Classifying miniaturised generators
State-of-the-art and future of vibration energy harvesting

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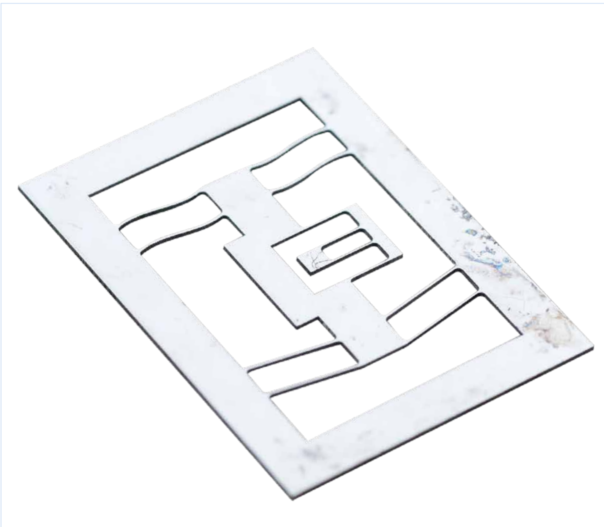
CLASSIFYING MINIATURISED GENERATORS

Although motion energy harvesting at the small scales has been a research topic for over 20 years, the implementation of such generators remains limited in practice. One of the most important contributing factors here is the poor performance of these devices under low-frequency excitation. In this research, a classification of miniaturised generators is proposed based on the dynamics of the nonlinear systems. This provides insight in the performance of different types of designs, which can be used to develop new designs with better efficiencies under realistic conditions.

THIJS BLAD AND NIMA TOLOU



Glossary

- Vibration energy harvester: Device that delivers an electrical output as a result of applied mechanical vibrations.
- Transducer: Part that converts energy from one form to another.
- Piezoelectricity: Electric charge that accumulates in certain solid materials in response to applied mechanical stress.
- Resonance: Phenomenon of amplification that occurs when the frequency of a periodically applied force is close to a natural frequency of a system.
- Bandwidth: Range of frequencies for which a satisfactory performance is obtained.
- Frequency up-converter: Device that incorporates a mechanism that takes a low-frequency input and delivers an output with increased frequency.

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Introduction

Small generators that harness ambient sources of energy can be attractive alternatives to batteries as wireless power supplies for low-power electronic devices. Of all ambient energy sources, kinetic energy in the form of motion or vibration is generally the most versatile and ubiquitous energy source available [1].

Generators that aim to use this source are grouped under the term vibration energy harvesters and have been investigated for over 20 years since the early work of Williams and Yates in 1996 [2], who investigated the piezo-electric, electromagnetic, and electrostatic transduction mechanisms for the purpose of vibration-to-electric energy conversion.

Generally, the power that can be harvested is in the range of micro- to milliwatts and may fluctuate greatly when the ambient motions are constantly changing. However, the expanding number of wireless devices and the great advances in their power consumption are continuously increasing the interest in the field of energy harvesting.

The most attractive applications are found in environments where battery replacement is expensive, inconvenient and/or prohibited by regulations. Examples of such applications are medical implants such as pacemakers, or wireless sensor networks composed of many small sensor nodes that can be used for the monitoring of structural health in buildings or for the tracking of goods.

In many of these applications it is reasonable to assume future power requirements in the order of a few microwatts. Given that a buffer is used to deal with fluctuations in generated power, this is certainly within reach for energy harvesters of modest sizes in many realistic vibration environments. In the case of the pacemaker, it was already demonstrated in vivo [3] that relevant amounts of energy can be harvested from the motion of the heart itself.

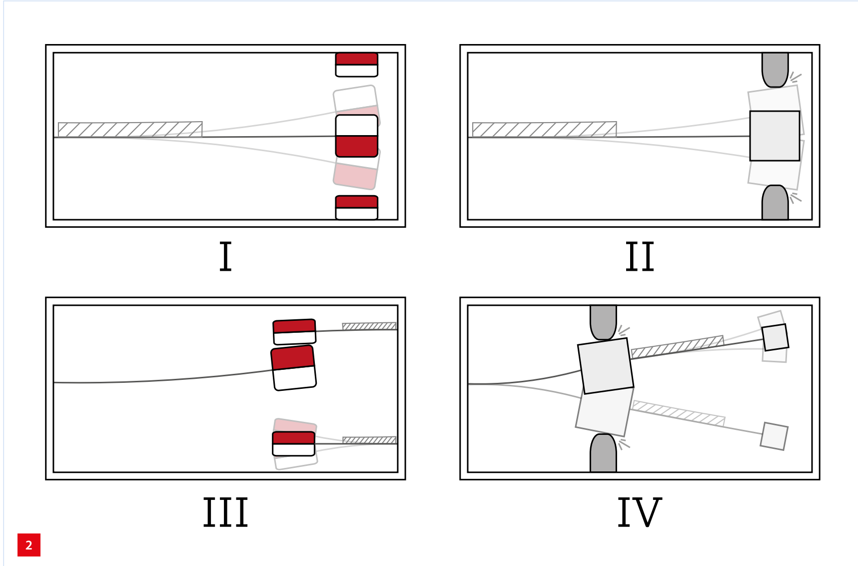
Working principles

Powering these devices requires the transformation of virtually useless energy from an ambient source into useful electric power. For this transformation two things are fundamentally required: an ambient source with a relevant amount of available energy and a device that can facilitate this transformation with a relevant efficiency.

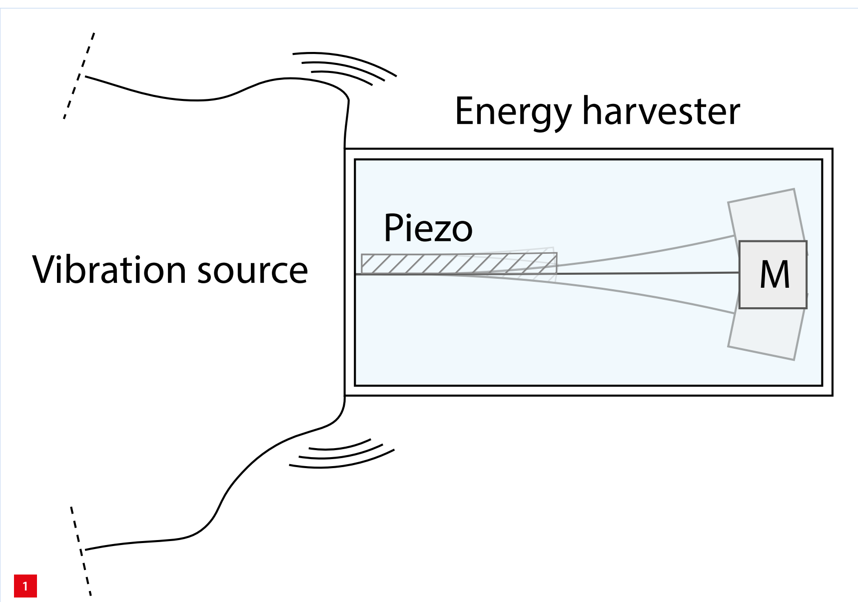
The basic working principle of the vibration energy harvester shown in Figure 1 is as follows. The housing of the generator is mounted on a vibration source. Inside the generator is a suspended inertial element (proof mass) that moves relative to the housing as a result of the applied motion. This relative motion results in an electrical power output due to a transducer such as a piezoelectric material.

Relevant parameters for the maximum power output are the dimensions and mass of the generator as well as the frequencies and accelerations of the applied vibrations. Furthermore, the actual power output is greatly dependent on the dynamic response of the generator to the applied vibrations. In cases where a vibration is applied with a fixed frequency and acceleration, a generator can be designed based on linear models to operate at resonance such that satisfactory power output is ensured. Using this strategy, generators have been reported with efficiencies up to 30% of the theoretical maximum [4].

However, in practical applications the generators will be exposed to vibrations with frequencies and amplitudes that change over time. Although excellent performance was achieved through a resonance-based strategy, the bandwidth over which this performance was found was extremely narrow.



Classification of miniaturised generators under low-frequency excitation.
Single-degree-of-freedom generator:
I) using soft stoppers;
II) using hard stoppers.
Frequency up-converter:
III) using plucking;
IV) using impact.



General concept of vibration energy harvesting using a piezoelectric transducer; the device is mounted on a vibrating source and generates output power as a result of internal motion.

Therefore, in realistic cases these devices may not deliver the required performance. To overcome this problem, more complex mechanisms with nonlinear elements are being developed and investigated. These mechanisms open up a range of nonlinear dynamics and have the potential to demonstrate relevant power outputs under realistic conditions. However, the design of their dynamic response is vastly more complex compared to the linear case, and as a result, the efficiencies of these types of systems are typically much lower.

Overview

When the size of the energy harvester approaches the amplitude of the applied vibrations (as can be the case with miniaturised generators under low-frequency excitation), the internal motion must be limited. The implementation of the motion limiter is an important design aspect and affects the dynamics of the device. Based on the dynamics found in these systems, the miniaturised nonlinear generators can be classified in the groups shown in Figure 2.

Single-degree-of-freedom generators (I + II)

The first class of nonlinear energy harvesters contains the generators with a single degree of freedom (DoF), which is used directly for the energy conversion. In this class we find two groups of devices: I) those that use soft stoppers, and II) those that use hard stoppers, to limit the internal motion.

Soft stoppers rely on a gradually increasing stiffness to limit the internal motion. In the design illustrated in Figure 2.I a moving magnet experiences a repulsive force from the oppositely-poled magnets at the motion limits. The closer the centre magnet moves towards the motion limits, the greater this repulsive force becomes.

The other group features devices with a very rapid stiffening effect at the end of their range of motion. In Figure 2.II it can be seen that a mechanical contact is used to produce the behaviour of a hard stopper.

Frequency up-converters (III + IV)
The other class of systems is the frequency up-converters. These are multi-DoF systems that use an inertial mass to excite a secondary oscillator. The energy is harvested from the motion of the secondary oscillator, which oscillates with an increased frequency compared to the frequency of the driving motion.

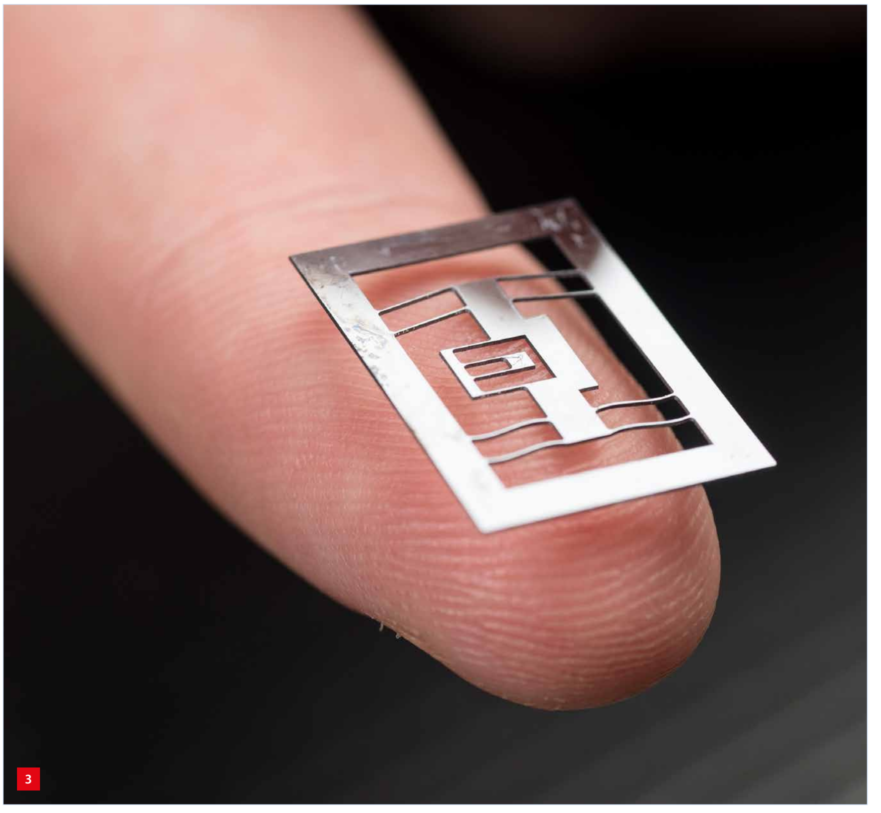
The first group of frequency up-converters comprises the systems that excite their secondary oscillator through plucking. The design illustrated in Figure 2.III consists of an inertial mass which snaps back and forth between two secondary oscillators, attaching magnetically. When the inertial mass detaches, the secondary oscillator starts oscillating at its natural frequency, which generates the output power.

The other group of frequency up-converters uses the impact of an impact member to excite the secondary oscillator. In Figure 2.IV a secondary oscillator is mounted in series with the inertial mass. Under a driving motion, the inertial mass makes contact with the mechanical stops at the end of its range of motion. As a result of this impact, the secondary oscillator begins to oscillate in its own natural frequency.

Conclusions

It was found that the efficiencies of nonlinear energy harvesters are typically reported between 0.1 and 1%. In general, generators found in groups I and II report higher efficiencies compared to those of groups III and IV. Reasons for this could be the significantly larger amount of reported work on the single-DoF generators and the increased complexity of the dynamics of frequency up-converters.

However, it was found that the frequency up-converters are likely to demonstrate a better performance when approaching greater degrees of miniaturisation. Furthermore, it was found that the nonlinearities that result from the stoppers or the use of frequency up-conversion, greatly improve the efficiency of the energy harvester over a much wider bandwidth compared to the linear systems.



Possibly the future of miniaturised generators; a class-IV energy harvester.

Future work

The focus of future work is to systematically benchmark the performance of typical nonlinear generator designs under varying conditions and at different scales to gain better insight in the design parameters and their sensitivities. This can be used to develop more accurate models to estimate the performance of vibration energy harvesters under realistic conditions. Using these models, we aim to develop better designs of miniaturised generators (Figure 3) to build the next generation of energy harvesters.

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