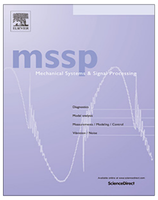
Mechanical Systems and Signal Processing 133 (2019) 106246

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp



Piezoelectric and electromagnetic hybrid energy harvesting with low-frequency vibrations of an aerodynamic profile under the air effect

Fevzi Cakmak Bolat [a],*, Sinan Basaran [b], Selim Sivrioglu [c]

[a] Department of Mechanical Engineering, Bayburt University, Bayburt 69000, Turkey
[b] Department of Mechanical Engineering, Bilecik Seyh Edebali University, Bilecik 11230, Turkey
[c] Department of Mechanical Engineering, Gebze Technical University, Kocaeli 41400, Turkey

ARTICLE INFO

Article history:
Received 30 January 2019
Received in revised form 16 April 2019
Accepted 16 July 2019
Available online 26 July 2019

Keywords:
Hybrid energy harvesting
Aeroelastic structure
Piezoelectric-electromagnetic harvester
Airfoil
Aerodynamic load

ABSTRACT

In this study, a novel hybrid energy harvesting system consisting of a piezoelectric material and an electromagnetic induction device is experimentally inevstigated. Flow-induced vibrations can be considered as an aerodynamics air effect and can be converted to electrical energy. By connecting an airfoil profile to a beam element, vibrations are occurred on the proposed structure by creating an aerodynamic air effect. This aerodynamic air effect is controlled by using an Arduino board with a solenoid valve connected to the air line. A piezoelectric transduction is attached on the beam, and an electromagnetic-Lorentz induction is connected to the airfoil element at the end of this beam. Energy is simultaneously harvested by using electromagnetic induction and piezoelectric transduction with respect to the vibration motion of the beam. Within the scope of the study, the amount of energy obtained using the piezoelectric material and Lorentz actuator by connecting resistors of different sizes are measured with an oscilloscope. The experimental results show that the amount of energy obtained from the proposed structure is at promising levels that can be used to run small electronic units which commonly used in aerospace applications.

1. Introduction

Energy efficiency is an important issue that has been considered in recent years. To improve energy efficiency, energy harvesters are commonly employed as supplementary or main energy sources for small-scale power grid systems. The energy harvesters generate energy by transforming energy from various forms into electricity. The most common method for energy harvesting is to benefit from the flow-induced vibrations. These vibrations are the most common phenomena in aerospace vehicles. Douchun et al reviewed the application of energy harvesters in aerospace vehicles [1]. To increase the amount of harvested energy, hybrid systems where at least two energy harvesting system is simultaneously employed can be used. The hybrid energy harvesting methods are very promising in terms of meeting the energy demand of the applications in which they are used, and they have potential to be an alternative to chemical batteries in the future.

---

* Corresponding author.
E-mail address: fevzibolat@bayburt.edu.tr (F.C. Bolat).

https://doi.org/10.1016/j.ymssp.2019.106246

Nomenclature

L_b	length of the beam
b_b	width of the beam
h_b	thickness of the beam
L_p	length of the PZT
b_p	width of the PZT
h_p	thickness of the PZT
d_{31}	load constant of the PZT
m_a	mass of the airfoil
m_b	mass of the beam
R_l	load resistance
L_a	length of the airfoil
C	width of the chord
C_l	lift coefficient
C_d	drag coefficient
α	angle of attack
R_i	Lorentz self-resistance value

With the development of technology, many small-scale sensors have been developed according to the needs of the society. These sensors generally require low-power energy and can work with wireless energy transfer. In order to obtain the energy requirements for these and similar situations, energy harvesting studies are carried out by utilizing ambient vibrations [2–7]. In the use of these small-scale sensors, the energy source has become necessary to prevent the disadvantages of batteries used as an energy source [8]. Additionally, an energy harvesting system should be scalable in terms of geometrical dimensional to power small electronic components for applications in aerospace structures operated in highly flow-induced vibration areas [9].

In order to increase the amount of energy obtained, hybrid methods continue to be the topic of a variety of the research [e.g., 10–13]. In these studies, piezoelectric material was attached on two magnetostrictive supports and a permanent magnet was placed on the back side of the beam to interact with this beam. For hybrid energy harvesting, Xu et al. applied vibration movement by a shaker and compared the results with theoretical values [14]. In another study, a multi-layer piezoelectric transducer (PZT) cantilever beam element was produced, and a permanent magnet was placed at the end of the cantilever beam. By using these beam vibrations, hybrid energy harvesting was performed from both the PZT and the PCB winding placed against the permanent magnet [15]. Ulusan et al. investigated hybrid energy harvesting by using a combination of piezoelectric, thermoelectric and electromagnetic structures, and showed that the amount of energy harvest obtained from the thermoelectric structure was lowest and from vibration based electromagnetic structure was the highest [16]. Toyabur et al. created a multi-degree of freedom structure and obtained hybrid energy harvest from vibrations at low ambient frequencies. In addition, four pieces of piezoelectric materials were placed on two beams, and with permanent magnets on each end. By placing windings across these permanent magnets, they obtained energy from the ambient vibrations [17]. Shan et al. obtained a novel mathematical model for the hybrid energy harvesting method and compared the experimental results with the analytical results [18]. Cornogolub et al. produced a hybrid energy harvesting structure using dielectric polymer and piezoelectric material. Based on their experimental results, the dielectric polymer material had a positive effect on energy harvesting of the proposed structure. At the same time, they measured energy values by performing different strain loadings on the polymer [19]. Fan et al. produced a hybrid structure containing electromagnetic and piezoelectric materials and also aimed to harvest energy at low frequencies and bi-directional excitations. They obtained an analytical model for hybrid energy harvest and compared the experimental results with simulation results, it was observed that the hybrid structure increased the amount of energy harvested [20]. Zhou et al carried out a theoretical analysis using Monte Carlo simulation considering nonlinear effects in their analysis showed that comparing to linear state, a higher amount of energy can be harvested in nonlinear state [6,21]. Yang et al. produced a layered cantilever structure using magneto-sensitive elastomer, piezoelectric polyvinylidene fluoride (PVDF) and eco-flex materials. And modeled the cantilever using the virtual work method and the Hamilton principle. In their studies, they studied the effect of gap distance between cantilever and PM onvoltage outputs [22].

In this study, an aeroelastic hybrid energy harvesting structure is formed by an airfoil profile assembly on the beam element. A solenoid valve is connected to the air line and controlled by the Arduino board to create an aerodynamic effect on the airfoil. This aerodynamic effect created the lift and drag forces on the airfoil and allowed the beam to move in a certain stroke. By providing this movement, energy is harvested simultaneously mechanically by the piezoelectric material bonded on the beam, and electromagnetically by utilizing the movement of the winding within the permanent magnets. The Lorentz actuator structure with a multi-surface permanent magnet is preferred to obtain more energy harvesting from the electromagnetic structure.

2. Hybrid energy harvesting structure

Aeroelastic hybrid energy harvesting structure is shown in Fig. 1. The energy harvesting is performed depending on the amount of movement on the beam. The movement of the piezoelectric and Lorentz actuator is formed by the aerodynamic effect of an air nozzle. This aerodynamic effect is achieved by controlling a solenoid pneumatic valve connected to the air line using an Arduino board. The general equation of motion of the single-degree aeroelastic structure can be written as follows.

$$(m_b + m_a)\ddot{x} + c\dot{x} + kx = F_x \tag{1}$$

where m_b is the mass of the beam, m_a is the mass of the airfoil, F_x is the force acting on the airfoil, c and k are the damping and stiffness coefficient of the beam element respectively.

Lift and drag forces will occur with the application of aerodynamic load on the airfoil element with a certain angle of attack as given below.

$$F_x = \frac{1}{2}\rho U^2 C L_a [C_l \cos(\alpha) + C_d \sin(\alpha)] \tag{2}$$

where α is the angle of attack (indicated in Fig. 1), C_l is the lift coefficient, C_d is the drag coefficient, and ρ is the air density. The parameters of the hybrid aeroelastic structure are shown in Table 1.

3. Principle of the hybrid energy harvesting

The main components of our proposed hybrid energy harvesting system are electromagnetic induction structure and piezoelectric structure. A rigid rod is used to connect the electromagnetic induction structure with the beam element which is attached to the airfoil that vibrated by the controlled air load.

3.1. Lorentz induction structure

The detailed view of the Lorentz actuator is given in Fig. 1. The actuator used as an induction structure performs electromagnetic energy harvesting by the translational movement of a coil at a certain stroke between the permanent magnets attached to the ferromagnetic yoke. The detailed structure of the Lorentz actuator is given elsewhere [23]. Structural equations for simple vibration of electromagnetic transducer:

$$\begin{bmatrix} F \\ \lambda' \end{bmatrix} = \begin{bmatrix} k_{sp} & Bl \\ Bl & L_c \end{bmatrix} \begin{bmatrix} z \\ I \end{bmatrix} \tag{3}$$

where λ' is the flux linkage, z is the relative displacement of the coil and magnetic field, I is the current in the coil, l is the total length of the coil and k_{sp} is the stiffness coefficient.

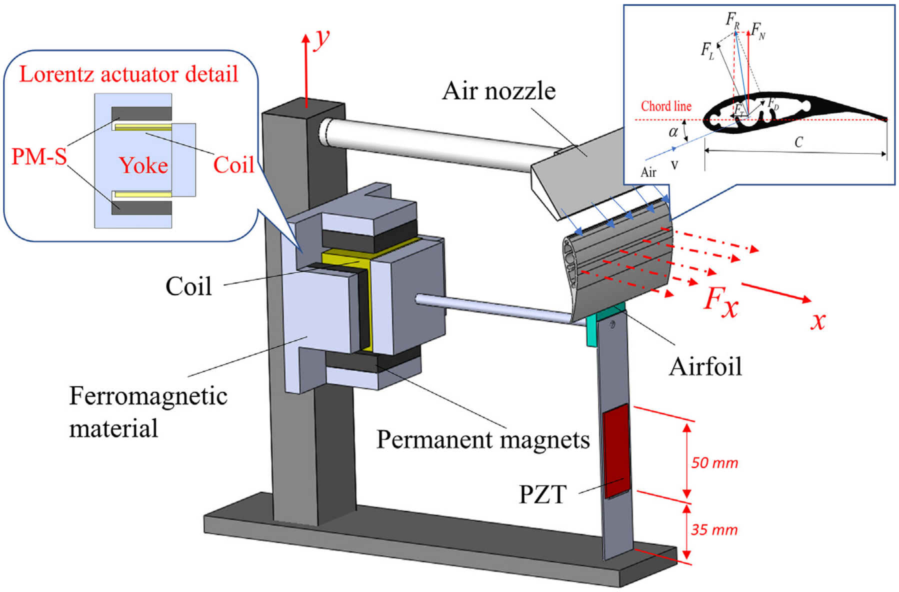


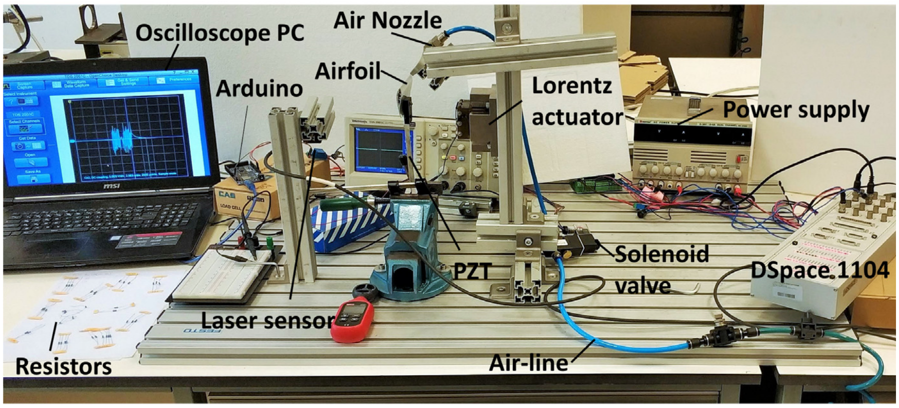
Fig. 1. Hybrid aeroelastic structure.

Table 1
Values of the hybrid system parameter.

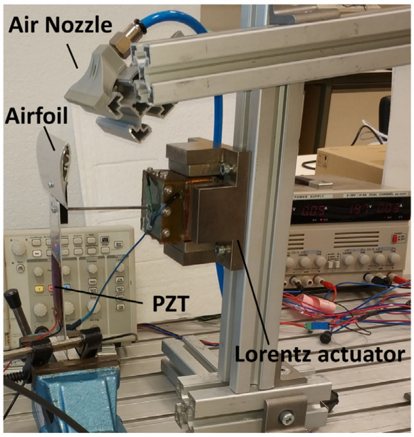
Symbol	Meaning	Value	Unit
L_b	Length of the beam	0.14	m
b_b	Width of the beam	0.04	m
h_b	Thickness of the beam	0.001	m
L_p	Length of the PZT	0.05	m
b_p	Width of the PZT	0.03	m
d_{31}	PZT load constant	$-180 \cdot 10^{-12}$	C/N
h_p	Thickness of the PZT	0.0005	m
L_a	Length of the airfoil	0.1	m
L_c	Lorentz inductance	1.62	mH
C	Width of the Chord	0.05	m
m_b	Mass of the beam	0.023	kg
m_a	Mass of the airfoil	0.038	kg
R_i	Lorentz self-resistance	5.1	Ω

The general equation of motion related to displacement for electromagnetic energy generation can be written as follows for this aeroelastic structure

$$\begin{aligned} &(m_b + m_a)\ddot{x} + c\dot{x} + kx - \tfrac{B_l}{L_a} I = F_x \\ &L_c\dot{I} + (R_i + R_l)I + B_l\dot{x} = 0 \end{aligned} \tag{4}$$



(a) General view



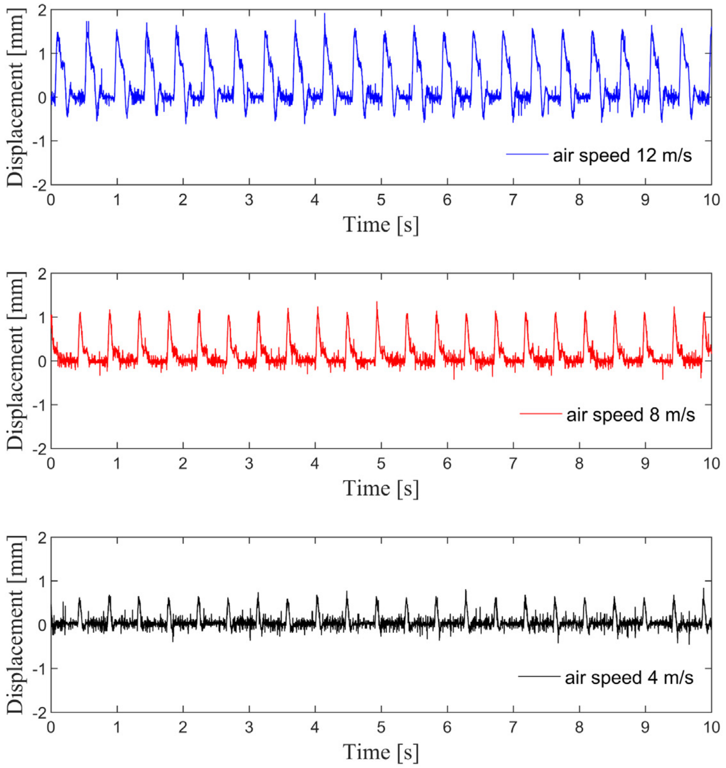
(b) Detailed illustration

Fig. 2. Hybrid aeroelastic energy harvester experimental setup.

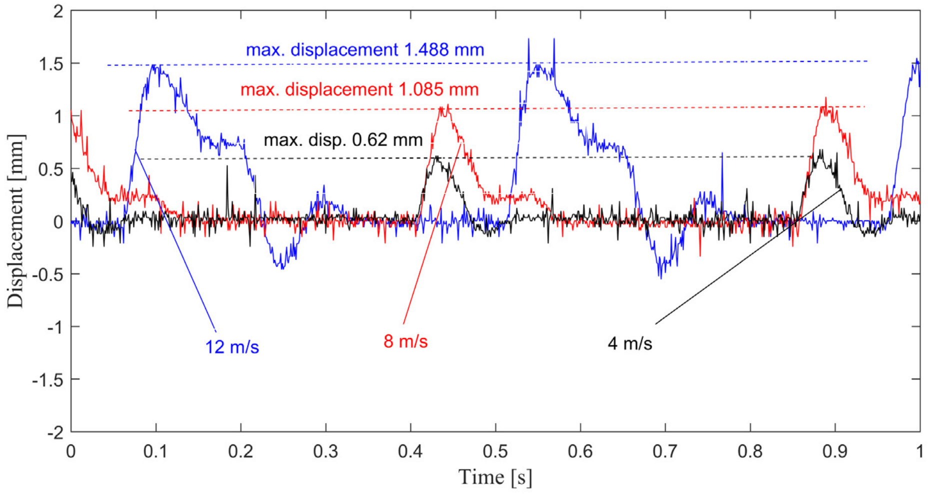
L_c is the Lorentz inductance and B_l electromagnetic coupling. The experimental electromagnetic power generated by the Lorentz induction is written as follows:

$$P_{em} = VI = \frac{V^2}{(R_i + R_l)} \tag{5}$$

where V is the experimental voltage value, and R_i is self-resistance of the electromagnetic structure.



(a) Displacement measured from the laser sensor for 3 air speeds.



(b) Maximum displacement for different air speeds

Fig. 3. Measured displacement according to the different air speed profile.

3.2. Piezoelectric structure

The piezoelectric property is a combination of both electrical and mechanical behavior of the materials. The equation for the spatial electric displacement is given as $D = \varepsilon E$ with permittivity ε. Combining these for all directions of the material into the so-called coupled equations,

$$\begin{aligned} S &= C_E T + d^T E \\ D &= dT + \varepsilon_T E \end{aligned} \tag{6}$$

S is the strain vector, T is the stress vector, E is the electric field vector and D is the electric displacement vector.

The piezoelectric structures are mostly used in energy harvesting systems due to their harvested energy values [24–26]. Deng et al. and Zhiyu et al. investigated how to improve the voltage output obtained from PZTs [27,28]. The energy harvesting obtained from the piezoelectric material depends on the specificity of the material properties and the amount of stress that will occur from mechanical energy. The general equation of motion related to displacement for piezoelectric energy generation can be written as follows for this aeroelastic structure.

$$\begin{aligned} (m_b + m_a)\ddot{x} + c\dot{x} + kx - \tfrac{\theta}{L_a}V = F_x \\ C_{pz}\dot{V} + \tfrac{V}{R} + \theta\dot{x} = 0 \end{aligned} \tag{7}$$

where $x, \dot{x}, \ddot{x}$ respectively displacement, velocity and acceleration of the blade element, θ is the electromechanical coupling, C_{pz} is the capacitance of the piezoelectric layer. The experimental power generated by the piezoelectric transduction is written as follows

$$P_{pt} = VI = \frac{V^2}{R_l} \tag{8}$$

where V is the experimental voltage value, R_l load resistance.

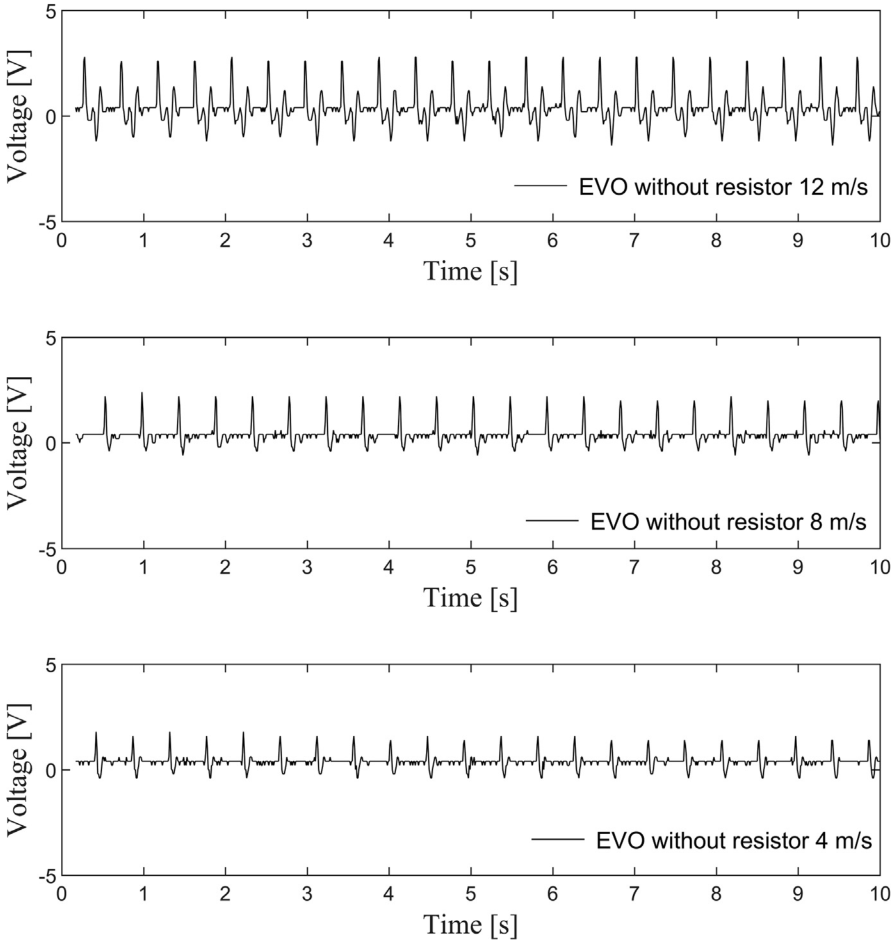


Fig. 4. Effect of different air load on electromagnetic energy harvesting.

4. Experimental results and discussion

The experimental setup is shown in Fig. 2(a) and detailed view is shown in Fig. 2(b). In the experimental setup, PI 876 A.12 DURACT piezoelectric transduction and a custom made electromagnetic-Lorentz actuator are used to energy harvesting from the aeroelastic structure. Power supplies, laser sensor, oscilloscope, Arduino board, and solenoid valve are other equipment used in this study. The instantaneous displacement information on the airfoil by the effect of the air load is measured by a laser sensor and processed on the dSpace 1104 control board.

The rate of displacement which generated by applied air at different speeds on the airfoil profile was measured experimentally. As seen in Fig. 3(a), air speed has a direct effect on the displacement of the amplitude value on the hybrid structure system. Fig. 3(b) shows the effect on the displacement amplitude and time for different air speed profile. According to the Fig. 3(a) maximum translational displacement measured for Lorentz actuator 0.96 mm at air speed 12 m/s, translational displacements are 0.70 and 0.40 mm for air speed 8 m/s and 4 m/s respectively.

The voltage and currents measurements for each speed value were taken experimentally by using different air speeds. Fig. 4 shows the electromagnetic voltage output (EVO) at different air speeds. Fig. 5 shows the piezoelectric voltage output (PVO) at different air speeds. It should be noted that these results captured by without using a resistor element.

Under the aerodynamic effect with a 12 m/s air speed, the electrical resistance load is connected to the piezoelectric material with different gain values. 1 MΩ, 220 KΩ, 68 KΩ, and 22 KΩ resistors are used to measure voltage and current outputs. Measurements taken under electrical load are shown in Fig. 6. Here Fig. 6(a) shows piezoelectric voltage output (PVO) and Fig. 6(b) piezoelectric current output (PCO) values. On the other hand, Fig. 7 shows the voltage and current measurements taken for electromagnetic energy harvesting with the same values of the resistors. Fig. 7(a) shows the electromagnetic voltage output (EVO) and Fig. 7(b) shows the electromagnetic current output (ECO) values.

Table 2 summarizes the amounts of electromagnetic and piezoelectric energy harvested under different electrical resistance loads. Fig. 8 shows the variation of the energy harvested from the piezoelectric structure and electromagnetic structure for four different capacitor values. As it is seen, with increasing load the power harvested from the piezoelectric structure

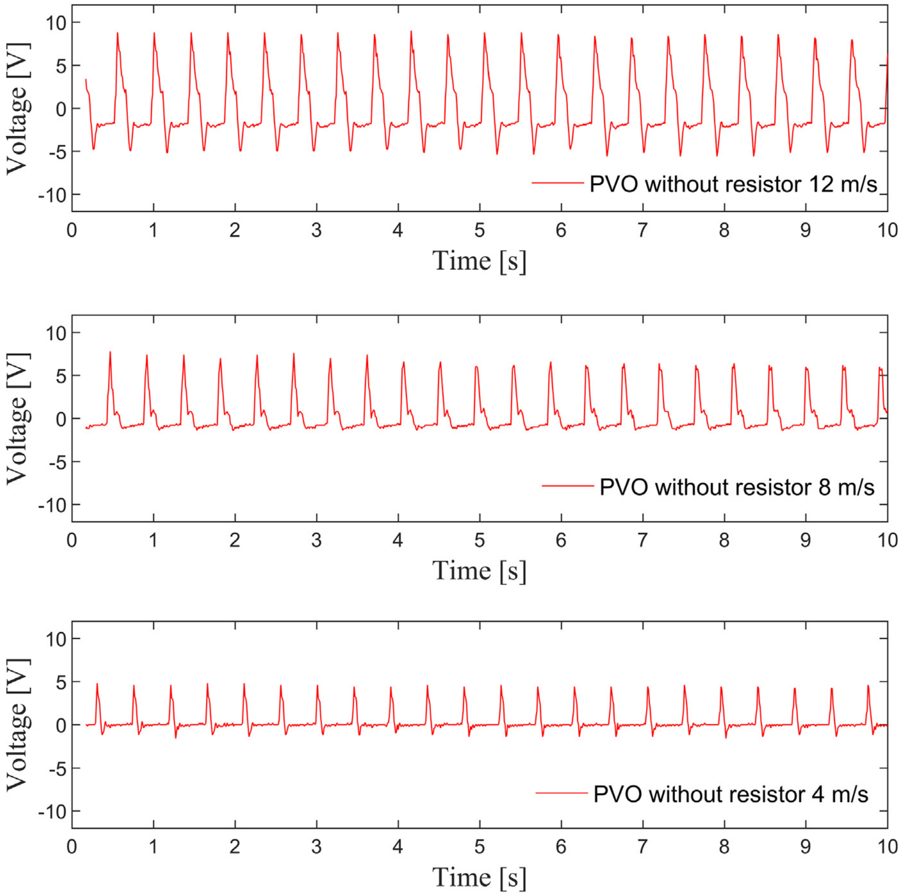
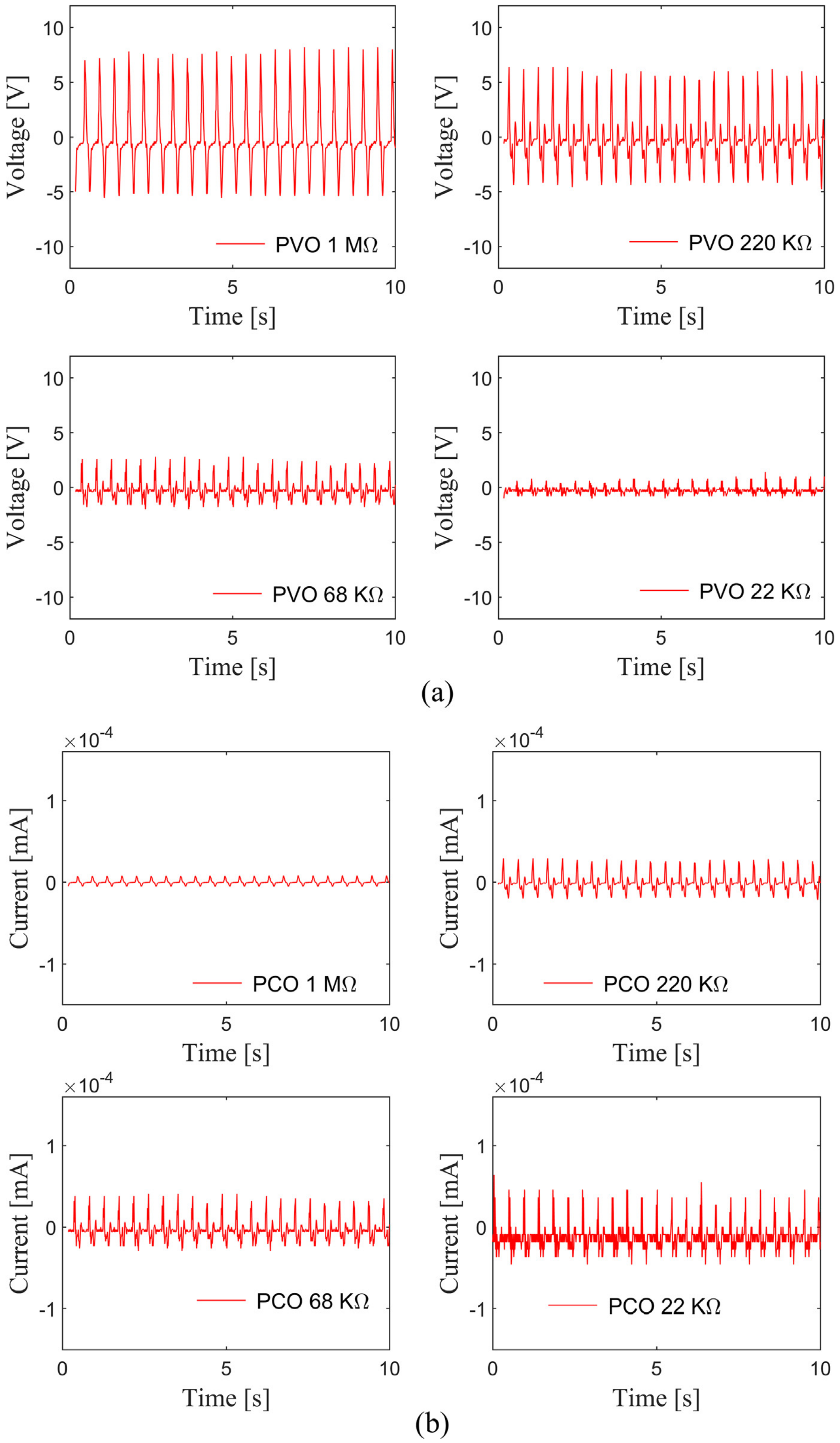


Fig. 5. Effect of different air load on piezoelectric energy harvesting.



(a)

(b)

Fig. 6. Measurement with different resistor values (a) piezoelectric voltage output (b) piezoelectric current output.

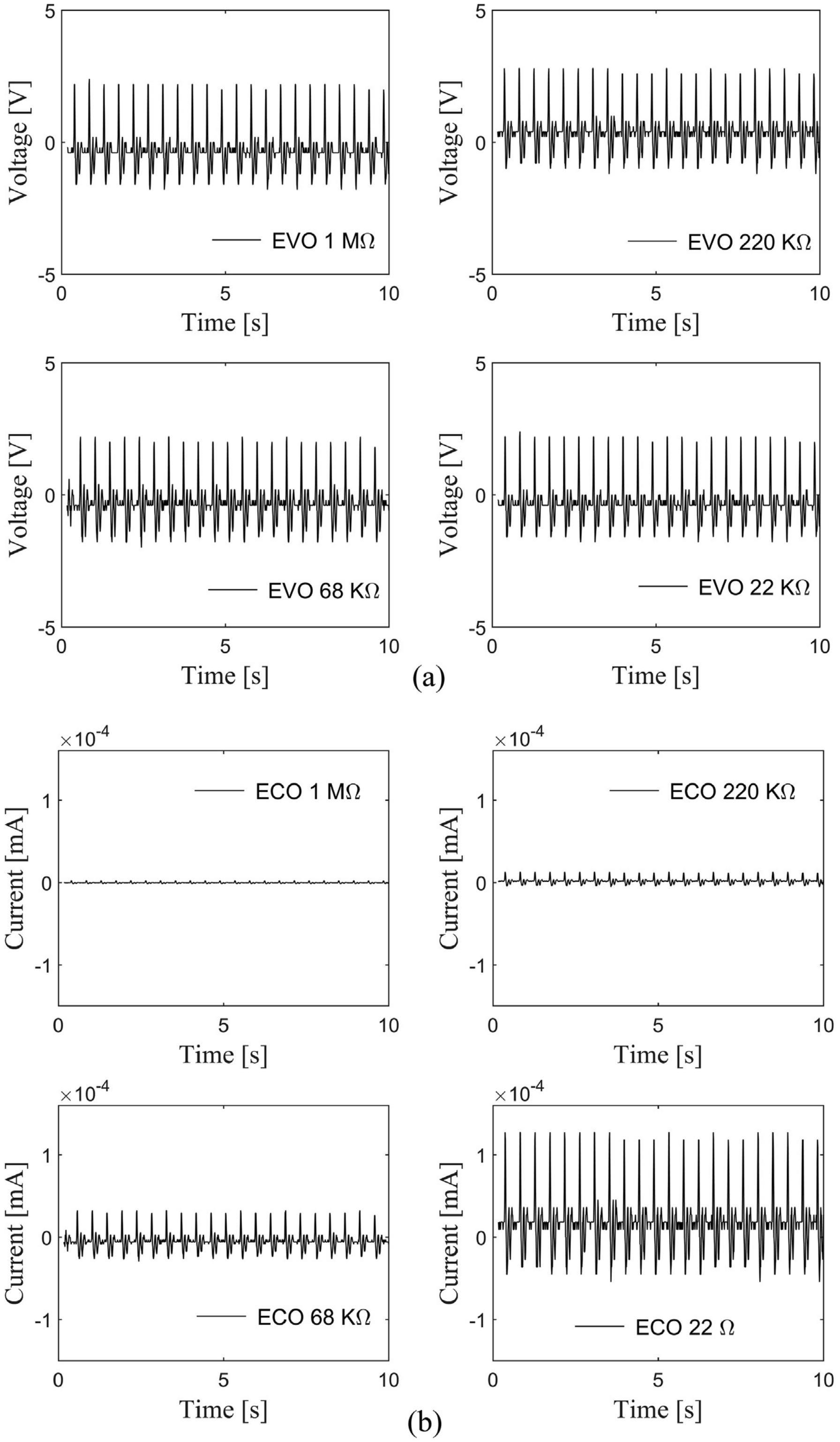


Fig. 7. Measurement with different resistor values (a) electromagnetic voltage output (b) electromagnetic current output.

show a significant increase at certain resistor value, while the amount of generated power exponentially decreases with increasing load on the electromagnetic structure. To improve the power efficiency of the hybrid energy harvester, an optimum electrical resistance load should be chosen.

Finally, low resistance values are examined. As shown in Fig. 9 the electromagnetic energy harvested current values are quite high at low resistance values. Therefore, the electromagnetic energy harvest is greatly increased. The variation of the electromagnetic energy harvest at low resistance values is given in Fig. 10.

5. Verification of the electromagnetic energy harvesting

After the experimental study, the amount of the voltage harvested from Lorentz actuator was confirmed using electromagnetic finite element analysis. The total displacement corresponding different air speeds applied on the airfoil profile is given in Fig. 3. This displacement values are experimentally measured with a laser sensor from the tip of the Lorentz actuator. This displacement gives the total translation motion of the Lorentz actuator coil. To perform a through analysis, a 3D model of Lorentz actuator used with different air load displacement profiles. Fig. 11 shows the model used in the electromagnetic analysis. To calculate the amount of the voltage harvested, a transient analysis is performed with translation motion in z-direction at certain time. The induced voltage from the motion of the coil in the Lorentz actuator model can be calculated with the help of the eddy effect excitations. Fig. 12 shows the behavior of voltage output with respect to the certain motion of the coil with increasing time. The total displacement and elapsed time data taken from the experimental results given in Fig. 3(b). Table 3 summarizes the translation motion of each air load and corresponding maximum induced current via induced voltage value divided by the internal resistance of the coil. As can be seen, the experimental results are in a good agreement with the simulated results.

6. Energy conversion efficiency

6.1. Piezoelectric energy conversion efficiency calculation

There are many different formulations related to efficiency in the literature. In this study, we calculated the efficiency as described in [29,30] for piezoelectric transducer structure.

Table 2
Harvested power from the hybrid setup (Experimental).

Load (kΩ)	Piezoelectric (μW)	Lorentz (μW)
1000	187	9
220	472	60
68	271	192
22	116	302

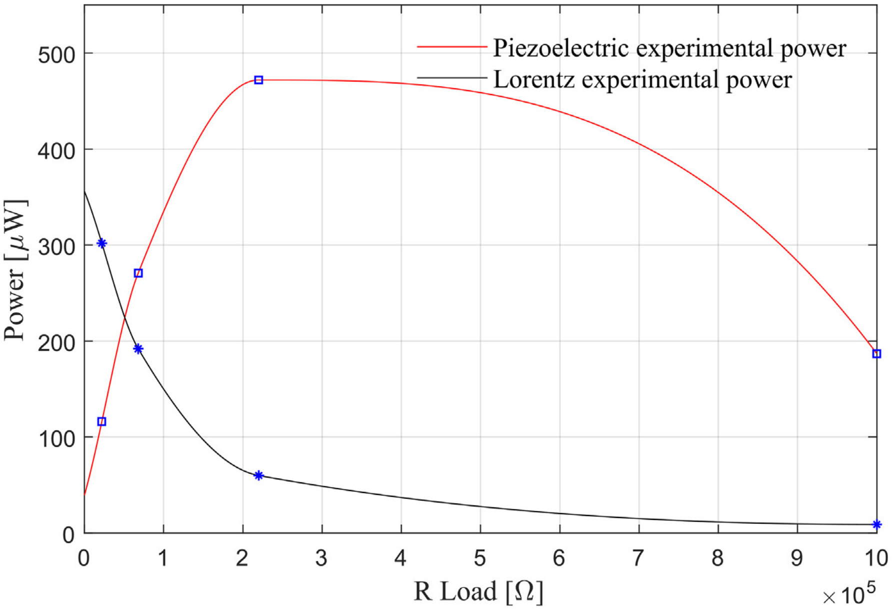


Fig. 8. Variation of piezoelectric and electromagnetic hybrid energy harvesting.

$$eff = \frac{r\frac{k^2}{\zeta}}{(r\Omega + \frac{\pi}{2})^2 + r\frac{k^2}{\zeta}} \tag{9}$$

where r is the normalized resistance, ζ is the damping ratio, Ω is the frequency ratio and k^2 is the electromechanical coupling coefficient. As can be seen in the equation, the most important parameters affecting the energy efficiency are the normalized load, damping ratio and the electromechanical properties of the piezoelectric material used.

Figs. 13 and 14 show the effect of frequency ratio and damping ratio effect on piezoelectric energy conversion efficiency. For all frequency ratio and damping ratio values, a sudden increase with increasing normalized resistance follows a steady decrease after around 1.5 normalised resistance. In addition, conversion efficiency decreases with both increasing frequency and damping ratios.

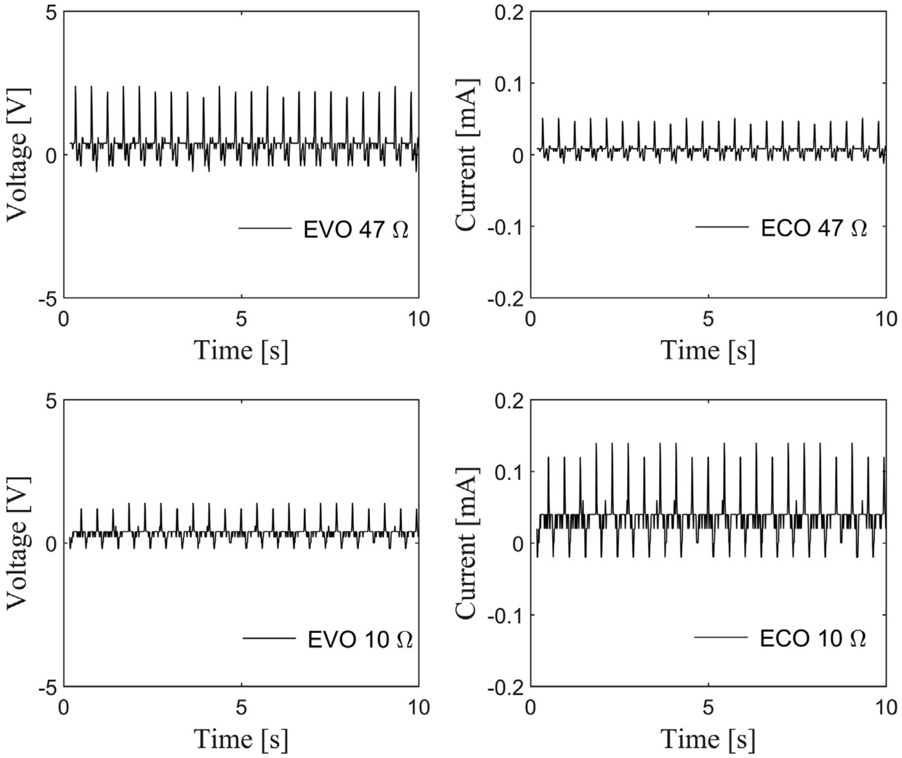


Fig. 9. Electromagnetic current output at low resistance load.

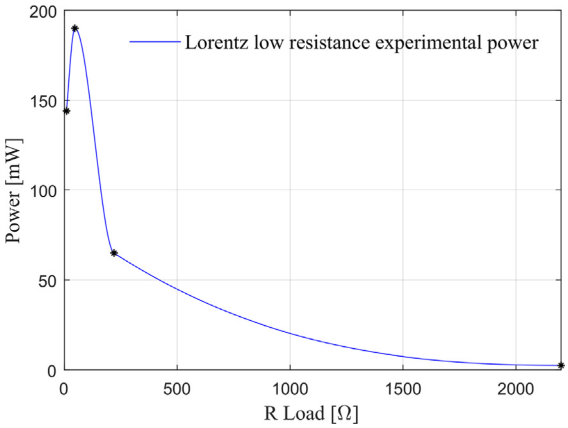


Fig. 10. Variation of electromagnetic harvested power at low resistance load.

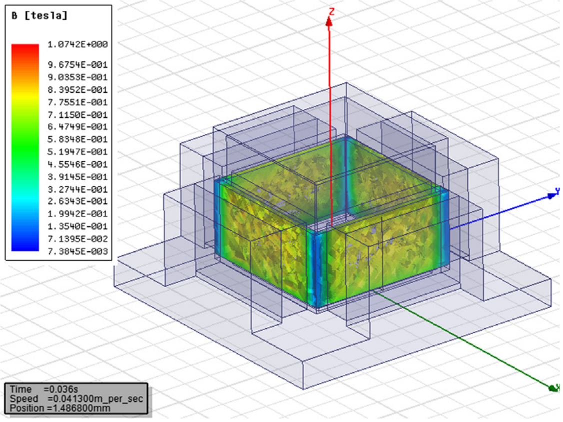


Fig. 11. Lorentz actuator finite element model.

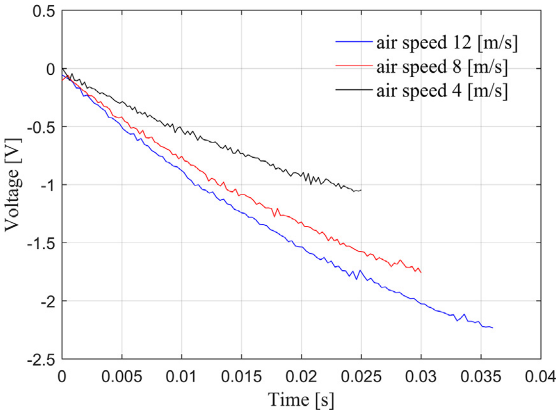


Fig. 12. Variation of induced voltage output.

Table 3
Harvested power from the hybrid setup (Simulation).

	Air speed for 4 m/s	Air speed for 8 m/s	Air speed for 12 m/s
Max. displacement of the coil	0.62 mm	1.085 mm	1.488 mm
Time	0.025 s	0.030 s	0.036 s
Speed of the coil	0.0248 m/s	0.0362 m/s	0.0413 m/s
Max. induced current (Maxwell)	0.208 A	0.345 A	0.438 A
Max. induced current (Experiment)	0.273 A	0.351 A	0.469 A

6.2. Electromagnetic conversion efficiency calculation

The theoretical maximum electromagnetic energy harvesting efficiency is expressed as follows [31]:

$$\eta = \frac{K_{em}^2 \alpha_{opt}}{C_p R_i (1+\alpha_{opt})^2 + K_{em}^2 (1+\alpha_{opt})}$$
$$K_{em}^2 = \left(\left(\frac{R_{opt}}{R_i} \right)^2 - 1 \right) C_p R_i, \qquad \alpha = R_l / R_i \tag{10}$$

where K_{em} is the electromechanic properties of the system and C_p is the damping coefficient. The optimum R_{opt} (47 ohm) is the value at which the maximum energy harvest is obtained. Fig. 15 demonstrates of the electromechanical properties effect on the energy conversion efficiency performance of the electromagnetic structure. Fig. 16 indicate of the damping coefficient effect on the energy conversion efficiency performance. The increase in electromechanics constant and the decrease of damping coefficient yields more energy conversion efficiency.

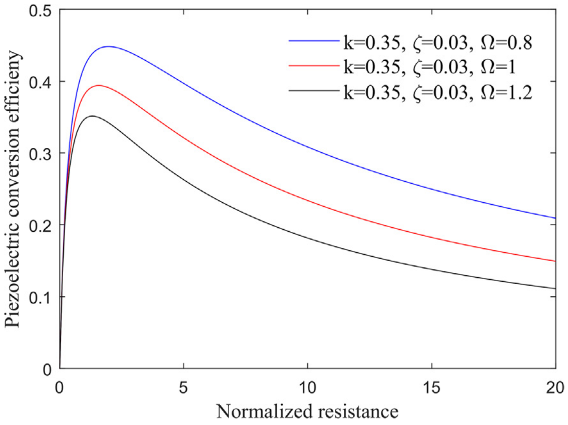


Fig. 13. Frequency ratio effect on piezoelectric energy conversion efficiency.

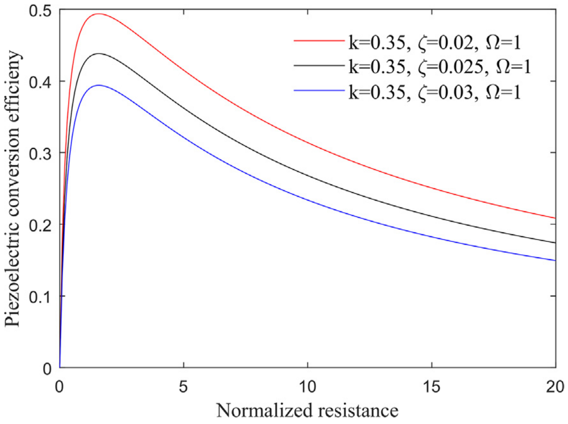


Fig. 14. Damping ratio effect on the piezoelectric energy conversion efficiency.

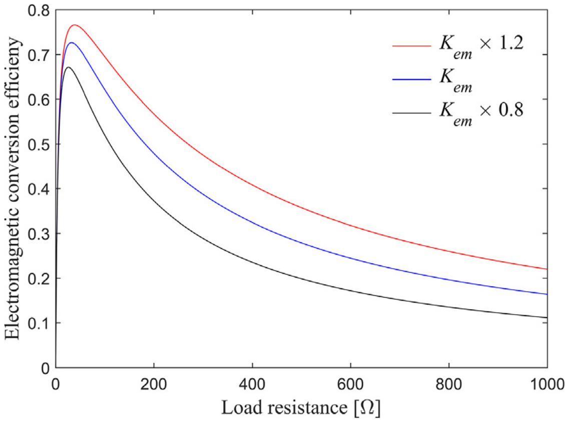


Fig. 15. Electromechanic constant effect on electromagnetic energy conversion efficiency.

7. Conclusions

In this study, aeroelastic hybrid energy harvesting was experimentally investigated using electromagnetic induction and piezoelectric transduction. A custom-made experimental setup that represents the flow-induced vibration was established. The aerodynamic effect was created with an air nozzle on the wing profile, and a movement was achieved to obtain the

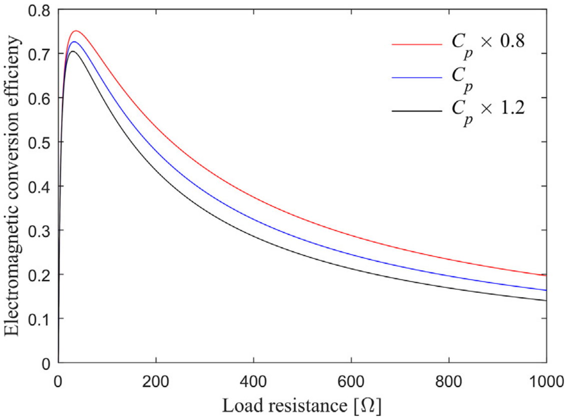


Fig. 16. Damping coefficient effect on the energy conversion efficiency.

hybrid energy harvest. Voltage measurements were taken by applying different air velocities and it was observed that as the air velocity increased, the voltage value was increased. By connecting different resistance loads, the voltage, current and energy values obtained from piezoelectric patch and electromagnetic induction were calculated. High resistance values were higher than the energy harvest obtained from piezoelectric transduction. It was observed that the amount of energy obtained by electromagnetic induction increased at low resistance loads. The finite element analysis also proofs the induced current from Lorentz actuator. On the other hand, energy conversion efficiency calculations were made for both energy harvesting structures and parameters which have an influence on the energy efficiency were examined. As a result, the harvested energy values from the evaluated hybrid structure are at a suitable level for small electronic units that require wireless energy transfer. It has been discovered that it is a wise method to use the energy harvesting method in hybrid studies to meet the energy required by the sensors in aerospace structure which they are generally exposed flow-induced vibration.

References

[1] Daochun Li, Wu Yining, Andrea Da Ronch, Jinwu Xiang, Energy harvesting by means of flow-induced vibrations on aerospace vehicles, Prog. Aerospace Sci. 86 (2016) 28–62, https://doi.org/10.1016/j.paerosci.2016.08.001.

[2] U. Javed, A. Abdelkefi, I. Akhtar, An improved stability characterization for aeroelastic energy harvesting applications, Commun. Nonlinear Sci. Numer. Simul. 36 (2016) 252–265, https://doi.org/10.1016/j.cnsns.2015.12.001.

[3] Carlos De Marqui Jr., A. Erturk, Electroaeroelastic analysis of airfoil-based wind energy harvesting using piezoelectric transduction and electromagnetic induction, J. Intell. Mater. Syst. Struct. 24 (7) (2013) 846–854, https://doi.org/10.1177/1045389X12461073.

[4] A. Bibo, M.F. Daqaq, Investigation of concurrent energy harvesting from ambient vibrations and wind using a single piezoelectric generator, Appl. Phys. Lett. 102 (24) (2013), https://doi.org/10.1063/1.4811408 243904.

[5] L. Yabin, J. Liang, Unified modeling, analysis and comparison of piezoelectric vibration energy harvesters, Mech. Syst. Sig. Process. 123 (2019) 403–425, https://doi.org/10.1016/j.ymssp.2019.01.025.

[6] S.K. Lai, C. Wang, L.H. Zhang, A nonlinear multi-stable piezomagnetoelastic harvester array for low-intensity, low-frequency, and broadband vibrations, Mech. Syst. Sig. Process. 122 (2019) 87–102, https://doi.org/10.1016/j.ymssp.2018.12.020.

[7] J.H. Park, T.W. Lim, S.D. Kim, S.H. Park, Design and experimental verification of flexible plate-type piezoelectric vibrator for energy harvesting system, Int. J. Precis. Eng. Manuf.-Green Technol. 3 (3) (2016) 253–259, https://doi.org/10.1007/s40684-016-0033-3.

[8] James M. Gilbert, Farooq Balouchi, Comparison of energy harvesting systems for wireless sensor networks, Int. J. Autom. Comput. 5 (4) (2008) 334–347, https://doi.org/10.1007/s11633-008-0334-2.

[9] J.A.C. Dias, C. De Marqui Jr, A. Erturk, Hybrid piezoelectric-inductive flow energy harvesting and dimensionless electroaeroelastic analysis for scaling, Appl. Phys. Lett. 102 (4) (2013), https://doi.org/10.1063/1.4789433 044101.

[10] L. Deng, Z. Wen, X. Zhao, Theoretical and experimental studies on piezoelectric-electromagnetic hybrid vibration energy harvester, Microsyst. Technol. 23 (4) (2017) 935–943, https://doi.org/10.1007/s00542-016-2853-z.

[11] M.F. Ab Rahman, S.L. Kok, N.M. Ali, R.A. Hamzah, K.A.A. Aziz, Hybrid vibration energy harvester based on piezoelectric and electromagnetic transduction mechanism, in: Clean Energy and Technology (CEAT) IEEE Conference on, 2013, pp. 243–247.

[12] H. Yu, Q. Yue, J. Zhou, W. Wang, A hybrid indoor ambient light and vibration energy harvester for wireless sensor nodes, Sensors 14 (5) (2014) 8740–8755, https://doi.org/10.3390/s140508740.

[13] M. Rajarathinam, S.F. Ali, Investigation of a hybrid piezo-electromagnetic energy harvester, tm-Technisches Messen 85 (9) (2018) 541–552, https://doi.org/10.1515/teme-2017-0086.

[14] X. Xu, C. Zhang, Q. Han, F. Chu, Hybrid energy harvesting from mechanical vibrations and magnetic field, Appl. Phys. Lett. 113 (1) (2018), https://doi.org/10.1063/1.5038412 013901.

[15] B. Yang, C. Lee, W.L. Kee, S.P. Lim, Hybrid energy harvester based on piezoelectric and electromagnetic mechanisms, J. Micro/Nanolithogr., MEMS, MOEMS 9 (2) (2010), https://doi.org/10.1117/1.3373516, 023002.

[16] H. Uluşan, S. Chamanian, W.M.P.R. Pathirana, Ö. Zorlu, A. Muhtaroğlu, H. Külah, Triple hybrid energy harvesting interface electronics, in: Journal of Physics: Conference Series (2016, Nowember) (Vol. 773, No. 1, p. 012027), IOP Publishing.

[17] R.M. Toyabur, J.W. Kim, J.Y. Park, A hybrid piezoelectric and electromagnetic energy harvester for scavenging low frequency ambient vibrations, in: Journal of Physics: Conference Series (2018, July) (Vol. 1052, No. 1, p. 012051), IOP Publishing.

[18] X. Shan, Z. Xu, R. Song, T. Xie, A new mathematical model for a piezoelectric-electromagnetic hybrid energy harvester, Ferroelectrics 450 (1) (2013) 57–65, https://doi.org/10.1080/00150193.2013.838490.

[19] A. Cornogolub, P.J. Cottinet, L. Petit, Hybrid energy harvesting systems, using piezoelectric elements and dielectric polymers, Smart Mater. Struct. 25 (9) (2016), https://doi.org/10.1088/0964-1726/25/9/095048 095048.

[20] K. Fan, Q. Tan, H. Liu, Y. Zhu, W. Wang, D. Zhang, Hybrid piezoelectric-electromagnetic energy harvester for scavenging energy from low-frequency excitations, Smart Mater. Struct. 27 (2018), https://doi.org/10.1088/1361-665X/aaae92 085001.

[21] X. Zhou, S. Gao, H. Liu, L. Jin, Nonlinear hybrid piezoelectric and electromagnetic energy harvesting driven by colored excitation, Energies 11 (3) (2018) 498, https://doi.org/10.3390/en11030498.

[22] Z. Yang, L. Tang, M. Xie, S. Sun, W. Li, K. Aw, Soft magneto-sensitive elastomer and polyvinylidene fluoride polymer based nonlinear piezoelectric energy harvesting: design, modelling and experiment, Smart Mater. Struct. 28 (1) (2018), https://doi.org/10.1088/1361-665X/aaee4e 015031.

[23] R.M. Schmidt, G. Schitter, A. Rankers, The Design of High Performance Mechatronics-: High-Tech Functionality by Multidisciplinary System Integration, IOS Press, 2014.

[24] R. Usharani, G. Uma, M. Umapathy, Design of high output broadband piezoelectric energy harvester with double tapered cavity beam, Int. J. Precis. Eng. Manuf.-Green Technol. 3 (4) (2016) 343–351, https://doi.org/10.1007/s40684-016-0043-1.

[25] H. Zoka, A. Afsharfard, Double stiffness vibration suppressor and energy harvester: an experimental study, Mech. Syst. Sig. Process. 121 (2019) 1–13, https://doi.org/10.1016/j.ymssp.2018.11.020.

[26] T. Yang, Q. Cao, Dynamics and energy generation of a hybrid energy harvester under colored noise excitations, Mech. Syst. Sig. Process. 121 (2019) 745–766, https://doi.org/10.1016/j.ymssp.2018.12.004.

[27] Licheng Deng et al, High voltage output MEMS vibration energy harvester in d31 Mode With PZT thin film, J. Microelectromech. Syst. 23 (4) (2014) 855–861, https://doi.org/10.1109/JMEMS.2013.2296034.

[28] Zhiyu Wen et al, Improving voltage output with PZT beam array for MEMS-based vibration energy harvester: theory and experiment, Microsyst. Technol. 21 (2) (2015) 331–339, https://doi.org/10.1109/JMEMS.2013.2296034.

[29] Cecilia D. Richards, Michael J. Anderson, David F. Bahr, Robert F. Richards, Efficiency of energy conversion for devices containing a piezoelectric component, J. Micromech. Microeng. 14 (5) (2004) 717, https://doi.org/10.1088/0960-1317/14/5/009.

[30] Yi-Chung Shu, I.C. Lien, Efficiency of energy conversion for a piezoelectric power harvesting system, J. Micromech. Microeng. 16 (11) (2006) 2429, https://doi.org/10.1088/0960-1317/16/11/026.

[31] Wenai Shen, Songye Zhu, Hongping Zhu, Experimental study on using electromagnetic devices on bridge stay cables for simultaneous energy harvesting and vibration damping, Smart Mater. Struct. 25 (6) (2016), https://doi.org/10.1088/0964-1726/25/6/065011 065011.