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Experimental Analysis of a Coupled Energy Harvesting System with Monostable and Bistable Configuration

D Hoffmann¹, **B** Folkmer¹ and **Y** Manoli^{1,2}

¹ HSG-IMIT – Institute of Micromachining and Information Technology, Wilhelm-Schickard-Str.10, 78052 Villingen-Schwenningen, Germany ² Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineering - IMTEK, University of Freiburg, Germany

daniel.hoffmann@hsg-imit.de

Abstract. In this paper we present experimental results from an energy harvesting system with two coupled energy harvesters. The energy conversion mechanism of the two coupled energy harvesters is based on the electromagnetic principle. The coupling is generated by two magnets in a repulsive arrangement. In this manner a bistable configuration can be obtained if the gap between the magnets is sufficiently small. We demonstrate that the total power output can be increased in comparison to a linear reference system, if specific conditions are fulfilled. In this respect, the highest power output occurs in the nonlinear region of a monostable system configuration, mostly near the transition to a bistable configuration. On the other hand, the results also indicate, that a bistable operating mode does not necessarily enhance the power output of the coupled system.

1. Introduction

The fundamental drawback of conventional vibration energy transducers is apparent when considering vibration profiles with a broad frequency spectrum or with a time-varying frequency content. For many years great effort was put into finding practical solutions to enhance the bandwidth of resonant vibration transducers [1]. In this respect the introduction of nonlinear systems with a bistable characteristic had a significant influence on the type of solutions so far [2, 3]. A further step towards a system with a coupled bistable structure was taken by Zhu et. al. [4]. In this system an assisting cantilever is coupled to a main cantilever in which only the main cantilever is able to generate energy. It was found that the power output is larger in comparison to a bistable structure without coupling. However, the assisting cantilever requires an additional volume, which could be used to accommodate another active energy harvesting structure.

In this paper, a coupled structure, which incorporates two cantilever-based electromagnetic energy harvesters coupled via a magnetic field, is investigated. The total power output of both energy harvesters together is considered and is compared to a linear reference system. The linear reference system incorporates two individual energy harvesters of the same size as in the coupled system. However, there is no coupling between the two energy harvesters in the linear case. In this respect, the volume occupied by the linear system is equal to the volume of the coupled system, which allows reasonable comparison between both systems.







Figure 2. Frequency spectrum of the vibration profile 30-50-1 with a frequency content between 30 Hz and 50 Hz and with an RMS amplitude of 1 m/s²

2. Experimental Setup

The coupled structure, which was investigated in this paper, is depicted in Figure 1. The structure comprises two cantilever-based energy converters with an identical design for magnetic circuit and coil. The influence of the Eigen-frequency of each energy harvester on the coupling dynamics and thus on the total power output was captured by varying the stiffness of the springs. In this respect, springs of two different thicknesses were used. The length and the width of the springs were kept equal. In this work two different spring configurations were investigated: An equal thickness of 0.7 mm was used for both springs in configuration one. As a result, both energy harvesters possessed the same Eigenfrequency. In a second configuration the thicknesses of the springs 1 and 2 were 0.8 mm and 0.7 mm. Consequently, the Eigen-frequency of the energy harvester 1 was larger in comparison to energy harvester 2.

The two different configurations of the coupled structure were excited using random vibrations with two different bandwidths and two different amplitudes resulting in four different vibration profiles. Vibration profiles 1 and 2 contain frequencies in the range of 30 Hz – 50 Hz. The RMS-amplitude was 1 m/s² for vibration profile 1 and 5 m/s² for vibration profile 2. The frequency spectrum of vibration profile 1 (30-50-1) is shown in Figure 2. Vibration profiles 3 and 4 contain frequencies in the range of 20 Hz – 60 Hz. The RMS-amplitude was varied in the same manner as for vibration profile 1 and 2.

For each combination (2 spring configurations times four vibration profiles) the RMS power of both energy harvesters was measured. For each measurement, the respective vibration profile was played for 1 min and the instantaneous power output at the load resistor (800 Ohm, matched) was recorded over time. The RMS power was then calculated and plotted as a function of distance between the two energy harvesters.

For better interpretation of the results the frequency response of each energy harvester was also investigated for varying distances d. In this regard, a harmonic excitation signal with an amplitude of 2 m/s^2 was applied. The voltage across a load resistance of 500 Ohm was measured.

3. Results and Discussion

Figure 3(a) and (b) show the frequency response of oscillator 1 and 2, respectively, for the spring configuration 1. For a gap of 14 mm both oscillators show an equal Eigen- frequency of approximately 40 Hz. The Eigen-frequency of both oscillators does not change much with varying distance d. For a gap of 4 mm the Eigen-frequency shifts down to a minimum value of 39.2 Hz. This system behavior



Figure 3. Frequency response of both energy harvesters for two different spring configurations: (a) and (b): Energy harvester 1 and 2 have an equal spring thickness of 0.7 mm. (c) and (d): The spring thickness of energy harvester 1 (c) and 2 (d) is 0.8 mm and 0.7 mm.

seems very interesting and was also observed for a spring configuration in which both springs had a thickness of 0.8 mm. From this it follows, that the power output will not change significantly with varying distances d. A bistable configuration is obtained for distances smaller than 3.7 mm.

A different behavior was observed for spring configuration two (Figure 3(c) and (d)). The initial Eigen-frequency of oscillator 1 (spring thickness of 0.8 mm) at the largest distance d is approximately 53.5 Hz (Figure 3(c)). When decreasing d from 14 mm to 3 mm the Eigen-frequency declines to 49 Hz. Moreover, small peaks are visible in the region between 30 Hz and 40 Hz. When looking at the frequency response of oscillator 2 (Figure 3(d)) it becomes clear, that the small peaks originate from this oscillator, which resonates in the respective frequency region. The magnetic coupling between the two oscillators becomes apparent. The frequency shift of oscillator 2 as a function of distance is much more significant. Here, the Eigen-frequency drops below 20 Hz for a distance of 3 mm. For distances smaller than 3.7 mm a bistable system configuration occurs. Therefore, the Eigen-frequency increases again if the distance is further reduced. At a distance of 2.5 mm the Eigen-frequency becomes 34 Hz. The oscillations of oscillator 1 are also coupled back to the energy harvester 2, which is apparent from Figure 3(d). In summary there are several important features to be considered for the coupled structure investigated in this paper: 1. there is a certain threshold distance at which a transition from a monostable towards a bistable configuration occurs. 2. If the stiffness of the two oscillators is unequal, the Eigen-frequency decreases when the distance is reduced from large values down to the threshold value. When the distance is further reduced the Eigen-frequency increases again. 3. The oscillations of each oscillator are coupled by means of the magnetic field. Therefore, the large amplitudes of a resonating oscillator lead to oscillations of the other.

Figure 4 shows the power output as a function of the distance d for spring configuration 1. In Each diagram a dotted vertical line indicates the threshold distance at which the transition between a monostable and a bistable configuration occurs. The power output is pictured for both energy





Figure 4. RMS Power output vs. gap for spring configuration 1 (equal spring stiffness): (a) Profile: 30-50-1. (b) Profile: 30-50-5. (c) Profile: 20-60-1. (d) Profile: 20-60-5.

harvesters and its summation. Moreover, the power obtainable with a linear reference system is also shown.

In general, the power output of both energy harvesters is very similar and does not change significantly with varying distance d. This is due to the fact that the frequency response, which is almost equal for both oscillators, does not depend on the distance d (Figure 3(a) and (b)). A very distinctive observation is that the largest power output occurs at a rather small distance d (ca. 4 mm). In comparison to the linear reference system, a larger power output is therefore achievable if a nonlinear monostable system configuration is chosen. Once the coupled system is configured bistable, the power output continuously declines if the distance is reduced further. Another characteristic of spring configuration 1 is that both energy harvesters always oscillate in a synchronous fashion even in the bistable configuration. As a consequence, no interwell oscillations occur. During experimental characterization oscillations always occurred within the potential well.

The power output of both energy harvesters differs significantly from each other when considering spring configuration 2 (Figure 5). For vibration profiles 1 and 2 the power output of energy harvester 1 is very low at a large distance of 14 mm. This is due to the fact that the Eigen-frequency is located outside the excitation frequency band (Figure 3(c)). In contrast, energy harvester 2 shows a much higher power output at the same distance since its Eigen-frequency is located in the center of the excitation frequency band (Figure 3(d)). When the distance is reduced, the power output of energy harvester 1 starts to increase while the power output of energy harvester 2 declines at the same time (Figure 5(a) and (b)). The total power output has its maximum near or at the transition towards a bistable system configuration. However, the power output of the linear reference system is not exceeded.

For vibration profiles 3 and 4 the initial power output of both energy harvesters is nearly equal at a distance of 14 mm since the Eigen-frequency of both oscillators is within the excitation frequency band (Figure 5(c) and (d)). Considering the total power output an increase is observed when reducing the distance. This again demonstrates the positive influence of the nonlinearity on the power output





Figure 5. RMS Power output vs. gap for spring configuration 2. Spring 1: 0.8 mm, Spring 2: 0.7 mm. (a) Profile: 30-50-1. (b) Profile: 30-50-5. (c) Profile: 20-60-1. (d) Profile: 20-60-5.

in comparison to the linear reference system.

In case of vibration profile 2 and 4 interwell oscillations occur once the system is configured bistable. However, the total power output is still below the linear reference system.

4. Conclusion

In this work a coupled energy harvesting system including two cantilever-based electromagnetic energy harvesters was investigated experimentally. The results indicate that there is no benefit in terms of power output if a bistable system configuration is used. Even in case of bistable operation (interwell oscillations) the power output was lower than that of the linear reference system. However, it must be noted that this conclusion is only valid with respect to the four particular vibration profiles applied in this work.

On the other hand, a power gain over a linear system can be achieved if a monostable system configuration with a certain nonlinearity is chosen.

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