0.73 for case 2. As for the energy at the damper, fig. 4 shows the quantities for the two cases.

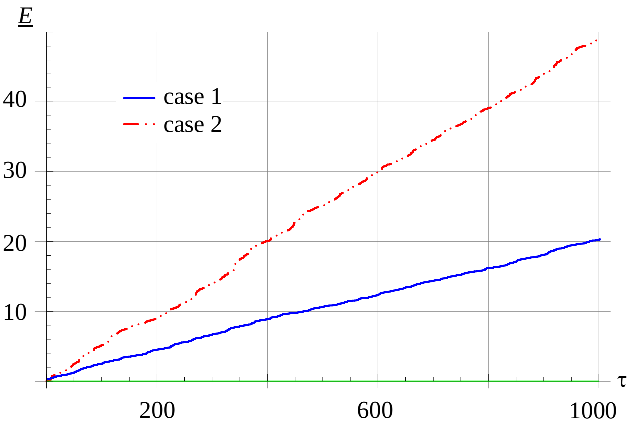

Fig. 4: Available energy for case 1: σ = 0.2, a =0.65, b= γ = 1, case 2: σ = 0.3, a =0.65, b= γ = 1.

It can be seen that NLBO can harvest more energy than LO if the intensity of the excitation reaches a threshold in relation with the device parameters. Moreover, as the total amplitude of the displacement is given by parameters *a* and *b*, it could be interesting to increase the height of the jump. But as it is increased, so is the average time τ_{av}. Therefore fewer switches would occur. As a conclusion, optimization of this strategy could consist in reducing the τ_{av} criteria.

Energy harvesting with periodically forced NLBO

Mc Innes et al. [5] have suggested that stochastic resonance phenomenon could increase the probability of switches. It has been shown that a stochastic dynamical system subject to random perturbation and additional periodic forcing (PF) may show a resonance which is not present when either excitation is absent.

It is supposed here that a PF denoted *FAdd* is added such as shown in Fig. 5. The energetic potential is then modified as follows:

$$U_2 = -a\,(1 + (a/2 + 1)\,2/a\;\eta\cos(\omega\,\tau))\,\xi^2/2 + b\,(1 - 3\,\eta\cos(\omega\,\tau))\,\xi^4/4 \quad (8)$$

The evolution of the potential with respect to τ is shown in Fig. 1. The dashed curves show the limit shapes of U_2 depending on the value of τ. We can now attempt at explaining the qualitative behaviour of the NLBO submitted to both *FEx* and *FAdd*. At τ = 0, set $\xi = \xi^-$. As time passes, it can be inferred from Eq. 7 that the average time residence within the well decreases, and that it reaches a minimum for $\tau = \pi/\omega$. Therefore, with high probability, the mass will jump from ξ^- to ξ^+.

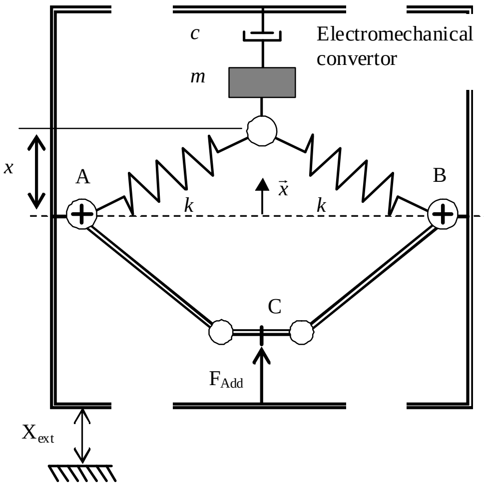

Fig. 5: Scheme of a forced mechanical NLBO.

Thus, an added PF is able to modify the behaviour of the device inducing jumps between the two stable equilibriums. Figure 6 shows the results for the case 1 compared to the same system parameters and the same excitation intensity but with an additional PF. Standard deviation of the position of the mass increases to 0.75, which is higher than the result for case 1 without PF.

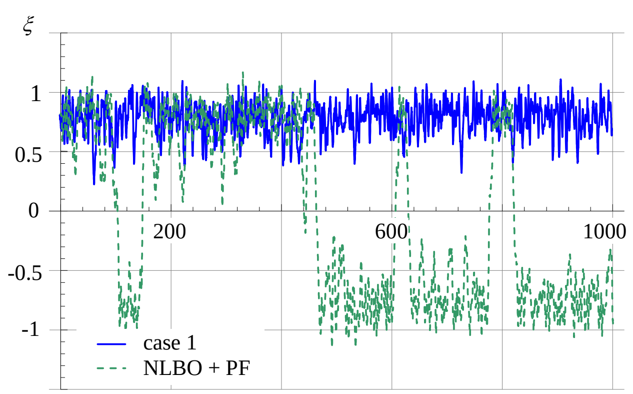

Fig. 6: displacement results for case 1: σ = 0.2, a = 0.65, b= γ = 1 and PF for which ω =0.26, η = 0.2.

To evaluate the theoretical available energy, the required mechanical work to generate the PF is also evaluated. It is then possible to estimate E from the difference between the dissipated and the provided energies. Figure 7 shows that the harvested energy can be slightly increased by an added PF.

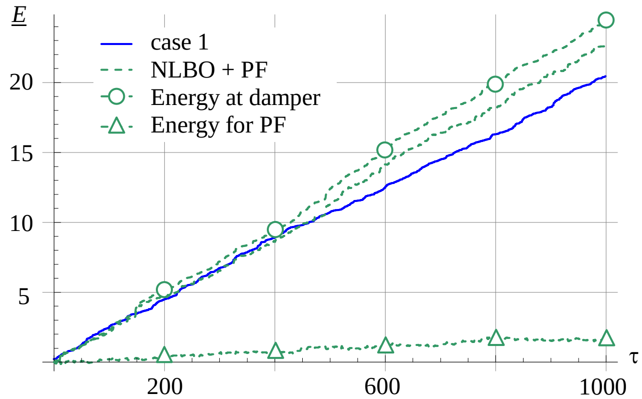

Fig. 7: Available energy at the damper for σ = 0.2, a =0.65, b= γ = 1 and with PF ω =0.26, η = 0.2.

The harvested energy with and without an added periodic forcing have been compared. Result show that there is a higher amount of harvested energy with the forcing. However, the required additional actuator may be a prior disadvantage regarding the efficiency and the feasibility of such PowerMEMS.

EXPERIMENTAL DEVICE

An experimental device has been built and tested. A central stainless steel beam of 20 µm thick, 10 mm width and 85 mm length is inserted in a ring structure made from the same material with 75 µm thick. The final device is shown mounted on the test rig in Fig. 8.

Fig. 8: Experimental NLBO mounted on a test rig.

The proportional coefficient between the displacement of point C and the horizontal displacement of both points A and B (see Fig. 5) is 2.02. A mass of m = 3.66 g is used. The identification parameters for the experimental device leads to a = 0.65, b = 1 for a prestress of 5 mm at the top of the ring. These are the values used for the theoretical and simulation studies.

The PF is generated from a piezoelectric actuator which bends the ring out of shape. By doing this, it is possible to modify the compression of the central beam in such a way that its associated energetic potential can be represented by Eq. 7.

CONCLUSION

The use of NLBO for large bandwidth energy harvesting devices appears to be a promising axe of development. We proposed a mechanical structure which presents the characteristics of a NLBO. A theoretical model has been proposed to study the effect of a noise excitation regarding the potential scavenged energy. Moreover, we have studied the effect of an additional periodic forcing on the NLBO. It appears that under specific parameters, the theoretical available energy can be optimized. An experimental device is currently under testing to provide support for the results.

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