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Development of a Pendulum-based Device to Harvest Energy from Large Low-Frequency Oscillations

Gairik P. Banerjee, Kefu Liu*
Department of Mechanical and Mechatronics Engineering, Lakehead University, Thunder Bay, Canada
*kliu@lakeheadu.ca

ABSTRACT

In this study, a nonlinear energy harvesting system is developed using a pendulum with dual spiral torsional springs and a Halbach magnet array. A pendulum under large oscillation exhibits softening stiffness, a desirable feature for wi`dening the low-frequency bandwidth. Normally, a motion limiter restricts the pendulum's motion range. Mechanical springs such as coil springs prevent hard contact. However, most mechanical springs behave like a hardening spring under large deformation. As a result, the overall stiffness of the pendulum plus the spring limiter becomes hardening. Hence, this study develops a near-linear (weak softening) spring as an angular oscillation limiter to enhance the performance of an electromagnetic energy harvester (EMEH) consisting of a Halbach array and a coil. Two spiral torsional springs are made of PLA using a 3D printer. A disc-spring interaction setup measures the spring force as a function of angular displacement. Curve fitting establishes a polynomial model for the restoring forces of the torsional springs. The springs (asymmetric characteristic) exhibit weak softening and weak hardening characteristics when negative and positive torques are applied, respectively. Thus, a dual spring system is employed in an opposite configuration, ensuring only the weak softening characteristic of the springs is utilized. A copper coil near the Halbach array harvests energy through electromagnetic induction. The study explores the Halbach array's configuration effect on magnetic flux strength in a curved arrangement, highlighting advantages for enhancing energy harvesting efficiency. Equations of motion for the pendulum system are derived, and voltage-time characteristics are measured experimentally. Results demonstrate that a peak open-loop voltage of 0.68 V is achieved in the configuration without spiral torsional springs. The configuration including the springs achieves 1.06 V. A third experimental setup, where both springs are fixed, results in a combined stiffness increase, achieving 3.04 V. For the three different experiments, data was collected using a vibrometer, and FFT analysis with MATLAB found the system's natural frequencies: the no spring system (0.68 V output) had a natural frequency of 1.46 Hz, the alternating dual springs system (1.06 V output) had 1.70 Hz, and the dual springs system (3.04 V output) had 1.95 Hz. This study showcases integrating nonlinear spring dynamics and advanced magnetic configurations as a promising approach for low-power energy harvesting applications.