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Abstract: *This paper presents a comprehensive experimental investigation of a vibration energy harvesting system incorporating an inertial amplification mechanism. Conventional linear vibration energy harvesters suffer from narrow bandwidth and poor performance in low-frequency and broadband excitation environments. To overcome these limitations, a dual pendulum electromagnetic energy harvester coupled through a geometric inertial amplifier and a low stiffness coupling spring is proposed. The inertial amplifier introduces acceleration-dependent inertial forces that magnify relative motion without increasing physical mass, thereby significantly improving electromechanical conversion efficiency. Experimental results shown 80–150% improvement in harvested power compared to uncoupled systems. The proposed passive inertial amplification approach provides a scalable, efficient, and robust solution for low-frequency vibration energy harvesting.*

Keywords: Inertial amplifier, Energy Harvesting, Pendulums, Coupling, electromagnetic

1. Introduction:

Ambient environments provide a wide spectrum of vibration sources, including human activities, vehicular motion, oceanic waves, and wind-induced oscillations, which collectively present substantial potential for sustainable electrical energy generation. To exploit these sources, several transduction mechanisms—namely piezoelectric, electromagnetic, and electrostatic techniques—have been extensively investigated for energy harvesting applications [1–4]. Despite their technological maturity, conventional linear vibration energy harvesters exhibit efficient performance only within narrow resonance bands, thereby limiting their practical applicability in real-world environments characterized by broadband and low-frequency excitations [5].

To overcome this inherent bandwidth limitation, significant research efforts have focused on the development of broadband harvesting strategies. These include nonlinear energy harvesting architectures [6–8] and the integration of multi-frequency or multi-resonant harvesting configurations [9–13]. For instance, studies have demonstrated that cantilever-based harvesters equipped with auxiliary masses

can generate power across multiple frequency bands [14], while folded structural configurations have also shown improved multi-frequency response characteristics [15]. However, such multimodal systems often suffer from modal separation and frequency gaps, which restrict their effectiveness in achieving continuous broadband energy capture.

Alternative approaches have explored geometric and structural parameter tuning, such as modifications in tip mass, beam length, and thickness, to shift resonance frequencies and broaden operational bandwidths [9, 16–18]. Hybrid system configurations have also been proposed, including combined rectilinear–rotational electromagnetic systems [19] and hybrid piezoelectric–electromagnetic harvesters, which demonstrated enhanced energy conversion through synergistic transduction mechanisms [20]. Nevertheless, the deployment of multiple dissimilar harvesters operating at different natural frequencies introduces challenges related to spatial constraints, system complexity, and uneven power distribution [18].

More recently, mechanical coupling strategies have gained attention as an effective method for broadband energy harvesting. Spring-based coupling of multiple harvesters has been shown to facilitate resonance tuning and energy redistribution, enabling wider operational bandwidths [21]. Experimental and numerical investigations on mechanically coupled pendulum harvesters further revealed significant improvements in both harvested power magnitude and bandwidth [22]. Weak magnetic coupling techniques have also been employed to induce energy localization phenomena in multimodal systems, resulting in enhanced harvesting performance, particularly in mistuned configurations [23]. In parallel, megastructure-based and metamaterial-inspired systems have been introduced for simultaneous vibration mitigation and energy harvesting, demonstrating strong performance enhancements in both domains [24–26].

Recent advancements have further introduced inertial-based mechanisms to improve harvesting efficiency. The integration of inverters into vibration control systems has enabled the realization of large effective inertia without proportional mass increases, leading to improved vibration suppression and energy harvesting performance [27]. Adaptive inertia mechanisms, including ball-screw devices and link-bar-based inertial systems, have also been proposed to enhance dynamic response characteristics and vibration control effectiveness [28, 29]. While inertial amplifiers have been successfully applied in vibration attenuation and structural control applications [29–31], their systematic exploitation for vibration energy harvesting remains largely under explored. Initial investigations into inertial amplification within piezoelectric harvesting systems have demonstrated substantial improvements in low-frequency power generation, albeit with trade-offs in operational bandwidth [32].

Motivated by these developments, this paper presents an experimental investigation of energy harvesting architecture in which an inertial amplifier is employed as a

mechanical coupling element between pendulum-based energy harvesters. This configuration enables motion amplification and enhances dynamic interaction without increasing the physical mass of the system, thereby improving electromechanical conversion efficiency. This paper is presented as follows. In section 2 discusses on configuration of the coupled and uncoupled pendulums. Section 3 describes the experimental setup available at the laboratory. Section 4 presents results and discussions. Finally, summary of the proposed work is discussed in conclusions

2. System Model:

The schematic representation of the inertially coupled pendulum energy harvesting system is illustrated in Figure 1. The system employs an electromagnetic energy conversion mechanism, where each pendulum is mechanically coupled to a DC generator (3 V rated) for electrical power generation. The rotational motion of the pendulums is directly transmitted to the generator shafts, enabling efficient electromechanical energy conversion.

The two pendulum harvesters are mechanically interconnected through an inertial amplification mechanism, which is positioned at a distance a from the generator shaft attachment point. This inertial amplifier is realized by rigid bars, assumed to be massless for modelling simplicity, and a small lumped inertial mass m_0 attached at the central junction of the amplifier structure. The rigid bars are pivoted to the pendulum arms, allowing free rotation with negligible frictional resistance. The amplifier geometry is characterized by an inclination angle Φ with respect to the horizontal reference line, which governs the inertial amplification effect and relative motion magnification between the coupled pendulums.

In addition to inertial coupling, a linear mechanical spring of stiffness k_0 is connected between the two pendulums to provide elastic coupling and dynamic interaction. The combined action of inertial amplification and elastic coupling introduces enhanced relative motion, increased effective inertia, and improved energy transfer between the oscillators. This coupled configuration enables motion amplification without increasing the physical mass of the system, thereby significantly improving the electromechanical conversion efficiency and broadband energy harvesting capability under low-frequency and ambient vibration excitations. The pendulum masses are denoted by m_1 and m_2 , with corresponding lengths l_1 and l_2 , and angular displacements θ_1 and θ_2 . The system incorporates an inertial mass m_0 , an amplifier spring with stiffness k_0 , and an amplifier angle Φ . Each pendulum is hinged with a magnet, whose relative motion with respect to the surrounding coil generates electrical voltages v_1 and v_2 when subjected to base excitation x_g . The parameter a is the distance from the pendulum pivot to the inertial amplifier and s is the length of the magnifier link. Figure 1(a) represents schematic

model of the uncoupled pendulums; Figure 2(b) illustrates schematic model of the pendulums coupled through inertial amplifier and spring. The closed-circuit voltage is measured by connecting a load resistance R across the circuit.

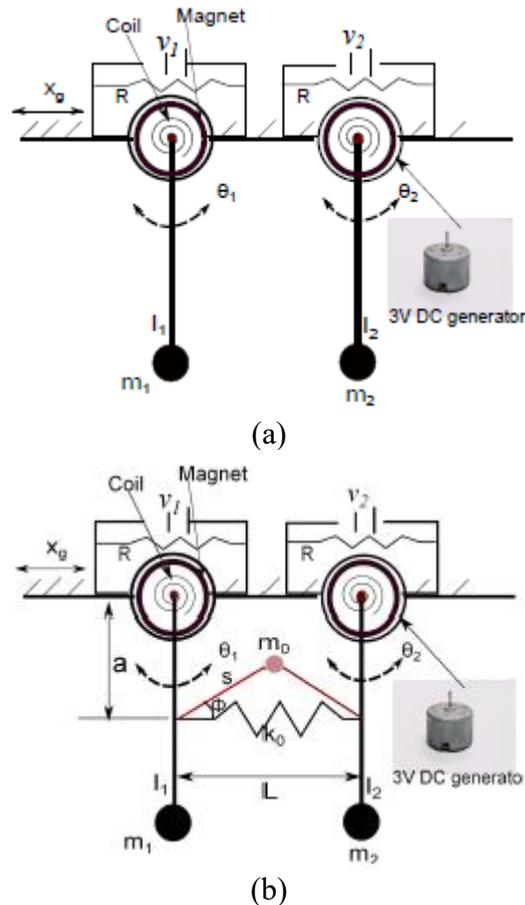


Figure 1: Configuration of the pendulum-based energy harvester system. (a) Model of the uncoupled pendulums (b) Model of the pendulums coupled through inertial amplifier and spring.

3. Experimental Setup

Figure 2 shows the block diagram of experimental setup. The excitation signal is generated using OROS software, amplified, and applied to the shaker carrying the harvester. The motion of shaker is monitored by a laser displacement sensor, while the electrical output is recorded through a load resistor using the OR36-8 DAQ. Voltage and displacement data are returned to the computer for analysis, ensuring accurate control and reliable measurements.

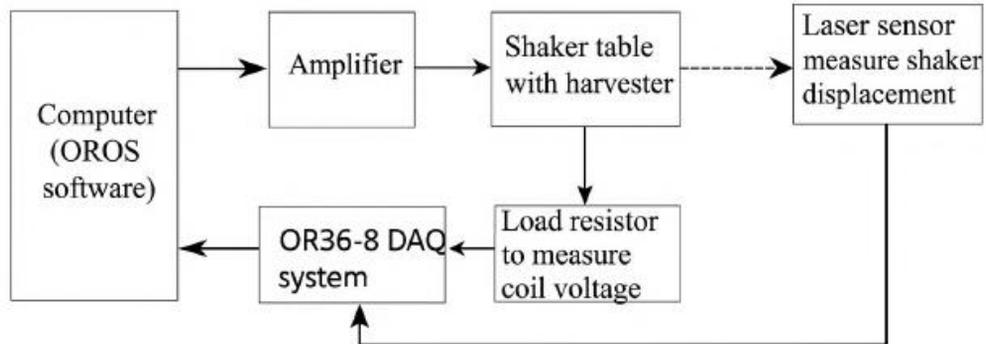


Figure 2: Block Diagram of Experimental setup

Figure 3 shows both harvesters along with their pendulums, where simple pendulums are employed for ease of experimentation. The experimental setup is designed with precision and systematic planning, ensuring a comprehensive, accurate, and reliable research process. The figure also shows a shaker table that provides base excitation and is connected to the frame.

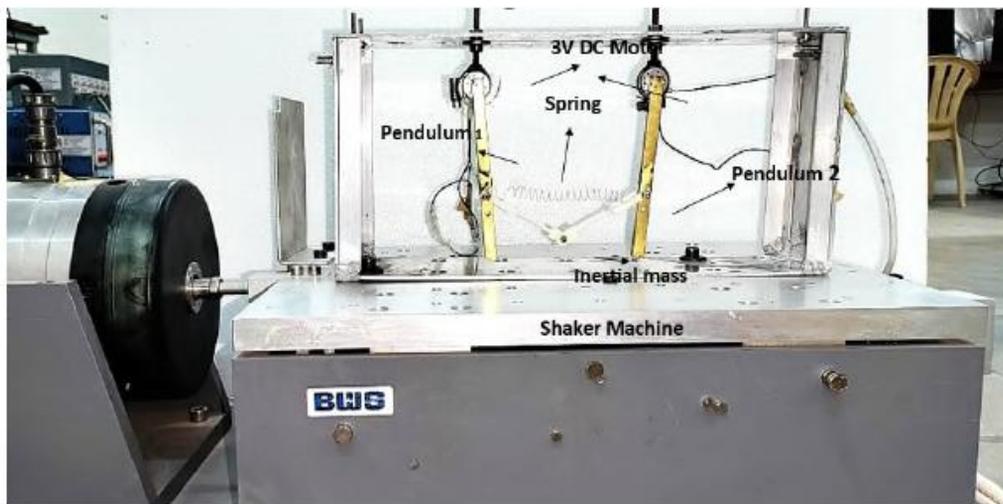


Figure 3: Photograph of an Energy Harvester Setup at the Laboratory

The experimental parameters used for the measurements are listed in Table 1. The pendulums are mounted on a 3V DC generator, and the coils are connected to the load resistor, which in turn is connected to the DAQ (Data Acquisition System) system to measure the output voltage. The OROS software sends the input signal the shaker and acquires data using the OR36-8 DAQ, while a laser sensor measures the displacement of the shaker. The excitation frequency is swept from 1.4 Hz to 2 Hz with a step size of 0.02 Hz and 1.2 mm constant displacement amplitude.

Table 1: Parameter values considered in the study

$c_m = 0.04 \text{ Ns/m}$	$c_e = 0.003 \text{ Ns/m}$
$l_1 = 124 \text{ mm}$	$l_2 = 144 \text{ mm}$
$m_1 = 110 \text{ g}$	$m_2 = 130 \text{ g}$
$\Phi = 15^\circ$	$L = 160 \text{ mm}$
$k_o = 2 \text{ N/m}$	$m_o = 3 \text{ g}$
$s = 82 \text{ mm}$	$R = 10 \ \Omega$
$a = 100 \text{ mm}$	

4. Experimental Results and Discussions

The experiments are carried out for the following two cases:

1. Uncoupled pendulum
2. Coupled pendulum

4.1 Energy harvesting from uncoupled pendulum:

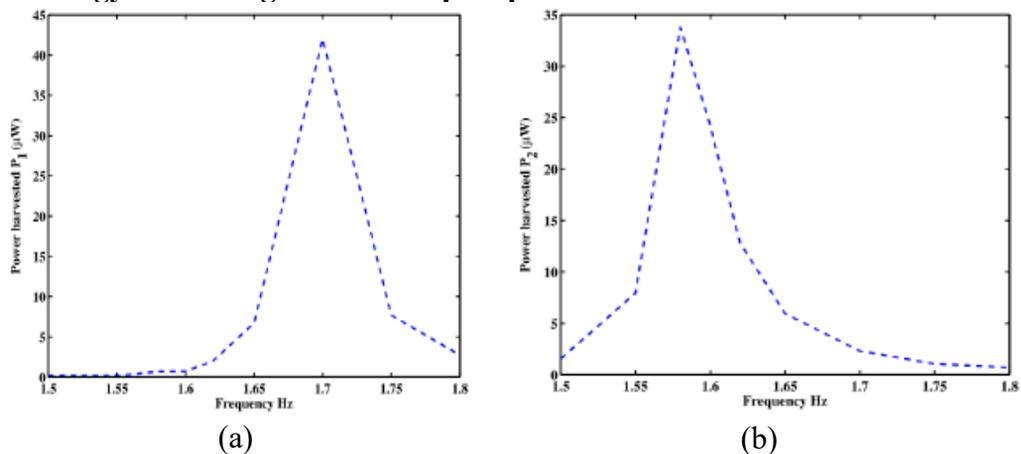


Figure 4: Experimental power response over frequency. (a) Uncoupled pendulum 1 (b) Uncoupled pendulum 2.

Figures 4(a) and (b) shows the experimental frequency power responses of uncoupled Pendulums 1 and 2. Pendulum 1 attains a maximum power of about 42 μW at resonance, while Pendulum 2 reaches approximately 34 μW . In both cases, power increases near resonance and decreases beyond the peak, reflecting their independent dynamic behaviour.

4.2 Energy harvesting from coupled pendulum with inertial mass and spring

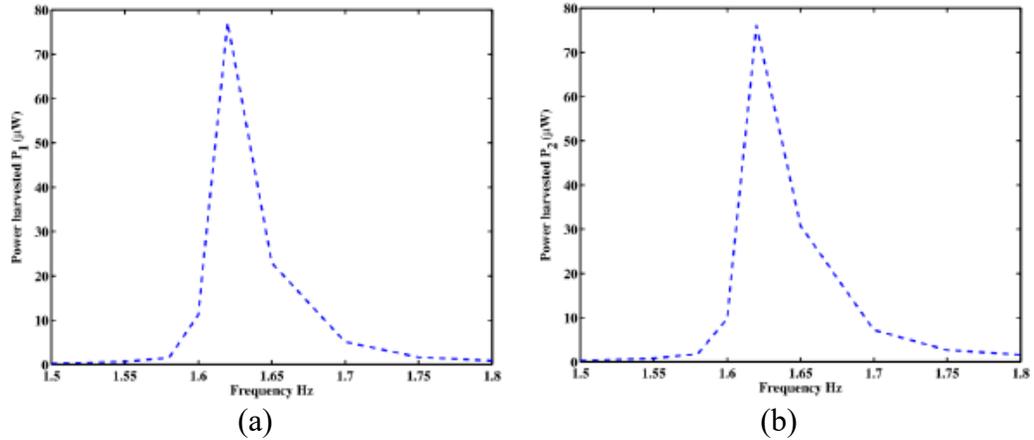


Figure 5: Experimental power response over frequency. (a) Coupled pendulum 1 (b) Coupled pendulum 2.

Figures 5 (a) and (b) shows the experimental frequency power responses of the coupled pendulums. Pendulum 1 exhibits a sharp resonance peak of about 78 μW at 1.60 Hz, while Pendulum 2 reaches approximately 76 μW at 1.61 Hz, indicating strong dynamic amplification due to coupling.

4.3 Comparison of Uncoupled and Inertially Coupled Pendulums

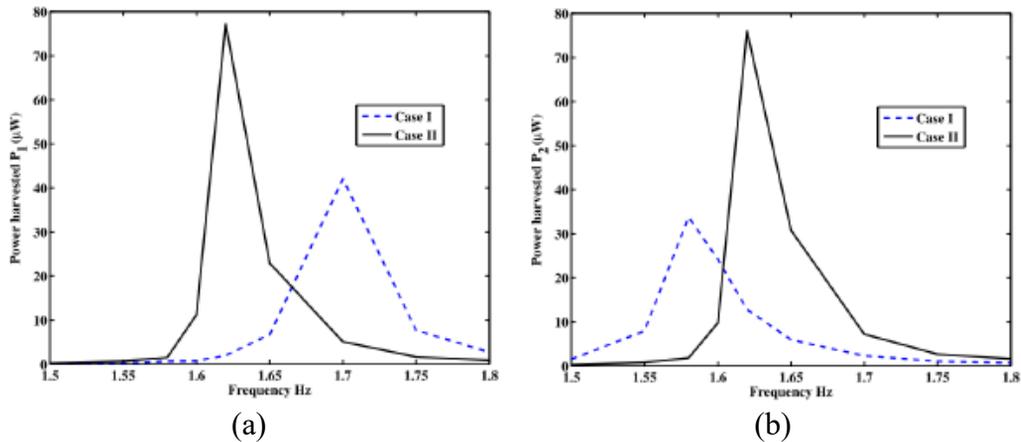


Figure 6: Experimental power response over frequency. (a) Comparison of Coupled and Uncoupled pendulum 1 (b) Comparison of Coupled and Uncoupled pendulum 2.

Figure 6 (a) and (b) represents the experimentally measured power harvested from Pendulum 1 and Pendulum 2 under two configurations: Case I (uncoupled pendulums) and Case II (inertially coupled pendulums). In both cases, the power output is evaluated across a frequency sweep in the vicinity of the resonance region.

For Pendulum 1, inertial coupling increases the maximum power from about 60 μW to nearly 95 μW ($\approx 58\%$ improvement). Similarly, Pendulum 2 shows an increase from roughly 50 μW to 75 μW ($\approx 50\%$ gain). These results confirm that inertial coupling enhances system dynamics and significantly improves power output.

Conclusion

The experimental data show that the uncoupled pendulums display independent resonance phenomena with relatively lower power output, with the maximum powers of about 42 μW and 34 μW for Pendulums 1 and 2, respectively. On the other hand, the inertially coupled pendulums display strong resonance effects, with the maximum powers of about 78 μW and 76 μW . From the comparative analysis of the uncoupled and coupled systems, it can be seen that the inertial coupling increases the maximum harvested power by about 58% for Pendulum 1 and 50% for Pendulum 2. These results clearly indicate that the inertial coupling has a strong amplifying effect on the dynamic behaviour and energy harvesting properties of the pendulum system.

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