30th International Conference
ENGINEERING MECHANICS 2024
Milovy, Czech Republic, May 14 – 16, 2024

DEVELOPMENT AND VERIFICATION OF NOVEL DUAL PLUNGER HYBRID KINETIC ENERGY HARVESTER

Sosna P.*, Hadaš Z.**

Abstract: *This paper presents the development and verification of a novel dual plunger hybrid kinetic energy harvester, which combines piezoelectric and electromagnetic conversion principles to effectively generate electricity from ambient mechanical motion and vibrations. This device utilizes two cantilevered steel plungers forming a parallel mechanism which makes non-arc oscillations, therefore maximizing energy harvesting efficiency. A single degree of freedom model is initially proposed for description, which is later extended to incorporate nonlinear effects with magnets. The paper discusses the optimization of resistance parameters, preliminary experimental measurements on the adhesive type and thickness for piezoelectric patches, as well as the measurement of the damping factor. Additionally, the verification and validation of the model through frequency sweeps for different input acceleration levels are detailed, along with the refinement of the model based on manufactured samples.*

Keywords: Energy harvesting, resonator, piezoelectrics, electromagnetics, dual plunger design.

1. Introduction

Energy harvesting from ambient vibrations and motion of structures is a rapidly developing subject in recent years due to the possibility to power low-consumption electronic devices and wireless sensor networks in IoT applications. There have been many techniques and methods developed to effectively convert mechanical energy of vibrations into useful electricity. This paper focuses on the development and verification of a novel dual plunger hybrid vibration energy harvester, which combines two common conversion principles: piezoelectric and electromagnetic. Piezoelectric (Yang et al., 2018), electromagnetic (Bradai et al., 2018; Zhu and Beeby, 2013), and electrostatic (Edwards and Gould, 2016) conversion principles have been extensively studied. However, each approach has its limitations and challenges, such as narrow bandwidth, low efficiency, and sensitivity to environmental conditions. The integration of multiple conversion principles offers the potential to overcome these limitations (Ryu et al., 2019) and improve overall energy harvesting performance (Margielewicz et al., 2023).

2. Design of novel dual plunger hybrid energy harvester

Building upon previous designs and techniques, our research aims to enhance energy harvesting efficiency by integrating piezoelectric and electromagnetic conversion principles in a novel dual plunger hybrid energy harvester. By leveraging the advantages of both technologies, we seek to develop a robust and versatile device capable of harvesting energy from a wide range of mechanical sources. Fig. 1 shows the schematic of the developed energy harvester, which consists of an adjustable piezoelectric parallel beam system, electro-magnetic circuit with coil and electrical load for both converters. The two-plunger design also allows for use in printed structures with integrated piezoelectric elements and such harvesting system could be fully integrated for a complex printable energy harvester.

* Ing. Petr Sosna: Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, petr.sosna@vut.cz

** Assoc. Prof. Ing. Zdeněk Hadaš, PhD.: Institute of Automation and Computer Science, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, hadas@fme.vutbr.cz

doi: 10.21495/em2024-286

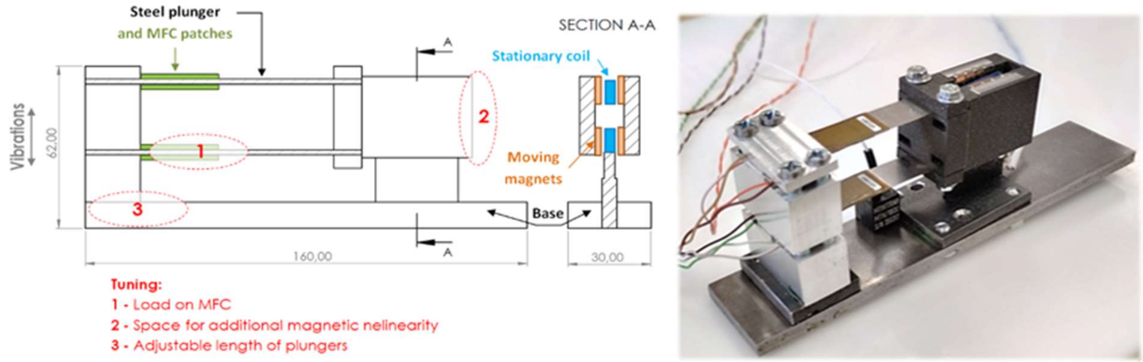

Fig. 1: Schematic of the developed energy harvester and manufactured sample.

The new hybrid tunable vibration energy harvester is approximately 30 mm wide, 160 mm long and has a height of 60 mm. The dual plunger hybrid energy harvester utilizes a parallel mechanism with two steel plungers to ensure non-arc oscillations, thereby maximizing energy harvesting efficiency.

As a piezoelectric converter we chose *macro-fiber composite* (MFC) layers of the company with dimensions of $28 \times 14 \times 0.3\ mm$. The MFC patch consists of rectangular piezo ceramic (PZT) rods sandwiched between layers of adhesive, electrodes and polyimide film. Stretching and compressing the fibers during oscillations creates voltage between the electrodes. The MFC patch is attached from both sides in a bimorph configuration to a steel plunger with dimensions $50 \times 14 \times\ 0.3\ mm$.

The design of the electromagnetic part features a stationary coil and the magnetic circuit, which is a part of the moving mass. This design of the electromagnetic part alone has proven to be efficient in real-world applications, so the idea is to use it as a part of the new hybrid harvester.

3. 1-DOF model of hybrid energy harvesting system

The 1-DOF model for description of the system is based on a discretization procedure described e.g., in (Erturk and Inman, 2011) or (Stanton et al., 2010) which utilizes energy formulation of a continuum system and Hamilton's principle and outputs the basic equations of motion with only four discretized parameters, discretized mass m, beam stiffness k, piezoelectric coupling Θ and piezoelectric capacitance C_p. This simple model is extended to also include viscous damping d_m, base excitation F_{EV}, electromechanical coupling C_{EM}, coil resistance R_c and nonlinear stiffness force F_{NL}. Applying these additions could extend the basic model and it describes the motion of the tip mass of the hybrid vibration energy harvester.

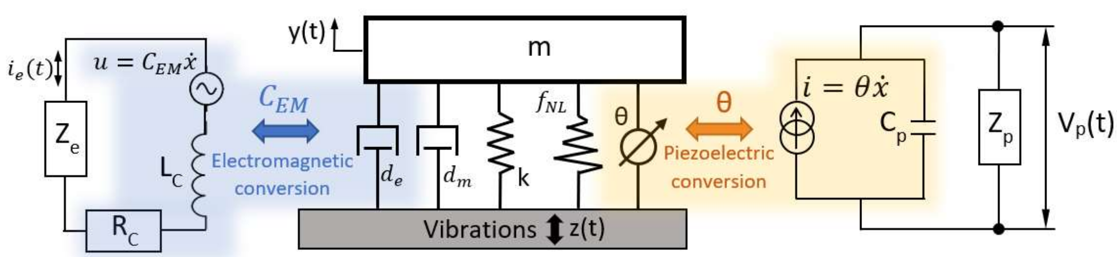

Fig. 2: The 1-DOF model of the proposed hybrid harvester. Mechanical oscillator is coupled to two other subsystems by piezoelectric and electromagnetic couplings.

$$m\ddot{y} + d_m\dot{y} + ky + f_{NL}(y, \dot{y}, t) + C_{EM}i_e + \theta V_p = F_{EV} \quad (1)$$

$$\theta\dot{y} = \dot{V}_p C_p + \frac{V_p}{Z_p} \quad (2)$$

$$C_{EM}\dot{y} = i_e R_C + i_e Z_e, \quad (3)$$

We only consider the simplest form of energy harvesting which is through resistive load Z_e and Z_p, the harvested power can be estimated as$P_e = i_e^2 Z_e$ and $P_p = 2V_p^2/Z_p$. Such that V_p is the total voltage on one bimorph beam considering the upper and lower patches connected in series. The factor of two signifies two bimorphs on the same harvester. Fig. 2 shows the schematic of the model. Such a model was transferred into MATLAB Simulink environment and can be time integrated.

Parameter	m	d_m	k	f_{NL}	C_{EM}	Θ	C_p	Z_e	Z_p	R_c
Value	92	0.326	1 586	0	13.15	0.73	52	1 200	1 450	145
Unit	g	Ns/m	N/m	-	N/A	mN/V	nF	Ω	$k\Omega$	Ω

Tab. 1: Discretized parameters of the energy harvester used for simulations.

4. Experimental verification

4.1. Preliminary experimental investigation on adhesive types

Two methods of fixing the MFC patch to the steel base are CA glue and epoxy resin ("5-minute epoxy") we tested for their effects on mechanical damping. We tested the glues by attaching together two steel plungers with dimensions $L_s \times w_s \times t_s = 80\,mm \times 15\,mm \times 0.2\,mm$. The schematic is in Fig. 3. Two samples are manufactured, their total and plunger thicknesses are measured, and the respective thickness of the adhesive layer is recalculated. The CA glue has average thickness of $t_g = 0.04\,mm$ and epoxy resin $t_e = 0.13\,mm$.

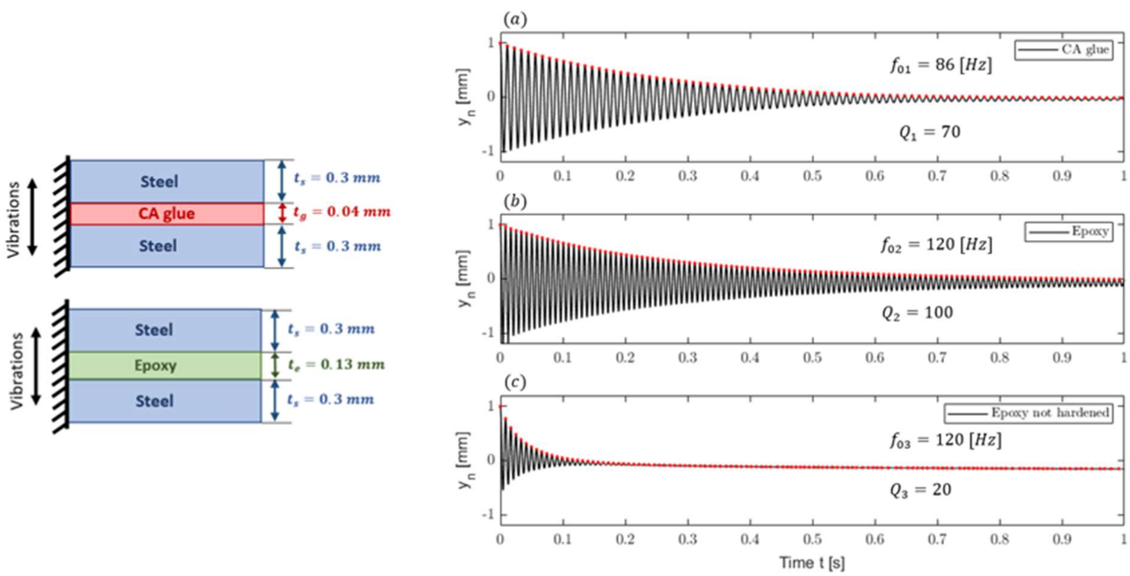

Fig. 3: Schematic of manufactured samples (left) to test the effect of adhesive type on the composite beam's first natural frequency and stiffness and the resulting free oscillations (right).

The quality factor is calculated from free vibrations and natural frequency and quality factor are determined. CA glue creates thinner layers but is quite brittle and breaks for higher strains. The epoxy creates a bond that can withstand higher amplitudes before cracking and that has better damping properties. Although the stiffness of the glue layer is negligible compared to the steel, it pushes the steel layer further away from the neutral axis of oscillations and therefore could affect the overall stiffness. For manufacturing, we decided to use epoxy resin, bearing in mind that Fig. 3c strongly suggests that the epoxy must be fully cured to ensure a stiff bond, in order to not lower the damping.

4.2. Frequency sweeps

The developed model is verified and validated through frequency sweeps for two different input acceleration levels. The manufactured sample was subjected to harmonic base excitation of vibration amplitudes $\ddot{z} = 50\ mg$ and $\ddot{z} = 100\ mg$. National instruments DAQ cards were used to record the voltages on the piezoelectric patches and the induced electromagnetic voltage. A series of harmonic tests were done for a range of frequencies, where the accelerometer was used to correct the input vibration voltage.

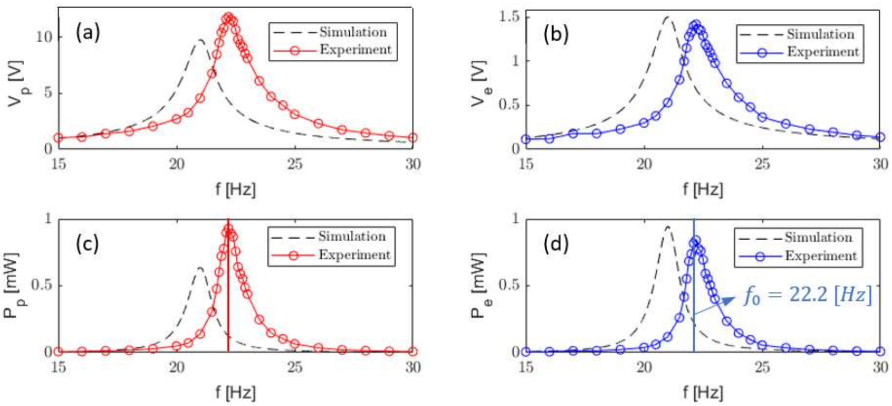

Fig. 4: Comparison of SDOF simulation results and experimental measurement.
Subplot (a) is summed measured piezoelectric voltage, (b) is measured electromagnetic voltage.
Plots (c) and (d) are recalculated harvested power on respective resistive loads Z_p and Z_e.

The biggest conclusion we can deduce is that the resonant frequency doesn't match, it differs by approx. $1\ Hz$. We assume that the reason behind that is the discretized stiffness k determined from can never be exact because of manufacturing variances in dimensions of the steel plunger, type of clamping and uncertainties in general. The glue thickness also affects the resonant frequency. We can see that the model of electromagnetic conversion fits correctly. Piezoelectric coupling, on the other hand, is pessimistic, only approximately 70 % of the generated power is predicted.

5. Conclusions

In conclusion, our paper presents a novel dual plunger hybrid energy harvester that effectively combines piezoelectric and electromagnetic conversion principles to generate electricity from ambient mechanical motion and vibrations. Through experimentation and modeling, we have demonstrated the efficiency and reliability of our device. Moving forward, further optimization and refinement will enhance its potential for practical applications in various fields, contributing to the advancement of renewable energy technologies.

Acknowledgement

The presented research was supported by the project GACR 22-14387J Design and manufacturing of 4D metamaterials based on printed structures with embedded elements of smart materials.

References

Bradai, S., Naifar, S., Viehweger, C. and Kanoun, O. (2018) Electromagnetic Vibration Energy Harvesting for Railway Applications. In: *International Conference on Engineering Vibration (ICoEV 2017)*.

Edwards, R. and Gould, C. (2016) Review on micro-energy harvesting technologies. In: *Proc. 51st International Universities Power Engineering Conference*, UPEC.

Erturk, A., Inman, D. J. (2011) Broadband piezoelectric power generation on high-energy orbits of the bistable Duffing oscillator with electromechanical coupling. *J Sound Vib.,* 330, 2339–2353.

Margielewicz, J., Gąska, D., Litak, G., Wolszczak, P. and Yurchenko, D. (2023) Influence of impulse characteristics on realizing high-energy orbits in hybrid energy harvester. *Energy Convers Manag.,* 277, 116672.

Ryu, H., Yoon, H. J. and Kim, S. W. (2019) Hybrid Energy Harvesters: Toward Sustainable Energy Harvesting. *Advanced Materials,* 31, 1802898.

Stanton, S. C., McGehee, C. C. and Mann, B. P. (2010) Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator. *Physica D,* 239, 640–653.

Yang, Z., Zhou, S., Zu, J. and Inman, D. (2018) High-Performance Piezoelectric Energy Harvesters and Their Applications. *Joule,* 2, 642–697.

Zhu, D. and Beeby, S. P. (2013) A broadband electromagnetic energy harvester with a coupled bistable structure, *Journal of Physics: Conference Series*, vol. 476.