Use of Non-Linear Oscillation to Harvest Vibration Energy

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Abstract

In the recent years, due to the technological advancements a significant research in energy harvesting has derived solutions to power the portable mobile devices. One of these autonomous solutions is vibration energy harvesting, obtained in presence of movements and noise. Mainly standard approaches to energy harvesting that are given by the ambient vibrations focus on resonant linear oscillators. In the succeeding research, dynamic characteristics of stochastic non-linear oscillators are explored for the suitable benefits in overcoming the limitations of the comparable methods. This research is an explanatory study that utilizes the qualitative research method and analytical techniques. Relevant theoretical evidence is maintained to project the standard performance of the linear oscillators in avoiding low efficiency, continuous frequency tuning, and narrow bandwidth. Experimental results from a number of studies indicating the successful outcomes of their implications have described including the toy-model oscillator. Most methodologies demonstrate general principles that are implementable to a wide range of energy conversion and diverse nonlinear oscillators.

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Introduction

The increasingly challenging task emerged due to the extensive use of portable electronic devices, in the recent times, is the search for more practical and lasting power solutions. Traditional approaches for charging batteries have proved impractical to support the unconventional remote distribution of wireless devices (Masana & Daqaq, 2011). Especially, for the mobile devices, it is considered that the power source and device are collocated. Therefore, the research explores suitable energy harvesting methods based on different nature (mechanical, thermal, and electromagnetic) and portability aspect (charge the device when needed) (Chen & Jiang, 2015). The stochastic resonance, by adding noise to weak signal in the non-linear system, which is a physical phenomenon that increases to resonated the response of the system under a certain probability (Joo & Sapsis, 2014). For application to energy harvesting for generating electric power by utilizing the environmental energy, utilizing the physical phenomenon of stochastic resonance, by weak environmental vibration, to generate a large response vibration, considering that outputs a higher power. The purpose of this study is to consider the possibility of probability resonance using a bi-stable system, to achieve efficient vibration power generation than conventional approaches (Ando et al., 2013). Although previous studies have experimented the strength of environmental vibration, by giving a small external force to the bi-stable system, that increases the vibration causing the probability resonance in an unknown state, that can be achieved to examine through the theoretical and experimental analysis.

Research Background

Ambient vibrations to achieve power involve a variety of motions, seismic noise, and movements. The vibrations are converted to electricity through piezoelectric, inductive, or capacitive methods based on the mechanical conversion of kinetic energy. Design of the mechanical oscillators is generally subjected to dominant ambient frequency via resonant tuning (Yang and Towfighian, 2016). The energy of ambient vibrations is usually distributed through a wide range of frequencies, where because of the dynamical constraints low frequency tuning and components are not mostly predominant. Cottone et al (2009) explored a new approach in exploitation of the different features and to resolve the issues associated with non-resonant oscillators. The researchers reflect the impact of appropriate operating conditions on a bi-stable oscillator, providing improved performance as compared to a widely distributed spectrum of vibration via a linear oscillator. The researchers demonstrated a piezoelectric inverted pendulum added with a tip magnet such a toy model oscillator.

Vibration is present in our personal belongings, heat, light, electromagnetic waves, a variety of energy, such as biological material. These are usually low density energy that is discarded without being utilized. These abandoned computing energy harvesting technology should be converted to electricity via the use of advance technology. This technique, without resorting to a wired commercial power, moreover, without the need for replacement or charging as the battery, is expected to supply power directly to the device or apparatus (Tang et al., 2016). Maintenance is required to prolong the life of such devices. Although, the abandoned energy is sufficient which adversely affect the global environment; therefore saving this energy for useful purpose is imperative. Energy harvesting technology, converts the discarded energy into electricity, which is a technique that aims to utilize the energy for better purpose. Oil or coal can be used to convert the unused energy other than nuclear power into electrical energy but it is a relatively expensive option. Thereby, it can be said that the energy harvesting in a broad sense, with respect to micro-energy harvesting is quiet cost effective, such as it can be especially applied to a micro-information equipment without additional cost (Chen et al., 2016). Therefore hydroelectric power and geothermal power, unlike the centralized power source such as a local and distributed sensor networks, is also be used as a variety of wearable devices. Wang & Tang (2016) demonstrated the energy harvesting the latest developments of technology as an overview of the future technology development for the optimal energy harvesting device technology and its design method to attempt the application of this technology. The energy harvesting techniques for industrial use is to create a new mechanism for the world; which is expected to lead to great innovation in the field.

Literature Review

Theoretical basis of the utilization of mechanical vibrations in conversion to electrical energy provides sufficient evidence for its practical implications. Powering the remote sensors through ambient energy is a cost efficient solution that eliminates the need of changing batteries. Lan and Qin (2016) proposed currently harvesters based on vibration energy function like linear resonator for attaining the optimal level of performance that also relate to their dominant ambient and natural frequencies. Mostly, the frequency spectrum of ambient vibrations is relevantly wide at low frequency distribution. Frequency bandwidth issue has been resolved through several methods in the last few years. Erturk et al (2009) studied the tunable energy harvest through resonance energy via changing stiffness system and magnetic force method.

Mann and Sims (2009) proposed the advanced approaches in energy harvesting technology to collect the vibration energy ubiquitous in the environment which is obtained by the proposed mechanism of collecting vibration energy with its typical frequency distribution. Vibration of interest is in the vibration frequency component has a plurality superposition, or continuous frequency distribution. In the collection of those of vibration energy, its resonance of the linear vibrator as a principle of energy collection mechanism is applied, while it is unable to absorb only the vibration energy of a specific frequency. However, focusing on the characteristics of the nonlinear oscillators and coupled oscillator based on the physical mechanism of resonance phenomenon the vibration frequency component has a plurality superposition or continuous frequency distribution in these oscillations. It indicates a possible energy collection. Jiang and Chen (2016) summarizes the results of these studies, where the major results obtained in a typical example is a resonant increasing the energy collection rate, the phase difference of an object which receives an external force and external force. If it is constant, energy collection rate is high. Similarly, when the frequency of the external force is more than one, defining an external force of a phase consisting of a plurality of frequencies, to dominate its phase energy recovery was to numerically clear. Chen et al (2016) highlighted a mechanism for performing energy collection from the vibration containing a large amount of low frequency; it proposes a coupled oscillator of the tree structure. It is theoretical and experimentally obvious that in this mechanism that works to narrow the frequency band possessed by the external force that provide a means of efficient energy recovery shown experimentally. In addition, the present mechanism of electromagnetism indicates that suitable for application energy converter having a natural frequency, such as inductive or piezoelectric element. The energy has been studied to try to collect energy from the continuous vibration of the frequency diffused. Principles vibrator which receives the excitation of minute vibrations of contiguous spectrum results in probability resonance energy. It can be applied to over collection mechanism. It is a method used to increase the energy collection rate in the structure. It is suggested considering the power factor principles of adjustment representing the time variation of energy. In their study Kluger et al (2015) described the non-linear oscillator and coupled oscillator in the collection system of vibration energy that has a possibility to utilize the characteristics, theoretical, numerical calculation, those principally apparent by experiment.

Data Analysis and Discussion

Non-linear mass spring systems have succeeded in recent times due to the recent research on vibration energy harvesting systems and its importance. For example, in a research, Ahmadabadi and Khadem (2014) analyzed the reversible hysteresis for broadband magneto-piezoelectric energy harvesting, which is used to improve energy harvesting from wideband vibration by nonlinear piezoelectric converters. Furthermore, there are several publications that highlight the benefits of non-linear springs, in particular that this in combination with large displacement amplitudes leads to a wide range of vibration harvester. Such as; Sapsis et al (2012) determined the uncertainty in performance for linear and nonlinear energy harvesting strategies. Joo & Sapsis (2014) encountered potential benefits of a non-linear stiffness within energy harvesting device. To generate kinetic energy through motion transduction mechanism is induced (Lu and Chen, 2016). Kluger et al (2015) presented invention related to a novel design of non-linear magnetic springs, which can be used for energy harvesting applications on vibrating base to obtain a vibration with greater bandwidth and with the possibility of an energy-efficient frequency adjustment. According to the present invention, the greater bandwidth allows to balance the spring characteristics in a simple manner to set a special customized non-linear behavior of the system. Furthermore, the proposed system has a very compact geometry in comparison with the known arrangements (Cottone et al., 2009). An adjustment of the resonant frequency e.g. as by changing the relative position between the magnets is only possible with actuators, which have at the same time, large forces and ways. This cannot frequently take place or only at long intervals with the energy harvested from the vibration. The present invention is explained in more detail with reference to the same parts with the same reference numerals and same component names. Furthermore, individual features or combinations of features from the embodiments shown and described may in it constitute independent or inventive solutions.

The non-linear mass spring systems are well known as a hysteresis. Therefore, the frequency response was recorded for both an increase as well as decrease the frequency. It can be deduced that the spring of the invention is capable of generating a significant non-linear restoring force at moderate excitation acceleration amplitude (6 m / s 2). The hysteresis width amounts to 6 Hz and the maximum voltage amplitude is 106 Hz (Tang et al., 2016). Accordingly, the spring of the invention is an alternative to the known concepts represent, but which is much more compact than the known springs. In particular, it allows the realization of a novel principle of a vibration transducer which has the following properties:

- A broadband energy conversion from vibration, achieved through the use of a novel, non-linear resonant system,
- The possibility of actively influencing the converter behavior by an energy-independent adjuster working for the acceptance of frequencies of the transducer (Ando et al., 2013).

- Thus, the option to move in a broadband sum acceptance window of the transducer in the frequency domain in order to optimally adapt it to the frequency spectrum of the energy source (Masana & Daqaq, 2011).

The use of energy harvesting technology enables power wireless, embedded micro systems by converting energy from their immediate environment into electric energy. Of great interest because often occurring in technical systems, processes and in nature, in this respect, the use of mechanical energy in the form of impacts, noise or vibration. The invention is particularly suitable for energy harvesting based on sound and vibration as an energy source. Independent of the mechanical-electrical conversion mechanism can basically two classes of vibration harvesters distinguished. An inertial frame, acting as a fixed reference is attached to the massive mechanical component confined with a transduction mechanism. Vibrations are transmitted by the inertial frame to the suspended mass m, which results in a relative displacement in between. In the given figure 1, the energy transmitted to reference frame from the vibrating body via inertial mass m is illustrated.

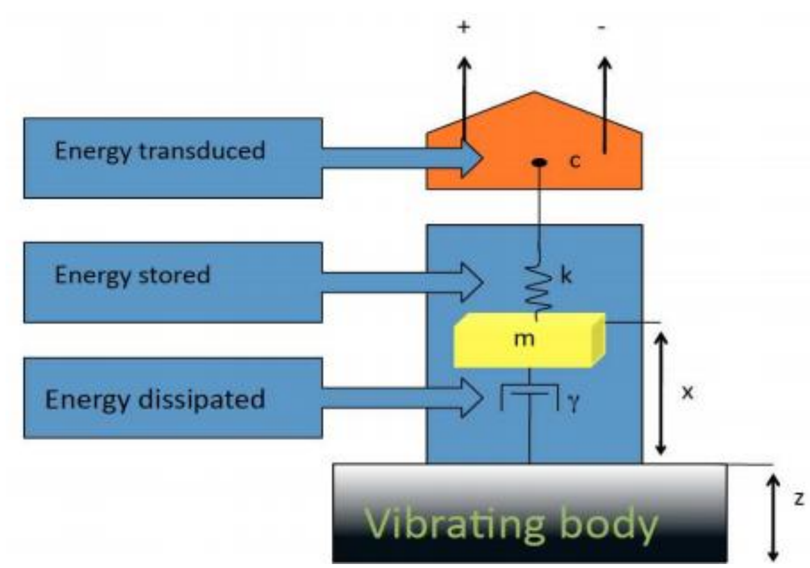


Figure 1: Vibration Harvesting (a Simple Scheme). (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

Explaining the mathematical model of the given scheme its functioning can be analyzed quantitatively in order to address the dynamics of the voltage difference V and mass displacement X. The two relevant quantities are consistent with the equations of motion and time function. The Newton's equation in standard form describes this displacement X; thereby, a differential equation of second order is given by:

$$m\ddot{x} = -\frac{d}{dx}U(x) - \gamma\dot{x} - c(x,V) + \xi_z \qquad (1)$$

Where;

U(x) corresponds to the energy stored

γx corresponds to dissipative force

c(x,V) corresponds to force of reaction caused by transduction mechanism

ξ_z corresponds to the vibration force

The equation below represents voltage V dynamics;

$$\dot{V} = F(\dot{x},V) \qquad (2)$$

The form of the functions to be connected is explained below, which describes the motion that generates energy. Since, (2) gives the differential equations of the first order connecting displacement velocity and electric voltage; thus, functions are given by (3):

$$F(\dot{x},V), \quad c(x,V)$$

(3)

A simple expression can be made to explain the piezoelectric conversion of the given functions as:

$$c(x,V) = K_V V \qquad (4)$$

$$F(\dot{x}, V) = K_c \dot{x} - \frac{1}{\tau_p} V$$

(5)

Therefore, a dynamic equation can be given by;

$$m\ddot{x} = -\frac{d}{dx} U(x) - \gamma \dot{x} - K_V V + \xi_z$$

(6)

$$\dot{V} = K_c \dot{x} - \frac{1}{\tau_p} V$$

(7)

Here, *T*p represents the constant time which is explained by the generator's electric circuit.

$$\tau_p = R_L C$$

(8)

The harvested power extracted from the scheme is given by;

$$W = \frac{V^2}{R_L}$$

(9)

Cantilever configuration is most commonly used harvester model, which is illustrated in the below figure:

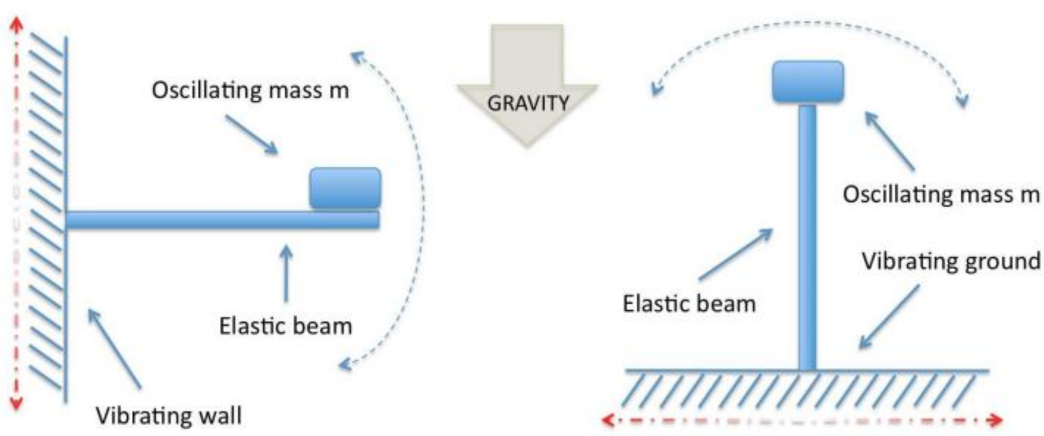


Figure 2: Cantilever configuration. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

The potential energy function is introduced for treating most of the harvesters within an approximately small oscillation and expressed by the function;

$$U(x) = \frac{1}{2}kx^2 \tag{10}$$

The above form is called harmonic potential. The equation of motion can be expressed as below, when derivative is taken and (3) is substituted in (6).

$$m\ddot{x} = -kx - \gamma\dot{x} - K_V V + \xi_z \tag{11}$$

$$\dot{V} = K_c\dot{x} - \frac{1}{\tau_p}V \tag{12}$$

The bi-stable dynamics is shown in the figure below for an inverted piezoelectric pendulum.

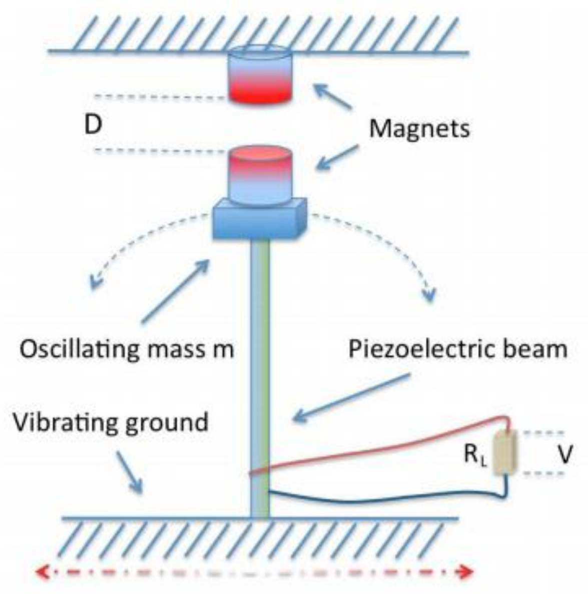
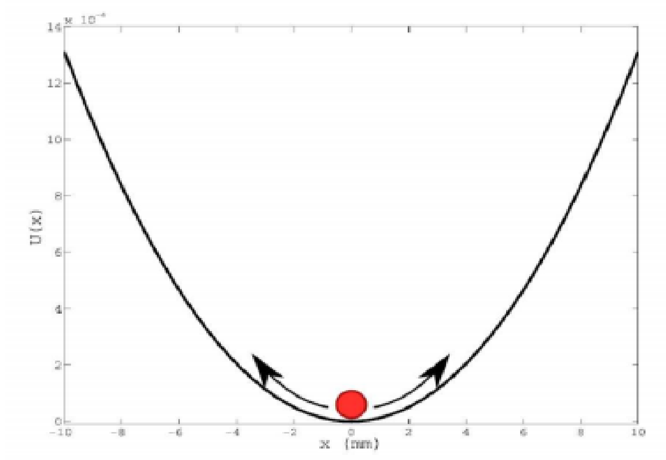


Figure 3: Piezoelectric inverted pendulum. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

The new potential is expressed by (13);

$$U(x) = \frac{1}{2}k_e x^2 + (Ax^2 + BD^2)^{-\frac{3}{2}} \tag{13}$$

Here, A and B expressed the physical parameters as constants of the pendulum, having D distance (Lefeuvre et al., 2006). The distance increase in the second part of (13) results in a negligible proportion, whereas there is a harmonic potential of cantilever configuration. In the figures 4, 5, and 6, analysis of the modified potential having a simulated dynamics which considers the repulsive force in presence of the magnets, where the new potential is expressed by (13).



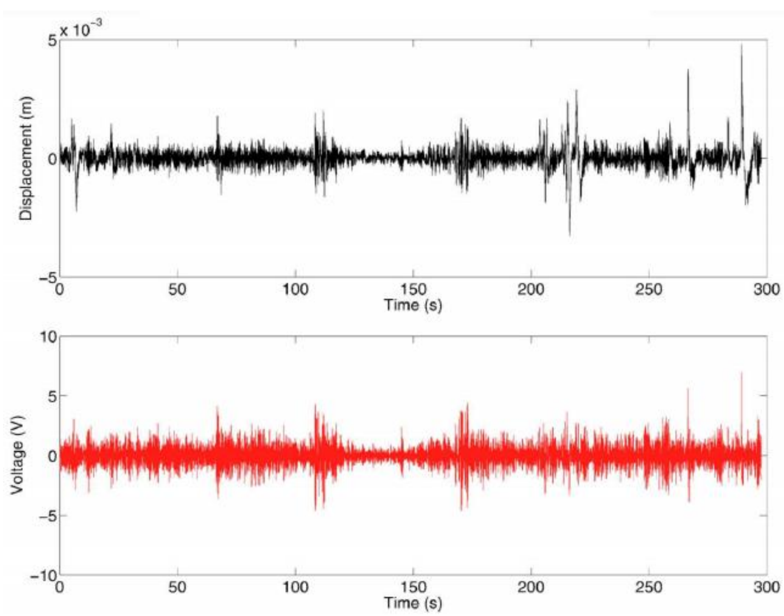
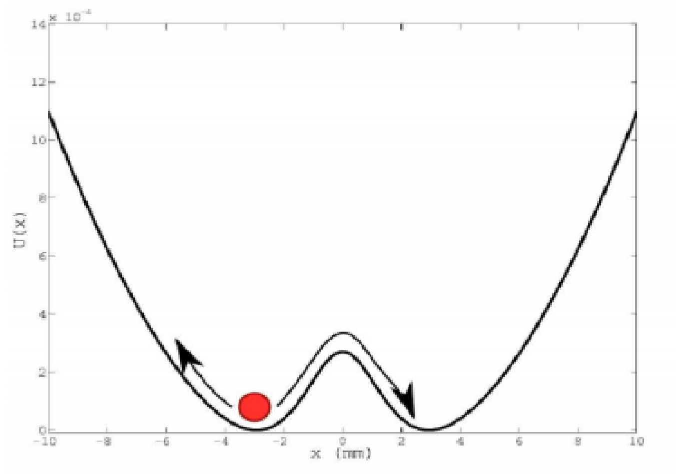


Figure 4: The upper panel expresses the U(x) of the equation (13), middle panel expresses the time series displacement by x, and time series V voltage is expressed in the lower panel. The correlation time 0.1s and fixed standard deviation within the correlated noise is known as stochastic force. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)



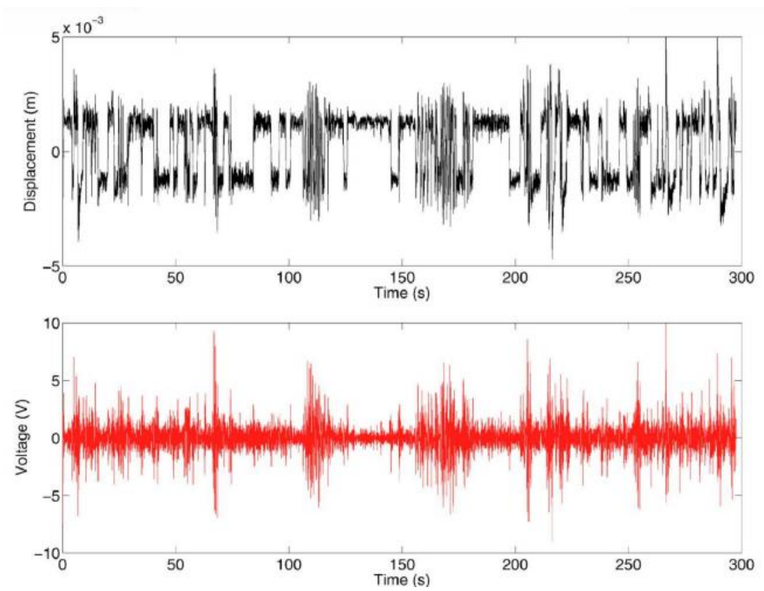


Figure 5: The upper panel expresses the U(x) of the equation (13), middle panel expresses the time series displacement by x, and time series V voltage is expressed in the lower panel. The correlation time 0.1s and fixed standard deviation within the correlated noise is known as stochastic force. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

The figure 5 shows the same quantities expressed in the figure 4, but with a distance covered $D=D_0$ by the magnets. In figure 5 it is noteworthy differential stochastic equations (6 & 7) results in the voltage V, is in line with the time series displacement x, which is because of the equation in voltage dynamics, represented by the special form given below.

$$\dot{V} = K_c \dot{x} - \frac{1}{\tau_p} V \tag{14}$$

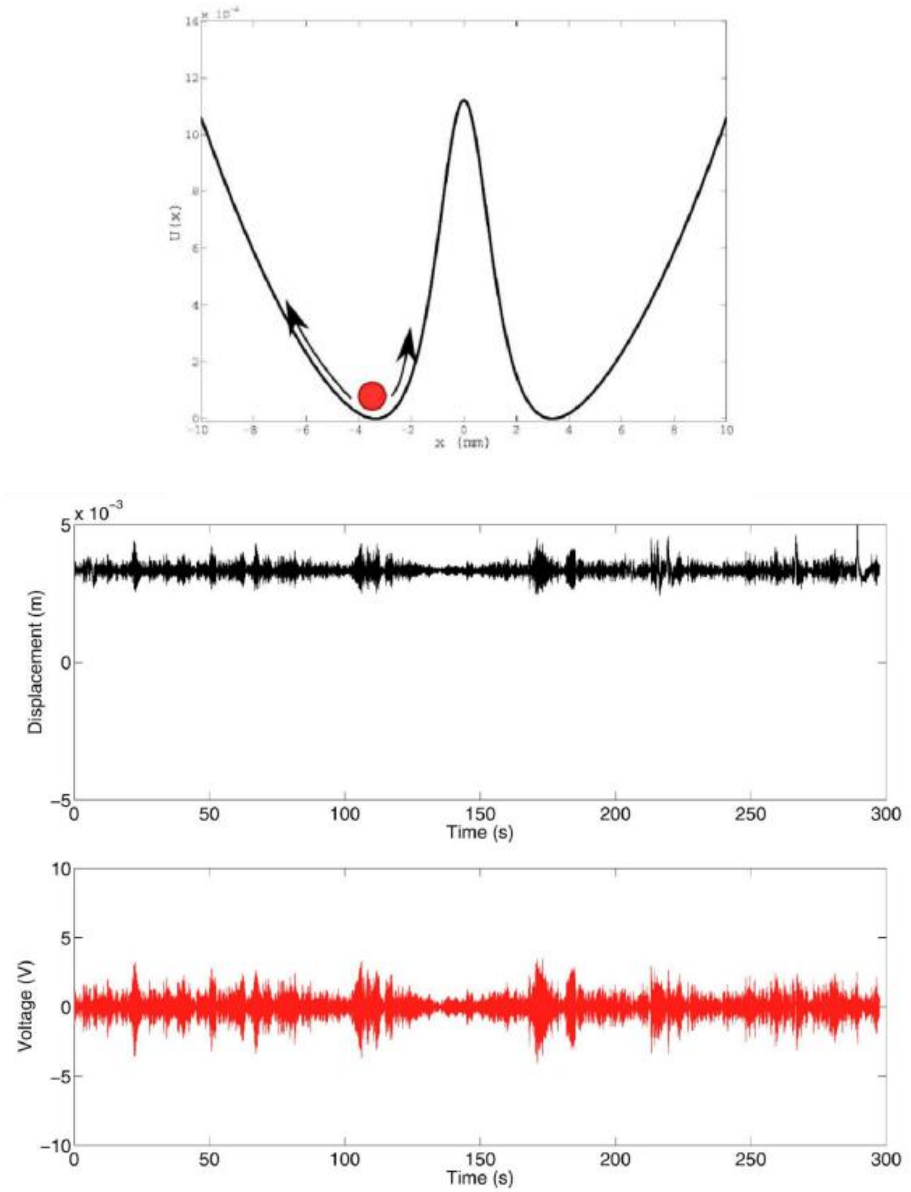


Figure 6: The upper panel expresses the U(x) of the equation (13), middle panel expresses the time series displacement by x, and time series V voltage is expressed in the lower panel. The correlation time 0.1s and fixed standard deviation within the correlated noise is known as stochastic force. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

In figure 6, the distance between two magnets is further decreased (D<< D_0).

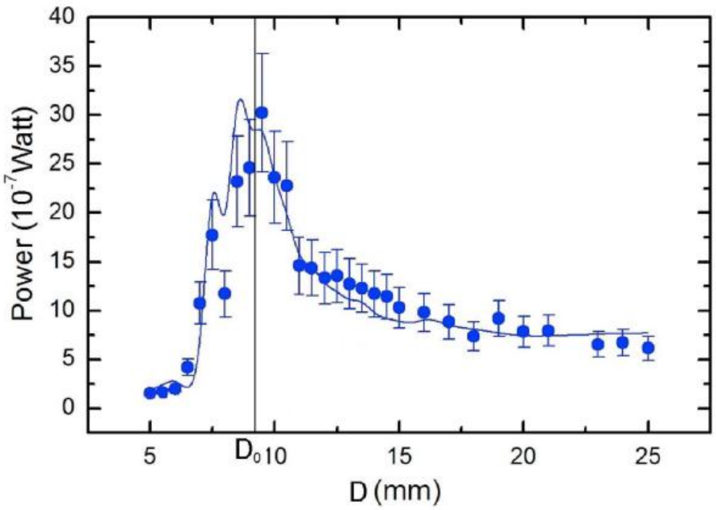


Figure 7: Data points express the average rms values for ten time series, which is sampled for 1 kHz frequency. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

Following form explains a simple bi-stable called as Duffing oscillator and given by (Cottone et al. 2009) as:

$$U(x) = \frac{1}{2}ax^2 + \frac{1}{4}bx^4 \tag{15}$$

Where, *U(x)* is considered a better approximation for non-linear oscillators practically available; such as beams and pre-bended membranes.

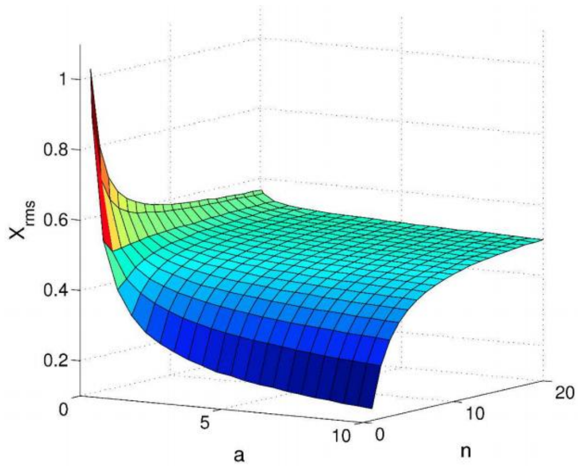


Figure 8: 3D Displacement plot. (Source: http://cdn.intechweb.org/pdfs/25373.pdf)

The figure 8 explains the numerical parameters given by (Gammaitoni et al. 2009, 2010) via 3D plot to show displacement.

Conclusion and Recommendations

Overall, the field of non-linear energy harvesters, however, represents only a few publications in the literature. The examples show the benefits of this approach in terms of a high bandwidth with high deflection. There are still many problems related to the hysteresis, which could not be resolved automatically before, so that generators for a non-linear spring principle until now are not suitable application (Zou et al., 2016). To actively influence the behavior of some generator mechanisms to adjust the resonance frequency were presented to the ambient vibrations. This type of generator is now at the center of most research activities on energy harvesting. The principle of operation is the same as in the large number of publications, only differences in the choice of mechanical-electrical energy conversion: When a mechanical system resonantly excited linear spring-mass system is used. The power transfer is increased when the quality of the resonator is increased by design. At the same time, however it reduces the usable bandwidth.

The principles used previously set each other on a simple positioning of multiple magnets. A disadvantage of this direct interaction between magnets proves the wide gap between the magnets (Yang and Towfighian, 2016). At the same time high deflections of the oscillating mass is required by the large distances, because the degree of non-linearity decreases with increasing distance from the magnet. In all systems already described is drawn to the general possibility to adjust the frequency characteristics by changing the magnet assembly. For example, the magnets for this purpose are specially fitted to screws by the distance to the oscillating magnetic mass easy to change. The focus is on the present invention magnetic principles. These are compared to electrostatic approaches that are completely passive, so that no additional energy must be expended to produce and use the corresponding non-linear effect can. When selecting the geometry is also important to ensure that a mechanism for varying the spring stiffness can be integrated.

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