Portable Energy Harvesters by Additive Manufacturing

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***Abstract*– Wearable devices keep growing in popularity while raising the interest in improved battery life. Energy harvesters that harness kinetic energy could offer an option to extend service life or even replace batteries. Body motion is rich in a complex combination of movement, which is mainly limited to planar motion. Traditional inertial generators are designed to resonate at a fixed frequency where devices need to be tuned for a particular operation. Nonlinear generators, on the other hand, offer the possibility of a wide bandwidth by altering the response. Besides, the subharmonic and superharmonic resonances make them of interest for applications where those frequencies can be used to generate energy in addition to the main resonant frequency. This work showcases one nonlinear design that employs the properties of thermoplastic materials and an electromagnetic generator to operate at 39 Hz with an RMS power of 1.6 µW.**

Keywords—energy harvesting, electromagnetic, low frequency, body motion, thermoplastics.

I. INTRODUCTION

Wearable devices have been growing in popularity in the last decade, while at the same time, the interest in improved battery life keeps rising. While there are existing technologies powering self-winding wristwatches, the power output has been found too low, below 10 µW for regular operation [1] or in bursts of 1-100 mW when actively operated, which is insufficient for the requirements of most activity trackers, smartwatches, or other portable devices [2]. Researchers have been exploring alternatives for decades, such as energy harvesting from mechanical vibrations [3] or body motion [4]. Most generators use an inertial proof mass under linear or rotational architectures, following electromagnetic [5,6], piezoelectric [7], or electrostatic transduction techniques [4,6].

Most energy-harvesting devices use linear springs that resonate at a fixed frequency and must be tuned for each application. An earlier study of the usage of nonlinear springs as compared to linear springs analyzing the vibration characteristics revealed a significant 48% increase in output power of a nonlinear spring system as compared to a linear spring system [8]. It has been shown that more power is harvested in systems with springs than in unsprung systems [5]. The addition of a spring improved the performance of the energy harvester by 365% for pseudo-walking input data, while for real-walking data, adding a spring improved the performance of the energy harvester by 68%. The mean power output difference between sprung and unsprung rotational energy harvesters can vary widely [6]. Wrist-worn energy harvesting devices had also been studied [9] where the experimentally harvested energy closely correlated with the simulated energy harvested. However, there is still a gap between the theoretical upper bound of energy harvesting and the actual real-world energy harvested. Recent research has shown that nonlinear devices produce higher output power in energy harvesting when compared to linear devices [11].

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This work explores the use of nonlinear springs for energy harvesting using electromagnetic transduction by employing a thermoplastic polymer as the spring material. Polymers add new properties that can be explored for nonlinear applications while reducing the cost of adoption for portable devices.

II. BODY MOTION

Walking is the most common daily activity where potential and kinetic energy is interchanged constantly during gait. The limbs, head, shoulder, trunk, and pelvis move to maintain balance during the walking cycle. Through the different phases of the stride, the center of mass of the body changes location not just vertically but sideways, following a sinusoidal path. The vertical displacement is found to be 4-5 cm, while the horizontal motion is near 4 cm [12] for the most common walking speed of 1.4 m/s [13]. Walking speeds have been found to be on the order of 0.6-2.2 m/s with step frequencies between 1.4-2.5 Hz [14]. The most common walking speeds reported range from 0.97-1.5 m/s [15] for a walking frequency close to 2 Hz. Understanding how the body moves helps to design wearables that take advantage of those characteristics. Motion can be considered as sinusoidal waveforms that act on the frontal plane and the sagittal plane.

III. DESIGN

The architecture of the electromagnetic generator follows a linear architecture described in [16] with the implementation of a nonlinear spring design. Flexible hinges (40 mm long, 10mm wide) are used with parallel cantilever beams to restrict the motion of the proof mass in the vertical direction (30 mm tall). Permanent magnets (Ferrite, grade 5, 6 mm in diameter, 2 mm thick) were placed at the end of flexible hinges as the moving part, while the stationary coil (AWG 34, 2.2 Ω) was placed on an air-core tube (7 mm diameter) to complete the generator design. The generator was selected as a preliminary design to evaluate the nonlinear characteristics for posterior wearable use. Additive manufacturing was used to develop a working prototype.

Polylactic acid, PLA, was selected due to its nonlinear force-displacement relationship, as shown in Fig. 1. Tensile tests were performed on an Instron 5965 Universal Testing Machine following the ASTM D638-14 standard at room temperature with type IV specimens using PLA at 20% infill.

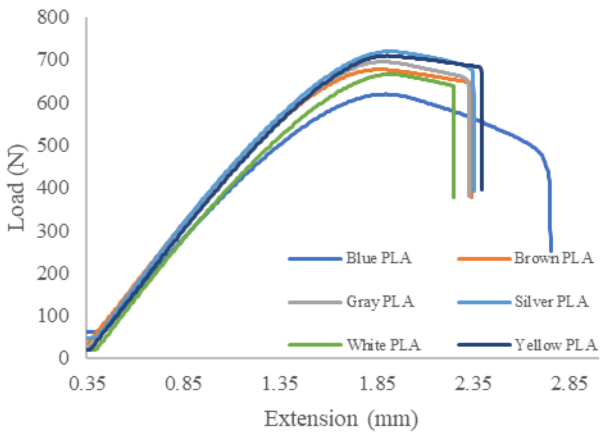

Fig. 1. Polylactic acid tensile testing results.

Tests were done using material from multiple sources and segregated by color to compare the effect of colorant additives. Modulus was determined as 4,800 MPa for most test specimens. Fig. 2 shows a picture of the developed generator using additive manufacturing while placed on a shaker.

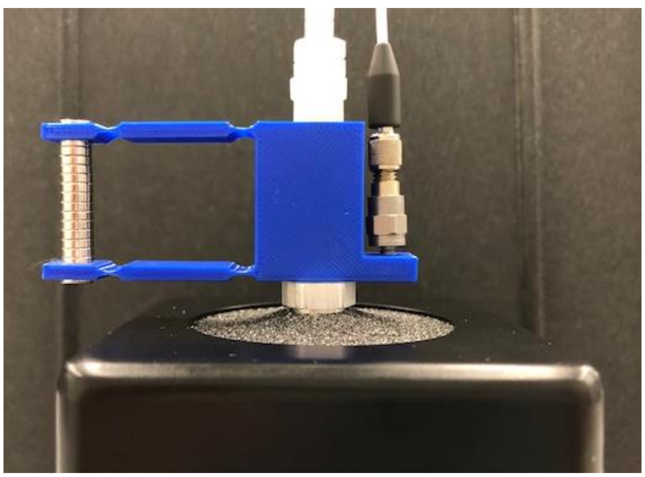

Fig. 2. Linear generator design with flexible hinges on a vibration shaker.

Kinetic energy is added once the system is perturbed from rest, whereas mechanical friction typically dampens the motion. A spring adds an elastic energy term to the system. The equation that describes the general motion for such a linear system on a fixed reference frame is

$$m\,\ddot{x} + b\,\dot{x} + k\,x \;= F(t) \qquad (1)$$

where m represents the mass of the system, b is the total damping, k is the stiffness of the torsional spring, x is the linear position of the proof mass, and $F(t)$ is the forcing function. An energy transduction mechanism, such as electromagnetic generation, will also decrease the motion. This combined damping, mechanical (b_m), and electrical (b_e), can be assumed proportional to the velocity of motion. When the forcing function consists of a sinusoidal waveform, the relative motion for a linear system presents a sharp peak at the resonant frequency of the structure, as shown in Fig. 3.

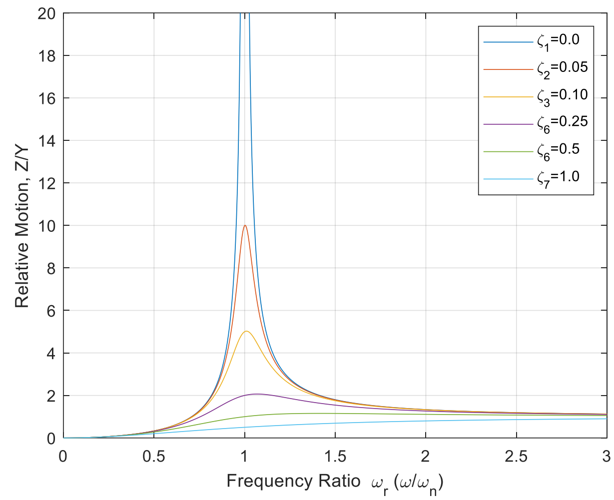

Fig. 3. Relative motion with varying frequency ratios and damping ratios.

When the flexible element has a nonlinear behavior, the resonant peak from Fig. 3 bends to the side and displays a jump phenomenon. This is observed in the results presented in the next section. This nonlinear effect can be described by the representation of the energy-storing element relationship from the force-displacement plot. A linear spring is represented as the term $k\,x$ in (1). The force representation in (1) for springs with nonlinear behavior is $k_1 x + k_3 x^3$. The equation of motion that models this nonlinear spring behavior is known as Duffing's equation.

IV. Results

A preliminary FFT analysis utilizing an ADXL335 accelerometer and Waveforms Digilent software was developed to determine the natural resonant frequency of the structure, found as 39 Hz and presented in Fig. 4. A matching resistance of 2.2 Ω was used to complete the circuit. Power delivered to the load P_L was calculated by measuring the induced voltage V, the coil resistance R_i and the load resistance R_L by

$$P_L = V^2/\,(R_i + R_L)^2\, R_L \qquad (2)$$

The generator was tested on a vibration shaker, SmartShaker K2007E01, with piezoelectric accelerometers, at multiple frequencies. Sinusoidal waveforms were tested between 20 and 100 Hz. Voltage was measured, and power delivered to the load was calculated and presented in Fig. 5. Frequency was slowly incremented near the vicinity of 39 Hz until an abrupt jump at 40 Hz was observed and recorded. It is interesting to note that a second peak was observed in the vicinity of 69 Hz. Fig. 6 presents a sample of the induced voltage output at 39 Hz.

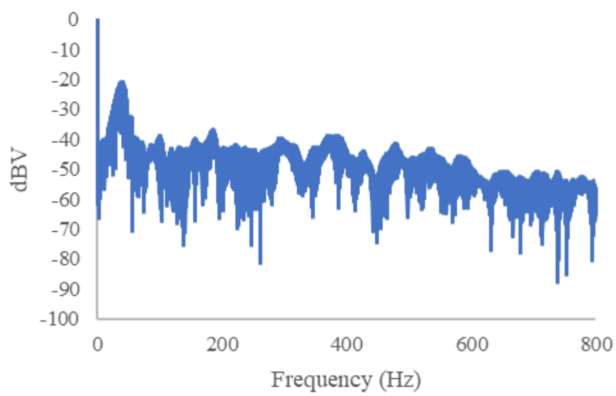

Fig. 4. FFT analysis

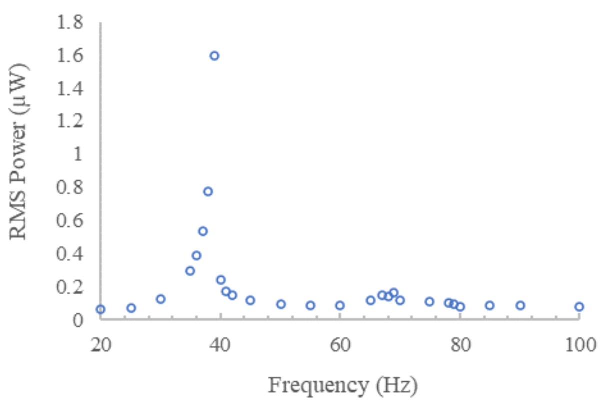

Fig. 5. Measured power output showing nonlinear behavior.

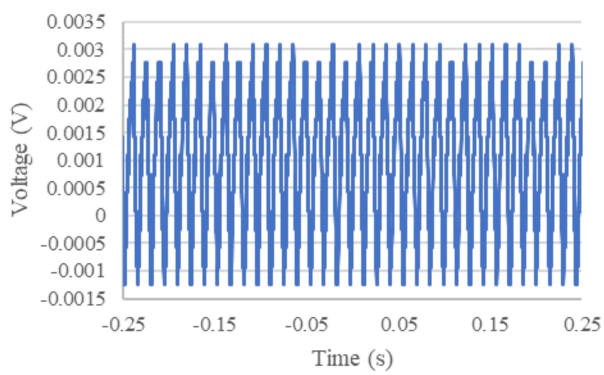

Fig. 6. Induced voltage

V. Conclusion

An experimental evaluation of a flexible hinges generator with linear topology using additive manufacturing was performed to study the nonlinear properties of a thermoplastic material. Nonlinear behavior consistent with a hardening spring was observed at the main resonant frequency of 39 Hz while observing a second peak near 69 Hz. The preliminary design used a small wire-wound coil to evaluate the nonlinear dynamics at different frequencies. Produced power can be increased by optimizing the geometry of the permanent magnets and coils (more windings).

Further work is needed to establish the parameters that promote the second peak, as well as to study how other thermoplastic materials behave under nonlinear conditions.

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