LARGE POWER AMPLIFICATION OF MEMS HARVESTER BY A SECONDARY SPRING AND MASS ASSEMBLY

R.J.M. Vullers, R. Elfrink, S. Matova, and Z. Wang
Holst Centre/imec, Eindhoven, The Netherlands

Abstract: Piezoelectric MEMS energy harvesters have been shown to generate powers of up to 500µW. This has been reached at vibration levels of several g's and with a narrow bandwidth. We present a method to increase the power or the bandwidth by the use of a special assembly. A packaged MEMS harvester is attached at the tip of a metal beam forming a system of two coupled oscillators. Due to the large mass and spring ratios of the original harvesters and the secondary oscillator, power amplification of more than 51 times has been reached, resulting in a sensitivity of 1.2mW/g^2. By adapting the settings, an increased bandwidth can be reached as well.

Keywords: energy harvesters, power amplification, coupled oscillators.

INTRODUCTION

The general operational principle of vibration energy harvesters is the amplification of the input vibration by putting a seismic mass at mechanical resonance. In the case of piezoelectric (PE) harvesting, the mechanical energy of the resonating mass is partly converted into electrical energy by a piezoelectric capacitor. We have designed and fabricated micromachined devices, ranging in frequency from 300 up to 1200 Hz. The low parasitic damping due to vacuum packaging and low electromechanical coupling factor of the AlN yields a high quality factor. As a result, the sensitivity of the devices ranges from about 20 up to 300 µW/g^2 and the maximum power output ranges from 50 up to 489 µW [1]. These harvesters are ideal for shock-induced applications like TPMS systems on the tire, where shocks are found to be in the order of 100's of g[1]. However, for applications with sinusoidal vibration sources (e.g. engines), the bandwidth of the harvester is too small and requires matching to the bandwidth of the input source. Furthermore, the accelerations are often too small to generate useful power. The use of a secondary mass- spring system will solve these issues, as we will explain in this paper.

THEORY

The general principle is shown in Figure 1. The energy harvester (with mass m_h and spring constant k_h) is connected to a second mass spring system (m_1, k_1). As a result, the original resonance frequency at f_h, is split up into two frequencies f_L and f_R around f_h. For $k_1/m_1 \approx k_h/m_h$ the amplitudes of both peaks are almost similar. By increasing the ratio α ($\alpha = m_1/m_h$), while keeping the ratio β constant ($\beta = k_1/k_h$), the amplitude of f_L and f_R increases as well. At values of α at around 100, one will get the situation that both peak amplitudes are larger than the original amplitude of the harvester. This is shown in Figure 2, where the amplification factor (the gain of the amplitude of the harvester compared to the original harvester amplitude) is plotted versus frequency. The basic idea had already been presented in 2004 [2], and recently got new attention [3][4]. However, when applied in a MEMS system, it is very difficult to get a large α value. One either ends up with the situation that the total die size of the harvester is increased to

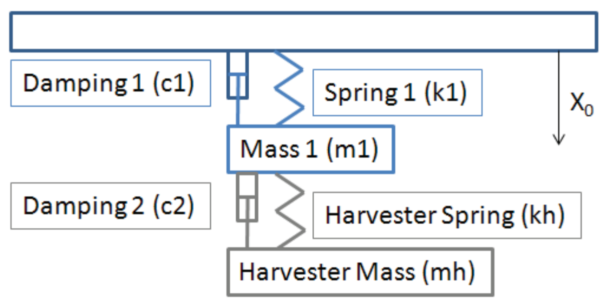

Figure 1: Schematic representation of two mass-two spring setup, where the harvester is connected to an additional mass-spring system.

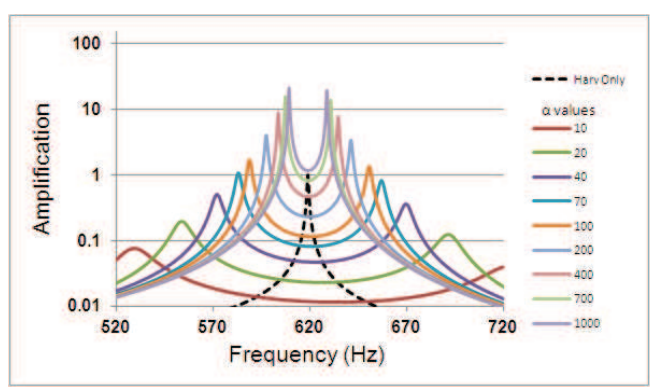

Figure 2: Modeling of the amplification effect. The relative gain of the harvester amplitude is plotted for different values of α and compared to the original harvester's amplitude (the black curve).

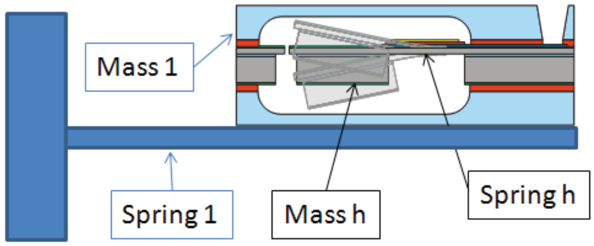

Figure 3. Practical setup of the two mass-spring system. The Energy Harvester has mass m_h, spring constant k_h. The mass of the packaged MEMS device (minus the mass of the harvester mass) and beam form mass m_1, is placed on a metal beam with spring constant k_1.

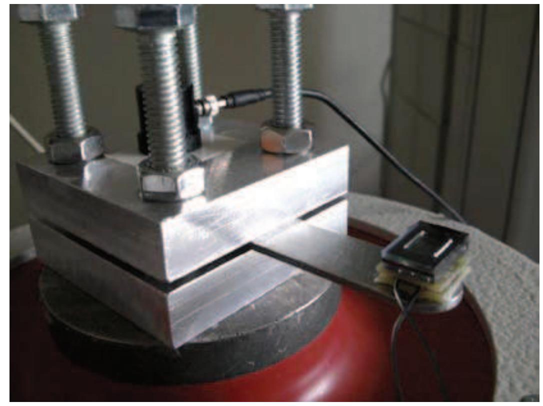

Figure 4: Experimental setup: The packaged MEMS harvester is placed on top a 1mm thick metal beam. The beam is clamped and attached to a shaker. On top of the metal clamping, the accelerometer (black) is visible.

unrealistic values (e.g. tens of cm's), or alternatively,the mass of the energy harvester becomes so low, that the total generated power is also very small. We propose a different concept, making use of the fact that our MEMS PE energy harvester is packaged. When the packaged harvester is placed on a beam with spring constant k_1, we obtain the situation sketched in Figure 3.

We have now created a coupled oscillator system, where the package of the harvester adds to the mass of the beam forming mass m_1, and the beam has spring constant k_1. Actually, the total mass m_1 consists of the mass of the beam and the whole package minus the mass of the harvester m_h. Typical values for m_h are 0.0393g, while m_1 is around 3 to 4 g, resulting in α of around 100. The spring constant k_1 can now be tuned by choosing the right length and thickness of the beam, which in our case is made of steel. Typical values in our experiment are length of a few cm's and a thickness of 1.0 to 1.6mm, while the width is 10 mm.

MODELING

For the modeling we use the conventions sketched in the schematic of Figure 1. Two springs (spring 1 (k_1) and the harvester spring (k_h)) are connected in series to a base which is sinusoidally driven at a constant acceleration and varying frequency, resulting in an amplitude of x_0. We now define the amplitude of spring 1 as x_1 and the amplitude of the harvester spring as x_h, while c_1 and c_h are the damping coefficients for the metal beam and the harvester, respectively. We can now write down the equations of motion for both springs (following the approach of [5]):

$$m_1\ddot{x}_1 = -k_1x_1 + k_h[x_h - x_1] - c_1\dot{x}_1 + c_h[\dot{x}_h - \dot{x}_1] + k_1X_0e^{i\omega t} + i\omega c_1X_0e^{i\omega t} \quad (1)$$

$$m_h\ddot{x}_h = -k_h[x_h - x_1] - c_h[\dot{x}_h - \dot{x}_1] \quad (2)$$

In the steady state, $x_1 = X_1e^{i\omega t}$, and $x_h = X_he^{i\omega t}$, which we fill in eq. (1) and (2), such that

$$-m_1\omega^2X_1e^{i\omega t} = -k_2X_2e^{i\omega t} + k_h[X_h - X_1]e^{i\omega t} - i\omega c_2X_2e^{i\omega t} + i\omega c_h[X_h - X_2]e^{i\omega t} + k_2X_0e^{i\omega t} + i\omega c_2X_0e^{i\omega t} \quad (3)$$

$$-m_h\omega^2X_he^{i\omega t} = -k_h[X_h - X_1]e^{i\omega t} - i\omega c_h[X_h - X_{21}]e^{i\omega t} \quad (4)$$

Next we solve and rearrange eq. (3) and (4) into

$$X_1[k_2 + k_h - m_2\omega^2 + i\omega c_2 + i\omega c_h] - X_h[k_h + i\omega c_h] = X_0[k_2 + i\omega c_2] \quad (5)$$

$$X_2[k_h + i\omega c_h] = X_h[k_h - m_h\omega^2 + i\omega c_h] \quad (6)$$

The latter can be rewritten as:

$$X_h = \frac{k_h + i\omega c_h}{k_h - m_h\omega^2 + i\omega c_h}X_2 \quad (7)$$

From which we find the following for X_2

$$X_2 = \frac{h_2H}{[h_2 + h_h - m_2\omega^2]H - h_h}X_0 \quad (8)$$

With

$$H = [k_h - m_h\omega^2 + i\omega c_h]$$
$$h_h = [k_h + i\omega c_h]$$

and

$$h_1 = [k_1 + i\omega c_1]$$

By plotting X_h/X_0 and comparing to the result without the coupled system, we can easily calculate the

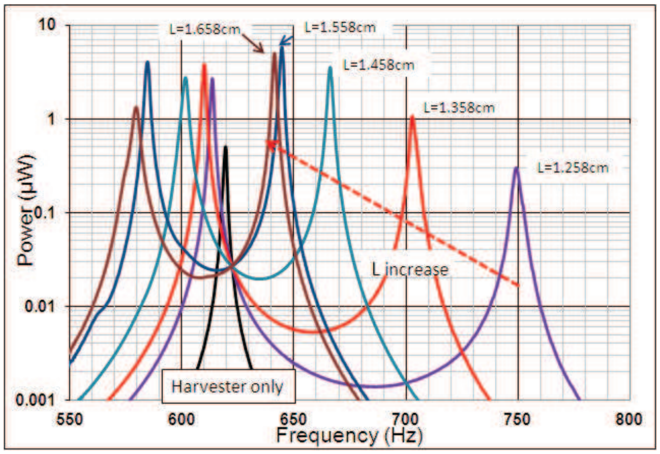

Figure 5. Resonance curves of the coupled system for different lengths L of the beam. For comparison, the original harvesters signal (black) is included (ext. input = 0.08g

mechanical amplitude gain (as plotted in Figure 2). Since power ~ X_h^2, even larger power gains can be obtained.

EXPERIMENTAL

We have used a harvester with a resonance frequency of 620Hz, a mass m_h of 39.3 mgr and a spring constant k_h of 595 N/m. The metal beam is made of spring steel: in the experiment we have changed the length of the beam, resulting in a change of the spring constant k_1, as well as a change of the mass m_1. In our experimental setup (Figure 4), there is no direct possibility to change the spring constant k_1 without changing mass m_1. By varying the length L of the beam, the combined effect of increasing (or decreasing) the spring constant and decreasing (or increasing) the mass is realized. The results for different values of the length of the beam are shown Figure 5. It can clearly be seen that a change of only 4 mm in length of the beam, has a dramatic effect on both the resonance frequency (f_l and f_r) and power output (P_l and P_r) of the left and right peak. We have summarized the results normalized to the original output of the harvester in Table 1. One can use this phenomenon to tune the harvester system to a specific resonance frequency, and will get power amplification as well. These data suggest a tuning frequency range from 580 to around 730 Hz could be obtained.

In Figure 6 two specific cases are plotted. First, the largest amplification case of 11.5 times is plotted in red (see *Figure 5*, L=1.558cm). We have calculated α (m_1/m_h) =102, while β= (k_1/k_h) 55. In the second experiment, we added extra mass to the package, while decreasing the length of the beam (α =137, β= 200). We thus obtained the blue curve. Here we find a smaller amplification but a considerable increase in bandwidth of a factor of 6. This preliminary data suggest that larger gains are to be reached by further optimization of the two coupled oscillators system.

As shown in Figure 2, the larger α, the larger the mechanical amplification. We have several different designs of PE harvesters. The harvesters with the highest resonance frequency, have the smallest mass, so a larger α can be obtained. We have tested this by replacing the 620Hz harvester, by a harvester with a resonance frequency of 1010Hz (a detailed description can be found here [1]). Indeed, we find an amplification factor of 51.3 (with α=212, β=212).

An important remark is that this technology increases the amplitude of the harvester. The sensitivity of the system therefore exceeds the sensitivity of the harvester: in this case it has increased from 0.024 to 1.2 mW/g^2. The maximum power output of a given harvester remains limited by the 600 µm maximum deflection as defined by the

Table 1: The frequency and amplitude ratios of the right and left resonance peak, with respect to the original harvester only peak (input 0.08g)

Harvester	f_h =619Hz		P_h=0.5µW	
L	**f_l/f_h**	**f_r/ f_h**	**P_l/P_h**	**P_r/P_h**
1.658	0.94	1.04	2.36	10.04
1.558	0.95	1.04	8.02	11.56
1.458	0.97	1.08	5.54	7.10
1.358	0.98	1.14	7.52	2.10
1.258	0.99	1.21	4.66	0.60

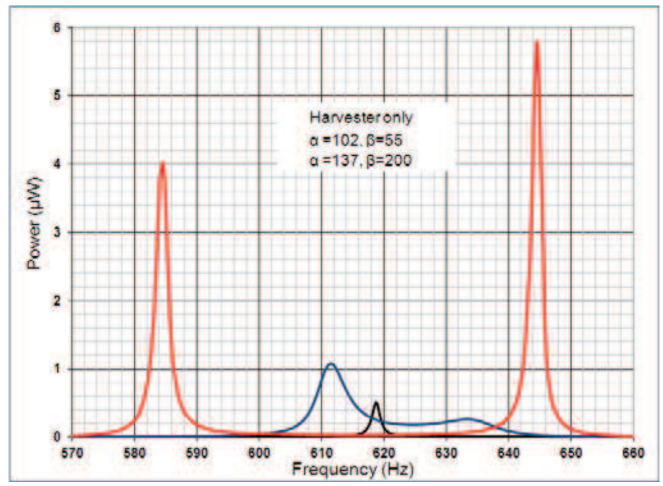

Figure 6. The original harvester power output (black line) compared to the amplified signal (red line). The maximum power is 11.5 times larger than the original maximum (α = 102,β = 55). An example of bandwidth broadening of the amplified signal (blue curve), by changing k_1 and m_1, such that α = 137, and β = 200 (ext. input = 0.08g)

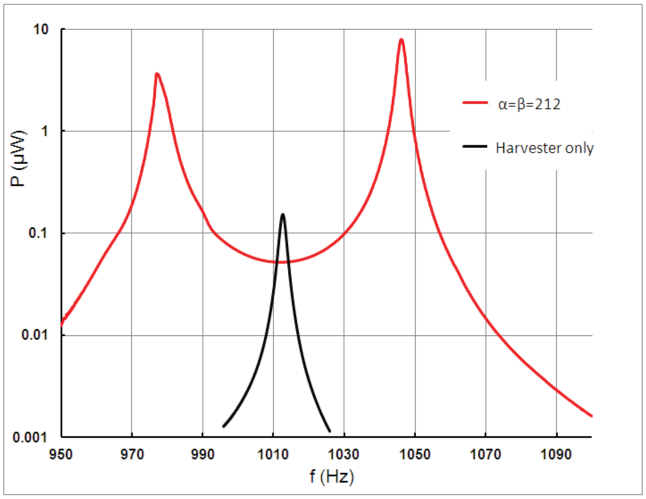

Figure 7: The power output for a PE harvester with f_h of 1011 Hz (external input= 0.08g). An amplification factor of 51.3 times is obtained (α= β=212)

package dimensions. However, due to the sensitivity increase, the maximum power will be reached at significant lower input accelerations. When we define $a_{max,0}$ as the acceleration value at which the maximum power is achieved for a harvester, we find in the case coupled oscillator system a value for a_{max} of

$$a_{max} = \frac{a_{max,0}}{\sqrt{\text{amplification}}} \quad (9)$$

DISCUSSION

We have presented data which shows that power amplification can be found of up to 51.3 times. This can easily be implemented in real applications where other electronics are needed, since only a thin beam of a few cm's length is required. A possible embodiment could be that a steel beam is placed on top of the PCB, on which the IC's as well as the rechargeable battery are placed.

This will only work if the steel beam has a small displacement during operation, such that the total device does not need much volume. In *Figure 8* we have plotted the calculated displacement of the energy harvester (x_h) and the beam (x_1), for α = 100 and different β values. For our harvesters, the maximum amplitude is 600 µm. In this case, that would be reached for β=120. We find that the maximum amplitude of the beam is around 50 µm. It can thus be concluded that the amplitude of the beam is much lower than the amplitude of the harvester, differing more than a factor of 10. It will thus be very easy to integrate the proposed setup in an existing wireless sensor node.

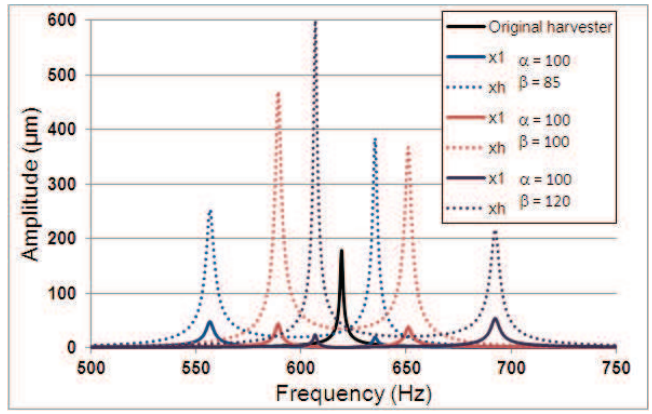

Figure 8.The amplitudes of the harvester (x_h, dotted lines) and the beam (x_1), for α=100 and different β values. For comparison, the amplitude of the original harvester amplitude is plotted (black solid line)

CONCLUSIONS

We have successfully implemented a simple coupled oscillator system, enabling to increase the power output of a MEMS packaged harvester. An amplification of up to 51 times has been obtained. The setup is very simple: the harvester was just placed on top of a thin metal beam. We have shown that the amplitude of the metal beam is maximum 50 µm, thus the total extra volume this setup needs is minimal. We believe that further optimization is still possible, reaching even large amplifications.

REFERENCES

[1] Shock induced energy harvesting with a MEMS harvester for automotive applications, R. Elfrink, et.al. , *Proceedings of the IEEE International Electron Devices Meeting (IEDM), Washington USA, 2011*, pgs. 29.5.1 - 29.5.4

[2] Petropoulos, T. , Yeatman, E.M. , Mitcheson, P.D. , MEMS coupled resonators for power generation and sensing, *Micromechanics Europe, Leuven, 2004*, Pages:261-264.

[3] Tang and Zuo, Enhanced vibration energy harvesting using dual-mass systems, *Journal of Sound and Vibration 330(2011)* 5199.

[4] O. Aldraihem and A. Baz, Energy Harvester with a Dynamic Magnifier*, Journal of Intelligent Material Systems and Structures 22(2011) pg*521

[5] J. Ormondroyd and J.P. Den Hartog. pages 87-106 *Mechanical Vibrations*, 4th Edition, (Dover, 1985) and William T. Thomson and Maria D. Dahleh, *Theory of vibration with applications* 5^{th} *ed*. ISBN 0-13-651068-X 199