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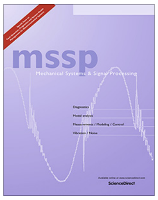

# Increased power output of an electromagnetic vibration energy harvester through anti-phase resonance

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## ABSTRACT

This paper proposes a novel method to increase the power output of a cantilever beam-based electromagnetic vibration energy harvester through anti-phase resonance. A new cantilever beam design is presented to achieve this. By introducing an anti-phase motion between the coil and the magnets at resonance under the same base excitation input, the relative velocity of the coil cutting through the magnetic field is significantly increased and hence its power output. An experiment is performed to compare the proposed method with the conventional method where either the coil or the magnet is fixed onto the vibrating base. Under a base acceleration level of 0.10 g and a natural frequency of 17.24 Hz, results shows a 185% increase in power for the proposed method when compared with the conventional method with a recorded maximum power of 7.4 mW at resonance. The power produced by this method is proven to be higher than the sum of power produced by two individual conventional harvesters under the same velocities. In addition, a 22% increase in frequency bandwidth is also recorded by the proposed method. In terms of the power density, the proposed method indicates a 38% increase when compared with the conventional harvester. Results also show a drastic reduction in the maximum power output and phase difference when the natural frequencies of the coil and the magnets differ by only 1.5%, hence defining the importance of frequency matching. Further analysis indicates that a glass fiber cantilever beam showed a higher decrease in electromagnetic damping as compared to the increase in mechanical damping when small bulk masses were added onto the beam, hence increasing its overall gain.

## 1. Introduction

### 1.1. Literature review

Over the past decade, advancement in wireless sensor network (WSN) technologies have allowed the development of low powered WSN [1]. Currently, most WSNs are still powered by conventional batteries, which has the disadvantages of a large volume, limited power supply and high maintenance cost. Hence, research in energy harvesting towards finding a sustainable source of power for WSN became increasingly popular [2–4]. One of the most promising source of energy that was

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initially proposed by William and Yates [5] is vibrations. Vibration energy harvesting emerged as an encouraging energy source due to its high power density in terms of electrical conversion and its abundance from the surrounding [6]. Many transduction methods exist to convert mechanical vibration energy into electrical power, with the two most common methods being piezoelectric conversion and electromagnetism. Piezoelectric conversion method demonstrated a higher power density at small volumes whereas electromagnetic conversion is more favourable when space is not a constraint [7]. However, Beeby et al. [8] showed that the power density of an optimized electromagnetic vibration energy harvester can surpass the power density of a piezoelectric harvester, even at small volumes.

Various researches have been conducted throughout the past decade to increase the power output and the frequency bandwidth of a vibration energy harvester. Thein et al. [9] performed a finite element optimization algorithm to determine the optimum topology for a piezoelectric vibration energy harvester that would result in the maximum power output. Similarly, Chen et al. [10] also conducted a topology analysis to determine which shape between rectangular, trapezoidal and triangular cantilever beam would result in the highest power output of a piezoelectric harvester. Ooi and Gilbert [11] proposed a dual-resonator design consisting of two cantilever beams facing each other, where a pair of magnets is attached to one beam and a coil is attached to the other. It was shown that under dissimilar resonant frequencies, the bandwidth between the two resonant frequencies was improved due to the effect of superposition. However, the maximum power recorded did not exceed the individual power outputs of both beams. Cottone et al. [12] proposed a technique to increase the power output of an electromagnetic vibration energy harvester through the concept of velocity amplification. By using multiple masses and springs, a 33 times increase in power gain was obtained when compared with a single mass configuration. Several researches have also explored the effect of a hybrid energy harvester in where the piezoelectric and electromagnetism transduction method was combined into a single harvester [13–15]. While an increase in power output was observed, the recorded power output was less than the sum of the power outputs from the two individual transduction methods.

The concept of anti-phase vibration have been explored by several researchers as an option to increase the power output of a vibration energy harvester. Kim et al. [16] performed a theoretical analysis on a two-degree-of-freedom bi-stable energy harvester composed of two piezoelectric cantilever beams. It was concluded that when the two beams are out-of-phase from each other, they exhibit a double well dynamic motion. Ando et al. [17] applied the concept of bi-stable parallel beams with tip magnets to achieve anti-phase motion. As a result, a ten time increase in power output from the two piezoelectric beams were recorded when compared with a single beam. However, it may be difficult to apply this concept for an electromagnetic harvester's design as anti-phase motion would also be desired for the coil. In a study made using dielectric elastomers in vibration energy harvesting, the design proposed by Yurchenko et al. [18,19] showed that the best voltage output was achieved from the anti-phase motion of the ball and the cylinder. Lee and Chung [20] applied the concept of anti-phase motion in a pendulum-based electromagnetic energy harvester and recorded a 37% increase in power when compared to a single-phase pendulum.

Despite the various power amplification solutions presented in past literatures, there have yet been a study that emphasises on an anti-phase motion at resonance for cantilever beam-based electromagnetic harvesters. The concept of anti-phase resonance may prove to be beneficial in terms of electromagnetic power output due to the increase in relative velocity. In this work, a method to increase the power output of an electromagnetic vibration energy harvester through anti-phase resonance was proposed. The idea was to maximise the relative velocity of the coil cutting through the magnetic flux of two permanent magnets by making the coil and the magnet vibrate out-of-phase from each other at resonance under the same base excitation input. Based on Faraday's law of electromagnetism, this will result in a significant increase in power output. The results from the proposed method were analysed and compared to the results of a conventional method in where the coil was fixed onto the vibrating base. Additionally, the effect of the phase difference on the power output of the anti-phase resonance method and the effect of the effective mass on the gain of an electromagnetic energy harvester were also studied.

### *1.2. Design of anti-phase resonance electromagnetic vibration energy harvester*

To achieve anti-phase motion at resonance, a new cantilever beam design was presented as seen in Fig. 1.

The design consist of two smaller beams (beam B and beam C) that are clamped to one end of a primary cantilever beam. The other end of the primary beam is clamped to a vibrating base. When the primary beam vibrates, the free-end of the primary beam would experience a maximum deflection and hence creating a significant amplitude gradient at this location. This will cause beams B and C to deflect in the opposite direction from the free-end primary beam. Fig. 2 provides a visual aid of the side view as to how the design would vibrate. The coil was modelled as a block mass for simplicity. It can be seen that when the free-end of the primary beam deflect downwards, beams B and C would deflect upwards. Conversely, beams B and C would deflect downwards when the free-end of the primary beam deflects upwards.

The new beam design must be paired with at least one individual cantilever beam (beam A) to generate power. A coil was attached to beam B and a pair of magnets is fixed onto beam A. A mass was added onto the other smaller beam to ensure a balanced mass. An unbalanced mass would result in a non-linear motion for beams B and C in where the beam with the larger inertial effect would vibrate stronger, causing rotation or twisting on the horizontal axis of the primary beam. This in turn would cause a non-linear phase change in the design making it harder to achieve the designs maximum potential. In addition, the induced rotation can also lead to physical contact between the coil and the magnets which can retard their