A SCALABLE PIEZOELECTRIC IMPULSE-EXCITED GENERATOR FOR RANDOM LOW FREQUENCY EXCITATION

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ABSTRACT

This paper introduces an impulse excited piezoelectric energy harvesting prototype. The device is aimed at large amplitude, low frequency excitation typical of human body motion. A rolling, external proof mass actuates an array of piezoelectric cantilevers that form a distributed transduction mechanism. After initial deflection, the beams vibrate at their natural frequency. This allows for improved electromechanical coupling and large operational bandwidth. Measurements are presented to include different excitations and proof masses and an IC for voltage regulation is evaluated. At an excitation frequency of 2 Hz and an acceleration of 2.72 m/s^2 a power output of 2.1 mW was achieved.

INTRODUCTION

The technological fields of microelectromechanical systems and wireless sensor networks are predicted to grow significantly in coming years [1], [2]. Where batteries have previously been the preferred solution as power supplies, energy harvesting from ambient sources has begun to generate a strong interest. One of the major advantages of this approach, especially for applications with a large number of individual devices or where the device is hard to reach, is the reduced maintenance burden [3]. In industrial applications, commercial harvesters are already successfully used. Large temperature gradients and high frequency vibrations facilitate the generation of significant power outputs in such an environment. In comparison, the possibility of powering bio-sensors, for improved patient well-being and for reducing the amount of surgeries, still holds a number of challenges. The overall device size becomes increasingly important. Thermal devices generally struggle with the limited temperature gradients available. Human motion is characterized by low and non-harmonic patterns. The vibration amplitudes are in general much larger than the harvester size, which renders resonant devices unsuitable [4].

This paper presents a motion harvester specifically targeted at applications with such excitations.

IMPULSE EXCITED GENERATOR

In [5], the theoretical limits for power generation from inertial devices are analysed. For harmonic excitation this leads to the following form, which will be used for comparison in the results section:

$$P_{max} = \pi f a_0 Z_L m \quad (1)$$

where Z_L is the internal displacement limit of the mass m, f is the excitation frequency and a_0 is the external acceleration amplitude.

Our concept (Figure 1), first introduced in [6], tackles the aspect of m in equation (1) by using an external steel rod with a much higher density than the typical integrated silicon element. In our group, a rolling proof mass was previously investigated in an electrostatic design [7]. However, the device showed difficulty to achieve a sufficient coupling over the given travel range. The new layout uses a series of bimorph piezoelectric beams for transduction. A magnet at the tip of each element pulls the beams up to the steel cylinder at each pass. As the cylinder moves on, the beams are released and left to vibrate at their damped natural frequency, which ensures a good electromechanical coupling.

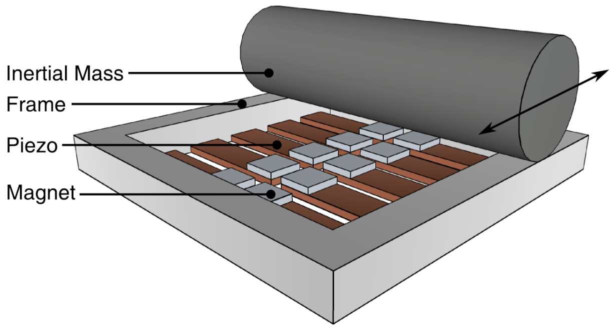

Figure 1: Concept model of the piezoelectric impulse excited generator

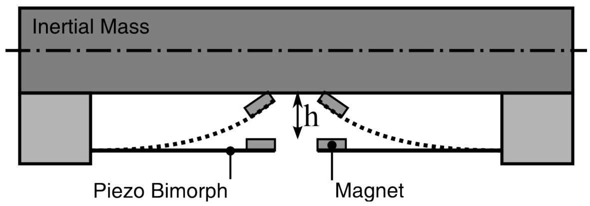

Figure 2: Section view showing the actuation of the piezoelectric transducers

The section view in Figure 2 illustrates that the travelling direction of the cylinder and the actuation direction of the transducers are perpendicular. With this solution the motion of the proof mass is not limited by the transducer displacement as is the case in some parallel plate electrostatic devices [5]. Obtaining the necessary actuation forces is now possible by choosing an appropriate beam geometry.

Other piezoelectric impulse excited generators include a device with a spring suspended mass [8], and a direct impact solution [9]. By comparison with these designs, distributed transduction, a rolling proof mass and perpendicular directions of travel and transducer actuation are novelties here.

EXPERIMENTAL SETUP

The larger scale functional model shown in Figure 3 was built to investigate the concept of the impulse excited harvester. The cylindrical proof mass is machined from mild steel and travels along two guiding rails. Eight piezoelectric beams are held in place by a clamping mechanism. Two aluminium blocks are used as end stops. All the relevant geometric parameters of this demonstrator were designed in an adjustable way in order to accommodate a large range of different beam geometries and to facilitate different test scenarios.

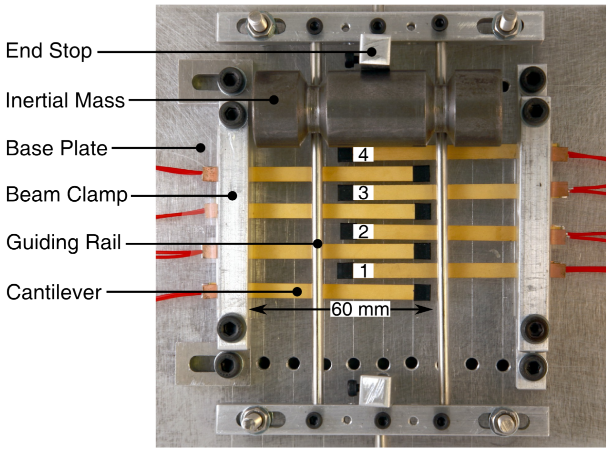

Figure 3: Macro scale test stand to prove the concept

The beams are made of PZT 507 from Morgan Electroceramics. The configuration is a series bimorph with a centre shim made of an FeNi alloy of 0.1 mm thickness. The PZT layers on the top and bottom are 0.2 mm thick which results in overall dimensions of 72×5×0.5 mm^3. After clamping, the free length of the beams is 60 mm.

The NdFeB magnets bonded on the tip of each beam are 5×5×1 mm^3 N52 type.

The experiments were performed on a rocking table providing a reproducible excitation source with a frequency range between 0.33 and 2 Hz (corresponds to settings between 20 and 120 rpm). Figure 4 shows the mechanical schematics of this setup. A connection rod transfers the motion from a driving wheel to the platform. The distance r between the attachment of the rod and the rotation axis can be adjusted. Consequently the tilt angle will change as well. Neglecting the centripetal acceleration, the external acceleration in the direction of proof mass travel can ultimately be given as:

$$a(t) = g\frac{r}{L}\sin(\omega t) = a_0 \sin(\omega t) \qquad (2)$$

where L is the distance between the pivot point and the mounting point of the connection rod on the platform and ω is the angular velocity of the driving wheel.

Based on this, the power output of the harvester was determined for four different configurations. A high acceleration a_1 = 2.72 m/s^2 (= 0.277 g) and a low acceleration a_2 = 0.873 m/s^2 (= 0.089 g) corresponding to tilt angles of 16.1° and 5.1° respectively were chosen. These values were obtained using data from an accelerometer mounted on the platform. At these two accelerations, measurements were performed using proof masses m_1 = 0.285 kg and m_2 = 0.143 kg (half of m_1).

The power from each beam was calculated as the square of the measured rms voltage divided by the load resistance. The optimal load of 120 kΩ was calculated to match the output impedance magnitude of the beam, i.e. $1/\omega C$, with C the piezoelectric capacitance (approx. 30 nF) and ω the natural (angular) resonance frequency of the beams, measured as 46.3 Hz.

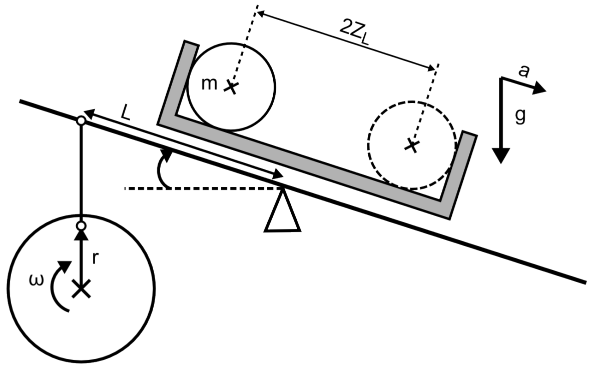

Figure 4: Measurement setup, rocking table with functional model

Finally, the output of the piezoelectric beams needs to be brought into a usable form. Recently, a number of companies have introduced electronic components specifically targeted at the energy harvesting market. One example is the Linear Technologies LTC3588-1 piezoelectric energy harvesting power supply [10]. This chip comes in a small 3×3 mm^2 package, accepts input voltages between 2.7 and 20 V and includes a full wave bridge rectifier. The chip was tested on the presented harvester with the regulated output of 3.6 V selected.

RESULTS

Figure 5 shows the measured power output for the four previously described configurations. It is important to know that the low acceleration a_2 was deliberately chosen such that the lighter proof mass m_2 only just has enough energy to travel the entire range (2 Z_L in Figure 4) between the end stops. In fact, if the cylinder is not initially released at one of the ends but in the center, it does not move at all. In practice this is nearly the ideal operation point for this device since it means most of the kinetic energy gets extracted by the transducers rather than by end-stop collisions. The power output up to 0.5 Hz is very close in all four curves. In the cases of higher acceleration and heavier proof mass, the cylinder gains a higher kinetic energy. However, the benefit of higher mass is only realised at higher frequencies where the lighter mass does not complete the full travel range, or in the lower acceleration case, ceases to move significantly. Nevertheless, a power output of up to 2.1 mW was achieved.

Comparing the two blue, dashed lines (low acceleration), there is a clear breaking point in the graph at 0.5 Hz. This is the upper limit for the lighter proof mass where it gets stuck on the magnets and barely moves at all. The heavier proof mass does not travel the entire range but manages to actuate most of the beams and does not get completely stopped.

When looking at the two solid, red lines for high acceleration, a similar breaking point can be observed all the way up at 1.67 Hz for the lighter proof mass. Up until that point the behaviour is quite linear and the results are fairly close to each other for both masses. This is, again, due to the fact that the transduction mechanism can not extract the additional energy stored in the heavier proof mass.

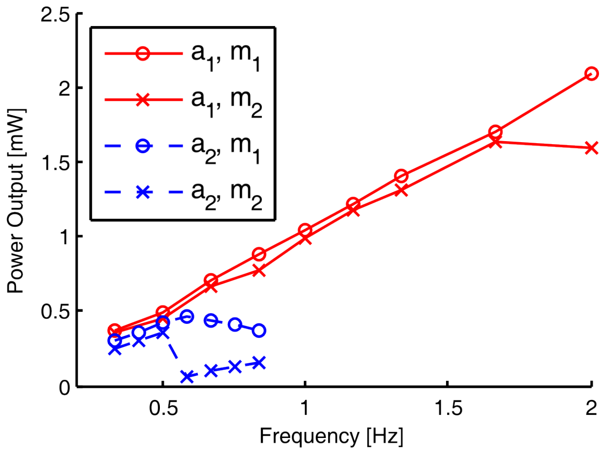

Figure 5: Measured power output

For comparison, Figure 6 shows the theoretical power output that should be achievable for this geometry according to equation (1). The benefits of higher acceleration and heavier proof mass in a theoretical sense are obvious.

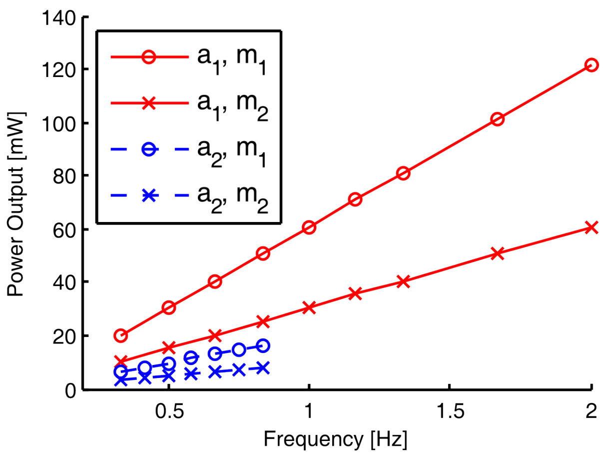

Figure 6: Theoretical power output

Finally, Figure 7 shows the effectiveness of the power conversion, i.e. the fraction of theoretically possible output that is achieved. This diagram clearly demonstrates that the best results can be gained if the transduction mechanism properly matches the proof mass. The crucial point though is that the effectiveness stays level across a broad frequency range. In the case of the higher acceleration this spans a bandwidth between 0.33 and 2 Hz, which is a factor of six. The impulse excited generator provides the possibility to remove the need for frequency tuning. The optimisation of the transduction mechanism is rather a matter of selected geometry than a matter of operating conditions and needs to be done only once during the layout. For example, choosing thicker piezoelectric beams would shift the ideal configuration towards heavier proof masses and accelerations because the amount of energy that can be harvested during one cycle increases.

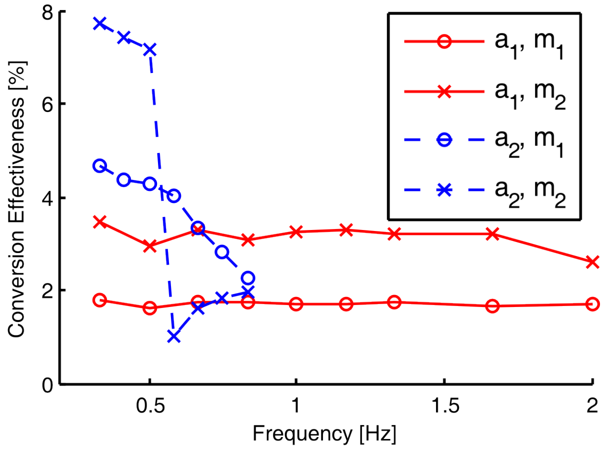

Figure 7: Effectiveness of power conversion

Figure 8 shows the start-up of the voltage regulator under high acceleration a_1 with the lighter proof mass m_2 for 0.83 Hz and 1.67 Hz, without load and measured on a single beam. This chip works by first rectifying the output from the piezo beams and then charging an input capacitor. Once this input capacitor reaches a threshold of 5 V, charge is transferred to the output capacitor. This explains why the output voltage rises in steps until it reaches the predetermined level (in this case 3.6 V). From the graph, a linear behaviour can be observed. If the excitation frequency, and thus the power output of the beam, is doubled, the start-up time drops to half its initial value of 25 s.

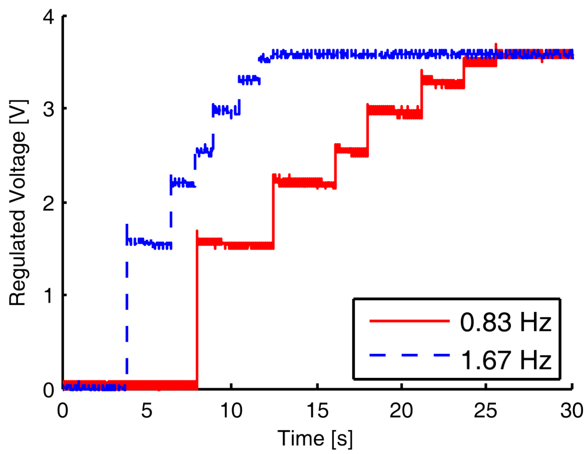

Figure 8: Voltage regulator start-up with no load

Figure 9 shows the start-up at 0.33 Hz and at 0.66 Hz with an attached resistive load of 1050 kΩ. Both curves show the discharging of the output capacitor between voltage rises. At 0.33 Hz, the regulator cannot cope with the demand from the load and never reaches 3.6 V.

The maximal power output after voltage regulation was determined by increasing the load, i.e. decreasing the resistance of a variable resistor until the voltage on the terminals collapsed. The obtained values were then compared against a measurement of the power output of the single beam into an impedance matched resistive load. The best efficiency achieved was 40%. This shows the importance of taking the power losses in the surrounding circuitry into account when developing an energy harvester.

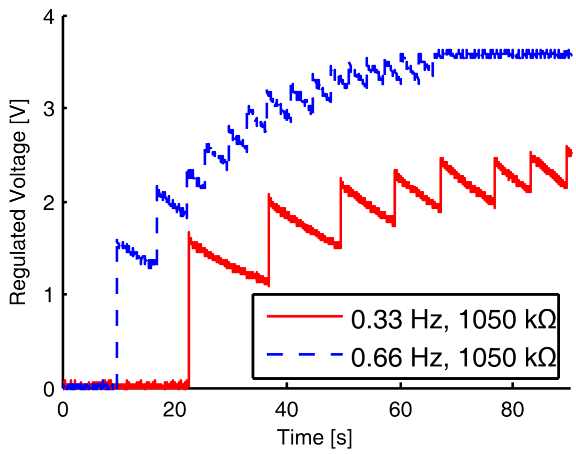

Figure 9: Voltage regulator startup and equilibrium under load

CONCLUSIONS

This paper presents a working prototype of an impulse excited energy harvester. The results show that the device behaves as expected in theory. It can operate over a large range of frequencies (up to six fold in our experiment) with a constant effectiveness and a linear relation between power output and excitation frequency at a given excitation acceleration.

Furthermore, the importance of matching the transduction mechanism to the design, more specifically to the proof mass, was shown. This can be done by choosing a different geometry for the piezoelectric elements, e.g. increased thickness. Doing so, a conversion effectiveness of almost 8 per cent at a low excitation frequency of 0.33 Hz was achieved. On the other hand, a maximum of 2.1 mW of power output was reached at the highest excitation with proof mass m_1. This value results from the limited frequency and acceleration range of the rocking table rather than the device itself.

It was also shown that the power losses caused by accompanying circuitry can not be neglected when developing an energy harvester. A currently available commercial voltage regulator designed for piezoelectric energy harvesting showed an efficiency of only 40%. The system needs to be regarded as a whole and all components need to be adapted to each other for the best results.

Finally, at a functional volume of 125 cm^3, the power output per unit volume with the lighter proof mass ranges from 3.8 to 13 μW per cm^3. It should be noted that these values are for a prototype device that is not fully optimised. For example, the length of the beams is 60 mm, whereas the length of the proof mass is only 45 mm, which is not an ideal usage of the space available. The design itself is however fully scalable, and piezoelectric beams are commercially available as standard components down to lengths of around 10 mm. With customised elements and MEMS fabrication techniques, minimal device sizes well below 1 cm^3 seem feasible.

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