Energy harvesting from human motion: an evaluation of current nonlinear energy harvesting solutions

P L Green, E Papatheou, N D Sims
Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom
E-mail: mep09plg@sheffield.ac.uk

Abstract. The concept of harvesting electrical energy from ambient vibration sources has been a popular topic of research in recent years. Recently, the realisation that the majority of ambient vibration sources are often stochastic in nature has led to a large body of work which has focused on the response of energy harvesters to random excitations - most of which approximate environmental excitations as being Gaussian white noise. Of particular interest here are recent findings which demonstrate the advantages that Duffing-type nonlinearities can introduce into energy harvesters. The aim of this paper is to identify how well these results can be applied to that of a real energy harvesting scenario. More specifically, the response of an energy harvester to excitation via human motion is studied using digital simulations in conjunction with acceleration data obtained from a human participant. As well as assessing whether Duffing-type nonlinearities can have a beneficial impact on device performance this paper aims to investigate whether Gaussian white noise can indeed be used as a good approximation for this particular ambient vibration source.

1. Introduction

Many recently published works on energy harvesting have been focused on gaining a better understanding of how energy harvesting devices respond to random excitations (often Gaussian white noise) which are thought to form a better approximation of ambient vibrations than monotone sinusoidal excitations. The main question which this paper will try to resolve is: how well can the results obtained from these works be applied to a real energy harvesting problem? More specifically, how well will the conclusions drawn about a device which is excited with white noise be transferred to a scenario where one is attempting to harvest electrical energy from human walking motion? The first part of this paper will focus on the response of a monostable energy harvester with nonlinearities similar to the Duffing oscillator. Of specific interest are the works of [1, 2] in which the Fokker-Planck-Kolmogorov (FPK) equation was used to show that, when excited by Gaussian white noise, Duffing type nonlinearities could be used to reduce the stroke of an energy harvesting device without effecting its power output. The second part of this paper will focus on the response of the bistable nonlinear device - specifically the idea that the useful bandwidth of such a device could be extended by having the system ‘escape’ from its potential well into a high energy solution [3, 4, 5] or by activating interwell dynamics [6, 7].

To this end, acceleration data obtained from the walking motion of an individual is used to excite digital simulations of different types of energy harvester, thus exploring the validity of
extends the afore mentioned nonlinear design solutions to a real energy harvesting scenario.

2. Excitation
To acquire the desired excitation signal, a DC accelerometer was placed on a participant who was then asked to walk on a treadmill. This data was gathered as part of an investigation into the effect that harvesting energy from human motion can have on the gait of an individual [8, 9]. Consequently, for information about the test procedure the reader is directed towards [8]. This paper focuses on the motion of one of the participants, walking at a speed of 3.6 km/h.

The frequency content of the resulting excitation signal is shown in Figure 1 where it is clear that the power in the excitation is distributed over a relatively large bandwidth and that the dominant frequencies of excitation are relatively low. When one considers energy harvesters of the electromagnetic type delivering power to a load resistor, the device circuitry can be modelled as series combination of an inductor and resistor. Such a configuration is known to act as a low pass filter and as such would not have a significant impact on such a low frequency application. However, the circuitry of piezoelectric devices are often modelled as a capacitor and resistor in series - a combination which is known to create a high pass filter. Depending on the level of capacitance of the device it is worth noting that, when harvesting energy from such low frequencies, an electromagnetic device may be preferable to a piezoelectric device.

An approximation of the excitation probability density function was obtained by taking histograms of the acceleration signal and normalising such the area under the histogram was unity (Figure 2). It is immediately obvious that this type of excitation does not have a gaussian distribution. This emphasises the need to investigate specific excitation conditions rather than that of Gaussian white noise.

3. Monostable nonlinear energy harvesting
The nonlinear monostable device of interest here was first proposed by Mann and Sims [10]. The basic operating principle of this energy harvester is that a magnet is made to levitate by the opposing magnetic poles of two outer magnets which are affixed to the shell of the device. In [10] it was shown that the restoring force on the centre magnet created by such an arrangement could be accurately modelled as the force from a nonlinear spring, similar to a hardening-spring
Duffing oscillator. Kinetic energy is converted into electrical using an electromagnetic coupling. The equation of motion of the device is:

\[ m\ddot{z} + (c_m + c_e)\dot{z} + kz + k_3z^3 = -my_a(t) \]  \hspace{1cm} (1)

where \( m \) is the mass of the centre magnet, \( c_m \) is the viscous damping due to mechanical losses, \( k \) is the linear stiffness, \( k_3 \) is the nonlinear stiffness and \( y_a \) represents the excitation of the base of the device due to the walking motion. The term \( c_e \) represents the damping introduced into the system as a consequence of the electromechanical coupling of the device (this is based on several assumptions which are detailed and validated experimentally in [2]).

The model was excited with the walking acceleration signal with the aim of finding whether one can indeed reduce the maximum displacement of the device in question without dramatically effecting its power output (a result that was proved for the case of Gaussian white noise excitation in [2]). It was immediately obvious that any increase in \( k_3 \) resulted in a drop in the optimum linear stiffness (a consequence of the ‘skewing’ effect that one can observe on the frequency response of a hardening spring Duffing oscillator). This shifting to higher frequencies made it difficult to harvest energy from the first harmonic of the excitation as, with an increase in \( k_3 \), the optimum level of \( k \) soon dropped below zero.

Figure 3 shows the variation of expected power and displacement variance with \( k \) for 2 different values of \( k_3 \). As the linear stiffness is increased (thus altering the natural frequency of the device) one can see peaks in the displacement and power when the device is tuned to the harmonics of the excitation. It can also be seen that, as stated in the previous paragraph, an increase in \( k_3 \) leads to a decrease in the optimum values of \( k \). The key conclusion that can be drawn from Figure 3 is that, in general, any benefits that \( k_3 \) can have with regards to the displacement of the device has come at the expense of the power output. This is different to the white noise excitation case studied in [2] where it was shown that \( k_3 \) could reduce the displacement variance without effecting the power output.
Figure 3. Variation of expected power (red) and displacement variance (blue) where \( m = 0.02 \), \( c_m = 0.08 \) and \( c_e = 0.08 \). Solid and dashed lines represent \( k_3 = 0 \) and 500000 N/m\(^3\) respectively.

4. Bistable nonlinear energy harvesting
In this section the behaviour of bistable devices are considered. Such devices are designed such that they have two potential equilibrium points. As mentioned earlier, it is clear that power in the walking excitation signal is distributed over a relatively large range of frequencies. The purpose of this investigation then is to identify whether a bistable device can harvest energy over a larger bandwidth and therefore outperform a linear resonant device (as stated in [6, 7]). The equation of motion of such a device is very similar to that of the monostable energy harvester discussed in the previous section (equation (1)) except that \( k \) can be allowed to become negative, such that, upon the appropriate selection of \( k \) and \( k_3 \), a device with a bistable potential is created.

Figure 4 shows how the power delivered to the electrical domain varied for different values of \( k \) and \( k_3 \). Interestingly, the optimum amount of power is harvested when \( k \) is positive and \( k_3 \) approaches zero - in other words, the monostable linear device out performs the nonlinear bistable device.

The first point to note in Figure 4 is that the power output in region where \( k \approx -10\)N/m is relatively small. In an effort to understand why, a phase portrait for the system with the afore mentioned value of linear stiffness was plotted for the case where \( k_3 = 8000 \) (Figure 5). It is clear that the system is stuck in one energy well and is unable to jump into the other. Figure 6 shows a similar plot for the case when \( k = -3 \). Clearly in this case, interwell dynamics have been activated although this has yielded little benefit with regards to power output. Additionally, there is also the school of thought that, even if a chaotic response could maximise the power delivered to the electrical domain, its unperiodic nature would make it difficult to collect and store the generated electrical energy [5]. Finally, Figure 7 shows the phase portrait for the linear monostable case. Clearly, periodic behavior is demonstrated. This not only outperforms that of the bistable nonlinear device but also provides an electrical signal which is preferable with regards to energy storage.

5. Discussion and conclusions
The aim of this paper was to investigate the applicability of previously developed nonlinear energy harvesting solutions to a very specific type of excitation condition. While it is clear that some of the proposed solutions were not effective in this case it is important to emphasise that
Figure 4. Variation of power delivered to the electrical domain with changes in $k$ and $k_3$ ($k = 2.85$, $k_3 = 0$, $c_m = 0.08$, $c_e = 0.08$).

Figure 5. Phase portrait of the system with $c_m = 0.08$, $c_e = 0.08$, $k = -10$ and $k_3 = 8000$.

Figure 6. Phase portrait of the system with $c_m = 0.08$, $c_e = 0.08$, $k = -3$ and $k_3 = 8000$. 
the aim of this work was not to criticise the work of other authors but to highlight the difficulties that can arise when attempting to apply fairly generalised solutions to a very specific problem. Detailed here is only one of the potential ambient excitations that an energy harvesting device may be subjected to - the conclusions of the paper could have been completely different if, say, bridge excitation was considered. Essentially, this paper is intended to show that future work could be directed towards finding which types of ambient excitation will allow one to effectively use any of the afore mentioned design solutions.

This study was partly supported by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Defence Science and Technology Laboratory (DSTL) through grant reference number EP/H020764/1.

[1] P L Green, K Worden, K Atallah, and N D Sims. The modelling of friction in a randomly excited energy harvester. Proceedings of ISMA 2012, Conference on Noise and Vibration Engineering, Leuven, Belgium, 20–22 September 2010, 2012.
[2] P L Green, K Worden, K Atallah, and N D Sims. The benefits of duffing-type nonlinearities and electrical optimisation of a mono-stable energy harvester under white gaussian excitations. Journal of Sound and Vibration, 0(0):0, 2012.
[3] B.P. Mann and B.A. Owens. Investigations of a nonlinear energy harvester with a bistable potential well. Journal of Sound and Vibration, 329(9):1215–1226, 2010. cited By (since 1996) 13.
[4] L. Gammaitoni, I. Neri, and H. Vocc. Nonlinear oscillators for vibration energy harvesting. Applied Physics Letters, 94(16), 2009. cited By (since 1996) 27.
[5] A. Erturk and D.J. Inman. Broadband piezoelectric power generation on high-energy orbits of the bistable duffing oscillator with electromechanical coupling. Journal of Sound and Vibration, 330(10):2339–2353, 2011. cited By (since 1996) 4.
[6] R. Masana and M.F. Daqaq. Relative performance of a vibratory energy harvester in mono- and bi-stable potentials. Journal of Sound and Vibration, 330(24):6036–6052, 2011. cited By (since 1996) 0.
[7] C.R. McHnes, D.G. Gorman, and M.P. Cartmell. Enhanced vibrational energy harvesting using nonlinear stochastic resonance. Journal of Sound and Vibration, 318(4-5):655–662, 2008. cited By (since 1996) 12.
[8] E. Papatheou and N.D. Sims. Developing a hardware in-the-loop simulator for a backpack energy harvester. Journal of Intelligent Material Systems and Structures, 23(7):827–835, 2012. cited By (since 1996) 0.
[9] E Papatheou, P L Green, V Racic, Brownjohn JM, and N D Sims. A short investigation of the effect of an energy harvesting backpack on the human gait. Proceedings of SPIE 2012, Smart Structures/NDE, San Diego, California, 2012.
[10] B. P. Mann and N. D. Sims. Energy harvesting from the nonlinear oscillations of magnetic levitation. Journal of Sound and Vibration, 319(1-2):515–530, JAN 9 2009.