COMPARATIVE STUDY OF CONCEPTS FOR INCREASING THE BANDWIDTH OF VIBRATION BASED ENERGY HARVESTERS

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Abstract: In this paper we report on new results from a comparative study of four selected concepts being considered as potential mechanisms for increasing the bandwidth of vibration based energy harvesters. For the first time comparative transient simulations were carried out based on uniform boundary conditions for each of the four principles. This approach allows direct comparison and evaluation of the different concepts being investigated. In this study four different vibration profiles with low level amplitudes were defined. We found that nonlinear techniques provide the greatest potential for increasing the overall output power from broadband vibration profiles in comparison to a reference device with a linear characteristic. Furthermore, an array configuration, which is often depicted as a practical solution for broadband energy harvesting, does not show any improvements. On the contrary, with an array configuration the output power is at least 50% less than that of the reference device.

Keywords: broadband energy harvesting, nonlinear energy harvesting

INTRODUCTION

The fundamental characteristic of conventional vibration energy converters utilizing a resonant mass-spring-damper structure is well known to the community: the effective energy conversion is limited to a narrow bandwidth. This is an essential drawback when considering vibration profiles with a time varying frequency spectrum. For many years great effort was put into finding practical solutions for enhancing the bandwidth of resonant vibration transducers [1], [2]. An overview of different strategies is given in Figure 1. In a multitude of technical publications individual strategies and their potential for broadening the effective bandwidth were investigated. However, a great difficulty will be encountered when trying to compare the different strategies among each other and against a reference device. This is due to the non-consistent boundary conditions (device size, transduction principles, vibration profiles, etc.) To the best of our knowledge there is no publication available, which considers the direct comparison of different bandwidth-enhancing strategies based on uniform boundary conditions and constraints. In this paper we describe the method and procedure required for evaluation and direct comparison of different broadband concepts and we present the results and conclusions from this comparative study.

From Figure 1 it is evident that there are a number of different principles to influence the bandwidth of resonant vibration energy harvesters. These principles can be further categorized into active principles and passive principles. In this paper we focus on passive principles that do not consume additional energy. Due to time and resource limitations four passive principles were selected by means of a rating matrix. The rating matrix is based on the analysis of over 20 preselected publications and includes the following principles: nonlinear stiffness (monostable), nonlinear stiffness (bistable), resonator array, resonance tuning, frequency conversion and multi-mode structure. The evaluation of the preselected principles was carried out with respect to low-level vibration profiles taken from a speed-controlled motor for fluid pumping.

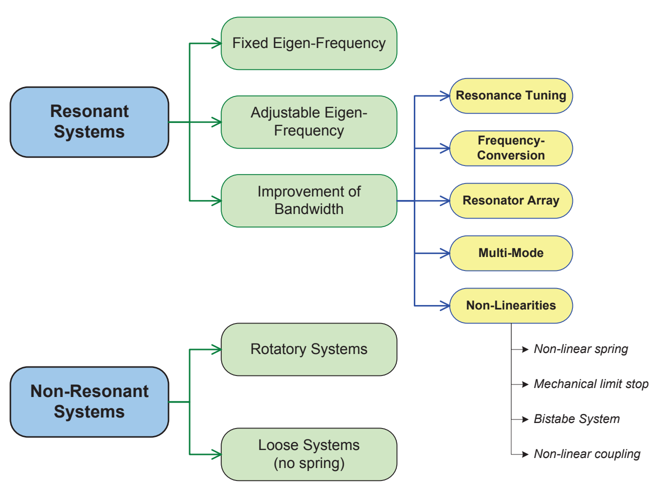

Figure 1: Classification of vibration energy harvester

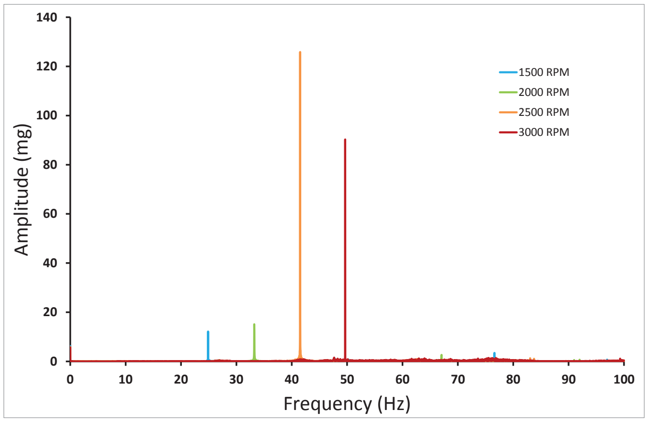

Figure 2: Frequency spectra of four vibration profiles at different speeds from a speed-controlled motor

The frequency spectra of the vibration profiles at varying motor speeds are shown in Figure 2. The Figure shows clearly a single dominant frequency, whose position changes as a function of motor speed in a frequency band between 25 Hz and 50 Hz. The acceleration amplitude is between 10 mg and 130 mg. At other measurement positions we measured acceleration amplitudes up to 500 mg. On the basis of this data four principles were rated as suitable mechanisms for enhancing the bandwidth of vibration based energy harvesters. These for principles include nonlinear stiffness (monostable), nonlinear stiffness (bistable), resonator array and multi-mode structure.

MODELLING & SIMULATION

First, a general set of boundary conditions was defined, which is mandatory to all principles being investigated (see Table 1). Most important is the use of an equal transduction mechanism and a constrained volume. In this study an electromagnetic energy conversion mechanism is applied. The architecture of the electromagnetic energy converter is parameterized (Figure 3) and a full parameter optimization is carried out for each individual principle. The free geometrical parameters being available for optimization are listed in Table 2. The dependent geometry parameters are a function of the free parameters. The presence of other parameters, which require optimization, is dependent on the principle.

Table 1: Applied boundary conditions

Fixed Parameters	**Value**
Transduction principle	electromagnetic
Architecture	A-VIII
Total transducer volume V_T	10 cm^3
Gap between coil and magnet g	1 mm
Inner radius of coil R_i	1 mm
Wire diameter of coil d_c	0.08 mm
Copper filling factor k_c	58 %
Magnetization grade of magnet	868000 A/m
Mechanical damping d_m	0.25
Max. internal displacement z_{max}	10 mm

Table 2: Free and dependent parameters

Free Parameters	**Value**
Magnet width B_M	variable
Magnet height H_M	variable
Height of back iron H_{ER}	variable
Dependent Parameters	**Value**
Height of coil H_S	$f(V_T, B_M, H_M, H_{ER}, g)$
Magnet length L_M	$2 \cdot B_M$
Length of back iron L_{ER}	L_M
Width of back iron B_{ER}	L_{ER}
Outer radius of coil R_a	$B_M - z_{max}$

In the following, the different principles are described in more detail. The nonlinear stiffness system with a monostable characteristic is realized by a linear spring with a nonlinear term. In this case the eigenfrequency of the linear system and the nonlinear coefficient of the spring are two more parameters, which require optimization. The nonlinear stiffness system with a bistable characteristic is modeled by means of a linear spring and a nonlinear force between 2 repulsive magnets (one attached to the seismic mass). The size of the repulsive magnets is fixed. Here, the eigenfrequency of the linear system and the gap between the two magnets are two further parameters which must be optimized. The oscillator array is composed of three sub-structures, where each sub-device is a linear spring-mass system. There are no

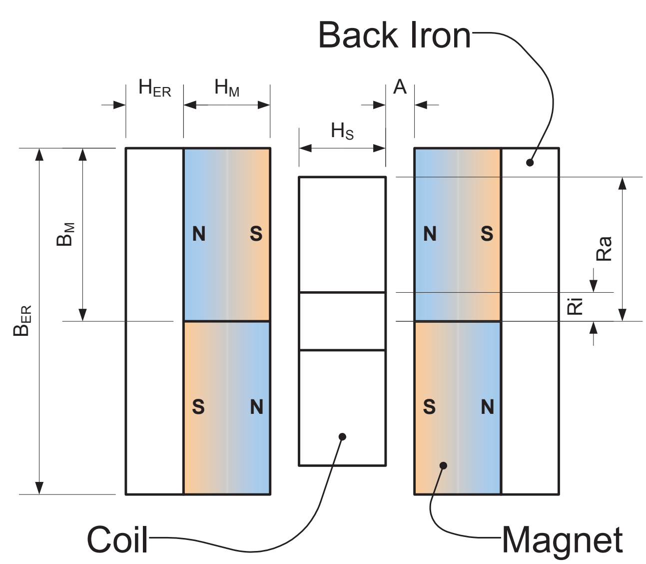

Figure 3: Parameterized architecture of the electromagnetic energy converter

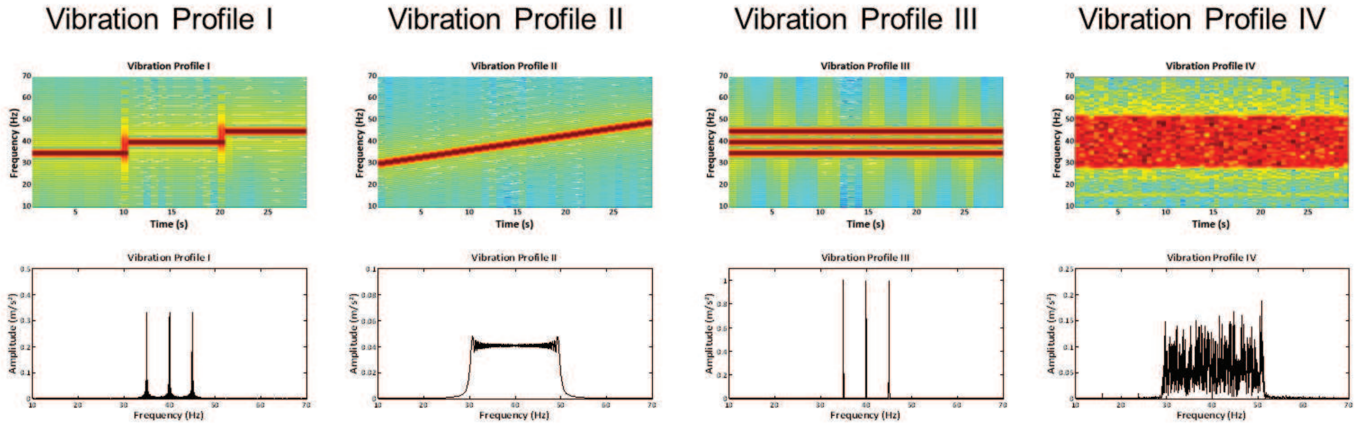

Figure 4: Spectrogram (first row) and spectrum (second row) of synthesized vibration profiles (VP). VP 1 & VP 2: one dominant frequency varying over time; VP 3: three dominant frequencies not varying over time; VP 4: random profile with frequencies evenly distributed in a frequency band between 30 Hz and 50 Hz.

other parameters. The multi-mode structure comprises a two-mass-two-spring system. As a result, the system will show two distinct eigenfrequencies. The multi-mode system includes 4 more parameters (m_1, m_2, c_1 and c_2), which need to be optimized together with the other geometrical parameters.

The output power was simulated using four synthesized vibration profiles each with a different characteristic (Figure ***4***). Based on the vibration measurements from speed-controlled motors for fluid pumping, the frequency content of the synthesized vibration profiles was limited to a frequency band ranging from 30 Hz to 50 Hz. Vibration Profile I (VP-I) describes a single dominant frequency, which changes over time in a discontinuous manner. The distinct frequencies are at 35 Hz, 40 Hz and 45 Hz. VP-II also contains a single dominant frequency which, however, changes continuously from 30 Hz to 50 Hz. In VP-III three dominant frequencies, time-invariant, are present at 35 Hz, 40 Hz and 45 Hz. VP-IV describes a random profile with frequencies evenly distributed in the given frequency band. The time signals of VP-I to VP-III are composed of harmonic components with an amplitude of 1 m/s^2. In VP-IV the RMS-value of the vibration profile is 1 m/s^2.

For comparison a linear reference device was added to the four principles. This reference generator also meets the boundary conditions listed in Table 1. The eigenfrequency of the linear device was set to 40 Hz and the geometry parameters were optimized with respect to a 40 Hz harmonic excitation signal with an amplitude of 1 m/s^2.

The multi-mode system was optimized in such a manner that the two eigenfrequencies are located at 35 Hz and 45 Hz. The eigenfrequency of the three sub-devices of the resonator array are 35 Hz, 40 Hz and 45 Hz. The free geometrical parameters were individually optimized with respect to a harmonic excitation signal with an amplitude of 1 m/s^2. The nonlinear monostable and nonlinear bistable structure were optimized with respect to each vibration profile.

RESULTS AND DISCUSSION

In Figure 5 the results from the transient simulation are summarized. The average output power of the reference design is normalized to 100%. The output power of the principles is then related to the reference design. The displayed value indicates the relative change in power output. From Figure 5 it becomes evident, that both the array configuration and the multi-mode structure generate significantly less power than the linear reference device. In this respect it is very interesting to analyse the results in more detail for the array configuration in conjunction with vibration profile III: Although each of the three subdevices is matched to one of the three dominant frequencies, which are continuously present (see spectrogram in Figure ***4***), the total power output from the array configuration is about 80% less than that of the reference device. This means, if a vibration profile is present with three dominant frequencies in its spectrum it is more effective to use a single device matched to one of the dominant frequencies instead of using three smaller devices, each matched to one of the dominant frequencies. This also means that the bandwidth of a single resonant device cannot be increased by using an array configuration as stated in [3]. This again confirms the strong effect of the generator volume and thus of the mass of the seismic mass on the power output capability.

Figure 5 clearly indicates that nonlinear techniques have the potential to significantly improve the performance of linear devices. In this study we found that both a nonlinear monostable system incorporating

Principle	VP 1	VP 2	VP 3	VP 4
Reference (single, linear)	**100 %**	**100 %**	**100 %**	**100 %**
Array (3 subdevices)	-79 %	-50 %	-79 %	-52 %
Multimode (two mass)	-73 %	-29 %	-73 %	-26 %
Nonlinear Monostable	+0 %	+479 %	+0 %	+52 %
Nonlinear Bistable	+11 %	+364 %	+11 %	+33 %

Figure 5: Comparison of the different principles against the reference design

a nonlinear spring and a nonlinear bistable system perform better than the linear reference device with the exception that a nonlinear monostable system does not outperform the reference device with respect to the vibration profiles I and III.

The nonlinear bistable system shows an increased power output for all four vibration profiles. For vibration profiles I and III the improvement is about 11%, which is moderate. Considering VP-II the power output increases by 364% if a bistable system is used in place of a linear device. An increase in power output of 33% is obtained for VP-IV. However, a nonlinear monostable system seems to outperform the bistable system with respect to VP-II and VP-IV. Here the improvement in power output is 479% and 52%, respectively. A possible reason is the fact that the level of input vibrations is very low. Masana et.al also observed that monostable systems outperform bi-stable systems for low levels of input vibrations [4]. This is because no inter-well dynamics in the bistable system occur and the dynamic trajectories remain confined within a single potential well. Indeed, we observed that no transitions were taking place between the two potential wells. For vibration profiles with accelerations of larger magnitude we also observed inter-well dynamics.

In conclusion, it was also found that the degree of how well a principle performs will not only depend on the vibration profile and the magnitude of the input accelerations but also on the transducer volume of the generator.

CONCLUSION

In this paper we have carried out a comparative study of concepts for increasing the bandwidth of vibration based energy harvesters. A general set of boundary conditions was defined and applied to all concepts being investigated. Also, a linear reference design and four synthesized vibration profiles were considered for direct comparison. For each concept a parametric system model was developed and parameter optimization was carried out to maximize the power output for each principle. In case of the nonlinear principles the device structures were individually optimized for each vibration profile. We found that nonlinear techniques outperform the linear reference device. For a random vibration profile 52% or 33% more power output is achievable if a nonlinear monostable or bistable system is used. Other concepts including resonator arrays and multi-mode structures are not capable of converting more power than the reference design. In contrast, the power output from these concepts is significantly less in comparison to the linear reference design.

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