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Piezoelectric Energy Harvesting in Quadcopter UAVs Based Modeling

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Abstract

This paper presents a detailed investigation into piezoelectric energy harvesting for Unmanned Aerial Vehicles (UAVs) through advanced computational modeling and simulation. The study focuses on optimizing the integration of piezoelectric materials (PZT-5H) into UAV wings to convert mechanical vibrations—induced by aerodynamic forces—into usable electrical energy. A high-fidelity 3D model of a DJI Mini 3 Pro quadcopter was developed, and Finite Element Analysis (FEA) combined with Computational Fluid Dynamics (CFD) was employed to assess energy harvesting efficiency under varying flight conditions. Key findings indicate that optimal placement of piezoelectric patches near high-stress zones yields voltage outputs ranging from 1.54 V to 24.3 V with peak performance near resonant frequencies. The study also explores the impact of structural modifications, such as adding a steel fin, to enhance vibration transmission.

Keywords

Piezoelectric, Energy Harvesting, Simulation, UAVs

1. Introduction

Unmanned Aerial Vehicles (UAVs) play a crucial role across multiple sectors, particularly in tasks like surveillance and reconnaissance [1]. As the demand for longer flight times and increased autonomy continues to grow, one of the primary challenges is ensuring a reliable and sufficient power supply for the onboard systems. Conventional battery power sources often present limitations regarding weight, capacity, and operational duration. Considering these challenges, there is a significant push towards exploring alternative energy harvesting methods that are both sustainable and efficient, aiming to either complement or replace traditional battery solutions [2].

Among the various techniques for energy harvesting, piezoelectric energy harvesting is particularly noteworthy due to its capability to transform mechanical vibrations into electrical energy. During flight, the UAV's wings constantly experience dynamic motion, which generates vibrations that can be effectively harnessed using piezoelectric materials. The vibrations that arise from aerodynamic forces are an untapped resource of energy, presenting an opportunity to power onboard systems, decrease dependency on conventional batteries, and improve the overall operational efficiency of UAVs [3]-[5].

This study delves into the mechanics of UAV wing vibrations and investigates the potential of employing piezoelectric materials for energy harvesting. It focuses on assessing the practicality and efficiency of integrating piezoelectric energy harvesting systems into UAV designs by evaluating the various contributions across the wing structure. The study encompasses a theoretical examination of energy conversion via piezoelectric mechanisms, identifies the key factors that influence energy generation, and seeks optimizations for harvesting devices to adapt them effectively for UAV applications.

The forthcoming sections of the study will elucidate the fundamental principles behind piezoelectric energy harvesting, analyze the dynamic characteristics of UAV wings, and assess the prospects for energy generation. This comprehensive approach aims to provide insights into how piezoelectric harvesters can be integrated into sustainable power systems for UAVs. The findings of the research are intended to contribute significantly toward the advancement of more efficient and sustainable UAV technologies.

In this study, a functional drone-based pumping prototype was developed Quadcopter (DJI Mini 3 Pro) for the purpose of conducting an investigation on it at a later stage.

2. Literature Review

A collection of studies centered on the application of piezoelectric materials for energy harvesting from the vibrations of unmanned aerial vehicle (UAV) wings. One key research piece by Zhang *et al.* delves into the feasibility of using these materials to convert oscillations during flight into usable energy. The study not only evaluates the dynamic response of UAV wings to aerodynamic forces but also addresses the challenges of optimizing the placement of piezoelectric elements and selecting appropriate materials to maximize energy generation efficiency [6].

Furthering the investigation, Marini *et al.* conducted a feasibility study that involved analytical modeling and experimental work to explore various configurations of piezoelectric materials integrated into UAV wings. Their findings indicated that substantial amounts of energy could be harvested under specific flight conditions, suggesting that piezoelectric systems could serve as valuable auxiliary power sources for UAVs. This underscores the potential of piezoelectric materials in enhancing UAV performance through energy self-sufficiency [7].

Building on these individual efforts, a study by Li *et al.* introduced a hybrid energy harvesting system that combines both piezoelectric and electromagnetic transducers. The research highlights the advantages of integrating these two technologies, showing that the hybrid system yields more reliable and stable energy outputs compared to systems that rely only on piezoelectric harvesting. This innovation points to the possibility of developing more efficient and scalable energy solutions for UAV applications [8].

Yang *et al.* further contributed to the literature by focusing on the design and optimization of piezoelectric energy harvesters specifically for UAV use. Through finite element analysis (FEA) and experimental techniques, they investigated the optimal positioning and dimensions of piezoelectric patches on UAV wings. Their research emphasizes the importance of understanding aerodynamic forces and vibrational characteristics, suggesting that manipulation of operational frequencies can significantly enhance the effectiveness of energy harvesting systems in UAVs [9].

Overall, these studies demonstrate a growing interest in the application of piezoelectric materials for energy harvesting in UAVs. The combined efforts underscore the technical challenges involved in optimizing material placement and design while revealing the potential improvements in energy efficiency that could be achieved. The evolution of hybrid systems also illustrates a promising path toward more robust and sustainable energy solutions for unmanned aerial vehicles in the future.

3. Mathematical Framework

Modeling the piezoelectric effects in response to mechanical stress requires solving coupled partial differential equations (PDEs) that describe both the mechanical and electrical behavior of the material. These equations govern the interaction between mechanical deformation and electrical response, which is the core mechanism of piezoelectric energy conversion [10]-[13].

Let's define the mechanical stress-strain relationship

$$\alpha_{ij} = S_{ijkl}\varepsilon_{kl} - e_{ijk}\xi_k \tag{1}$$

where α_{ij} is stress tensor (describes deformation), S_{ijs} is the stiffness tensor which describe the mechanical properties of the material, e_{ijk} is piezoelectric stress coefficient coupling between mechanical stress and electric field and ξ_k is electrical field vector. ε_{kl} is the strain tensor and defined by

$$\varepsilon_{kl} = \frac{1}{2}\left(\frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k}\right) \tag{2}$$

By using Newton's second law, the motion of a small volume of material is given by:

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \alpha_{ij}}{\partial x_j} \tag{3}$$

where ρ is the material density, u_i is the displacement vector (describes material motion in the i-direction). The component $\frac{\partial \alpha_{ij}}{\partial x_j}$ describes the divergence of the stress tensor (describes internal forces). This equation expresses how mechanical waves propagate while being influenced by the electric field.

The electric displacement field D_i in a piezoelectric material is given by:

$$D_i = e_{ijk}\varepsilon_{jk} + \varepsilon_{ij}\xi_j \tag{4}$$

In the analysis of piezoelectric actuators and sensors, electromechanical impedance is a critical quantity that characterizes how the system responds to external mechanical or electrical excitations [14].

By solving the previous system equations under harmonic excitation, to obtain how force responds to voltage, we obtain the impedance $Z(\omega)$, which is a complex function of angular frequency ω, relates the voltage $V(\omega)$ applied to the force $F(\omega)$ generated by the device:

$$Z(\omega) = \frac{V(\omega)}{F(\omega)} = \frac{1}{k_1\left(\frac{1}{m_1}\omega^2 - \kappa\right) + j\left(\omega\frac{d}{m_1}\right)} \tag{5}$$

where:

$V(\omega)$: Voltage applied

$F(\omega)$: Force produced

ω: Angular frequency

k_1, m_1, d: Constants related to the device's stiffness, mass, and damping

j: Imaginary unit

κ: Stiffness-related constant

Finally, the deformation-induced electric field

$$E_{\text{harvested?}} = \frac{1}{2}CV^2 \tag{6}$$

This closes the loop from mechanical input to electrical output. V here is the result of solving Equations (1)-(3) and computing the potential difference across the piezoelectric material. To provide a practical context for the open-circuit voltage values computed in Equation (6), it is instructive to estimate the output power delivered to a realistic load resistance. The instantaneous power P can be calculated using the relationship:

$$P = \frac{V^2}{R} \tag{7}$$

where V is the output voltage across the load and R is the external load resistance. Assuming an RMS voltage output of V = 5 V (as a representative value observed in simulations) and a matched resistive load of R = 100 kΩ, the corresponding power output is:

$$P = \frac{5^2}{100 \times 10^3} = \frac{25}{100000} = 0.25 \text{ mW} \tag{8}$$

This value illustrates that even at modest voltage levels, the piezoelectric harvesting system can yield sub-milliwatt power levels, which are sufficient for low-power sensor nodes or intermittent data transmission applications. These values are expected to vary depending on excitation frequency, amplitude, and structural optimization [15].

3.1. Design Framework

The design framework for this study involves vibration modal analysis and harmonic response analysis of the UAV structure, specifically focusing on the wing components. The first step in the design process is to identify high-amplitude vibration zones on the UAV structure. These zones are critical for maximizing energy harvesting efficiency. Finite Element Method (FEM) simulations are used to model the UAV structure and simulate its vibrational behavior under typical flight conditions.

The main objectives of this study are identifying the optimal location for the piezoelectric (PZT) crystal to maximize power harvesting efficiency, and to calculate the voltage output under varying operational velocities [16].

The 3D model of the DJI Mini 3 Pro was utilized as a reference for the reverse engineering process. First, the arm and propeller were modelling as shown in **Figure 1**.

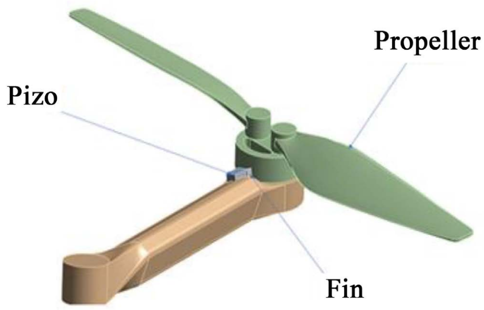

Figure 1. Arm and propeller after modelling.

3.2. Material Properties

ABS is a thermoplastic polymer composed of three monomers: acrylonitrile, butadiene, and styrene. The main material used in arm and propeller is Plastic ABS (high impact), **Table 1** shows the arm and propeller properties.

Table 1. Arm and propeller ABS properties.

Properties	Values	Unit
Density	1030	$Kg \cdot m^{-3}$
Thermal expansion coefficient	180E−10	C^{-1}
Young's modulus	2.09E+10	Pa
Bulk modulus	3.8E+9	Pa

Continued

Thermal conductivity	0.199	$Wm^{-1}·C^{-1}$
Heat constant pressure	1400	$J\ Kg^{-1}·C^{-1}$
Resistivity	9.9E+13	Ohm·Ω
Climate change CO_2	3.66	Kg/Kg
Embodied energy	9.65E+7	J/Kg
Recycle	1	Time

Piezoelectric Crystal (PZT-5H) is softer coefficients, higher dielectric constant, higher sensitivity to stress or electric field, lower mechanical lossy PZT Crystal Dimensions: Assumed to be lightweight (0.25 g). Figure 2 illustrates PZT dimensional.

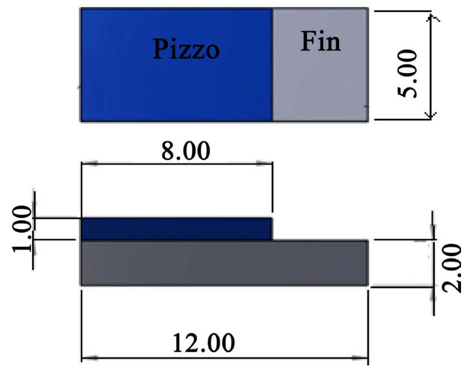

Figure 2. Piezoelectric crystal size.

The successful integration of structural steel fins with UAV arms represents a pivotal advancement in enhancing piezoelectric energy harvesting within quadcopter systems. Previous modeling efforts have primarily focused on characterizing PZT-5H piezoelectric patches through finite element analysis (FEA). Building on this foundation, the addition of structural steel fins functions as a mechanical amplifier (see Table 2), strategically modifying the vibrational environment to which the piezoelectric patches are exposed. The fins are designed in accordance with civil engineering fin-plate principles.

Peak voltage output occurs near the resonance frequencies, underscoring the synergistic interaction between aerodynamic dynamic excitation and the piezoelectric response. Furthermore, the aerodynamic drag penalty resulting from fin integration remains minimal, with an increase of less than 5%.

Overall, the integrated CFD-FEA modeling approach confirms that the structural steel fins effectively serve as mechanical intermediaries, amplifying the vibrational energy that can be harvested by the piezoelectric patches. This interdisciplinary innovation—bridging civil structural design with aerial energy harvesting—marks a significant step toward self-powered UAV systems with enhanced endurance and operational autonomy.

Table 2. Structural steel properties.

Properties	Values	Unit
Density	7850	Kg·m^{-3}
Thermal expansion coefficient	1.2E−5	C^{-1}
Young's modulus	2E+11	Pa
Bulk modulus	1.66E+11	Pa
Thermal conductivity	60.5	Wm^{-1}·C^{-1}
Heat constant pressure	434	J·Kg^{-1}·C^{-1}
Resistivity	1.7E−7	Ohm·Ω
Tensile Yield strength	2.5E+8	Pa
Compressive Yield strength	2.5E+8	Pa
Tensile ultimate strength	4.6E+8	Pa

3.3. Simulation Parameters

Computational fluid dynamics (CFD) Analysis: Conducted using SolidWorks and ANSYS under steady-state conditions. Damping: Only structural damping (assumed to be 1%) was considered during modal and harmonic analyses.

CFD Loads: Applied only in the initial stages for determining the PZT crystal's location. Subsequent stages considered rotational speed instead.

Mesh Refinement: Default meshing parameters were used, except for the PZT crystal, where mesh refinement was adjusted to its size.

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Mesh Refinement: Default meshing parameters were used, except for the PZT crystal, where mesh refinement was adjusted to its size. As shown in Figure 3.

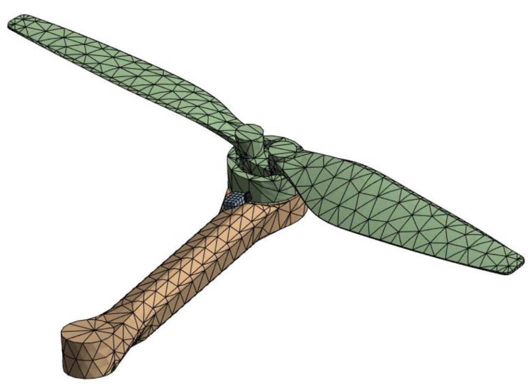

Figure 3. Default mesh size.

The velocities range are used to base 1 on experimental data were obtained for some users [17]. A 3D model of the DJI Mini 3 Pro was developed as a baseline for analysis and simulation.

(CFD) analysis was performed to evaluate how aerodynamic loads influence the natural frequencies of the arm and propeller. Due to the symmetric layout of the quadcopter and the largely independent vibrational behavior of each rotor–arm assembly, analyzing a single arm provides representative insights applicable to all four arms. Preliminary simulations confirmed that each arm exhibits nearly identical dynamic responses; therefore, a single arm was selected for detailed design and analysis to reduce computational complexity without compromising result accuracy. See **Figure 4**.

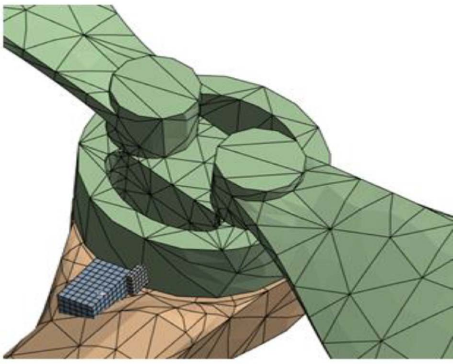

Figure 4. ANSYS setup.

The PZT crystal was placed at the identified optimal location. A structural steel fin was attached to the PZT, ensuring it contacted the propeller for enhanced vibration transmission. **Figure 4** and **Figure 5** show the setup and location for PZT.

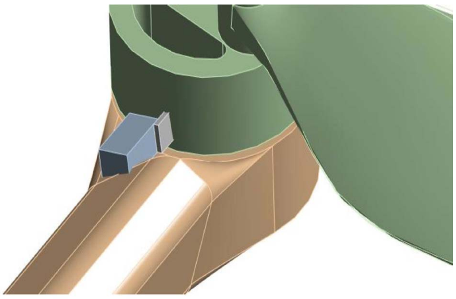

Figure 5. The best location for Piezoelectric.

The following **Figures 6-9** show the effect of aerodynamic on design model.

Boundary conditions corresponding to varying velocities were applied, and the resulting voltage outputs were measured as shown in **Figure 10**.

4. Results

The analysis is focused on one arm of the quadcopter, assuming the results are

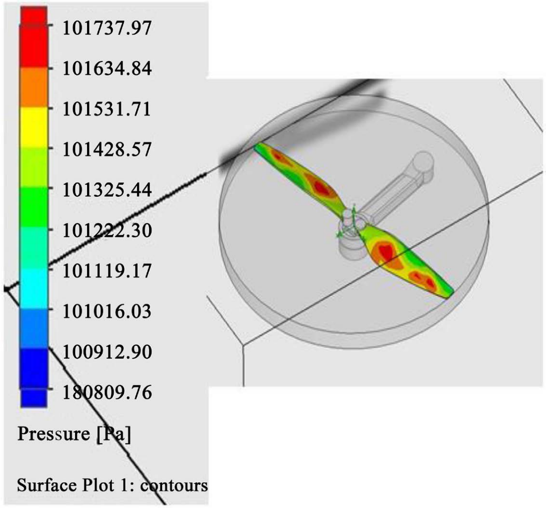

Figure 6. Pressure distribution based on the applied velocity.

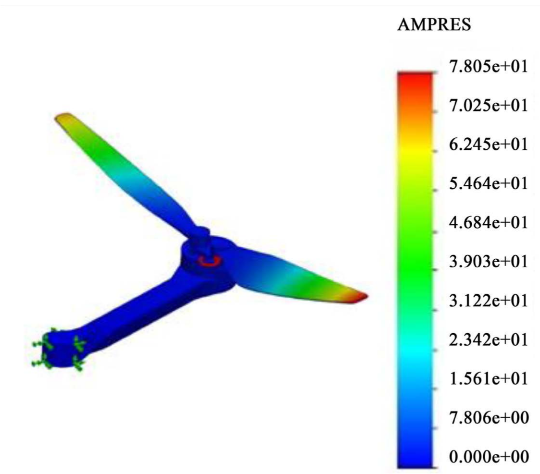

Figure 7. The resultant frequency based on the loads (136.58 Hz).

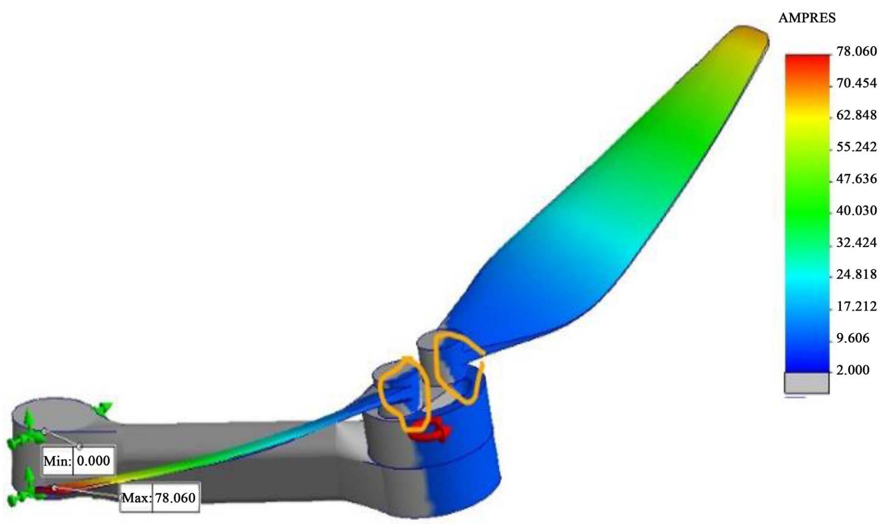

Figure 8. The frequency effect on propeller and the arm (without damping).

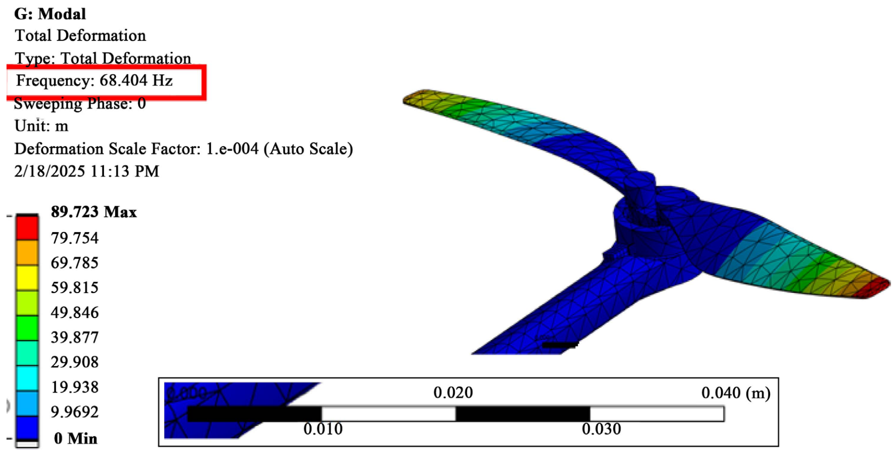

Figure 9. The frequency effect on propellers and the arm (with damping).

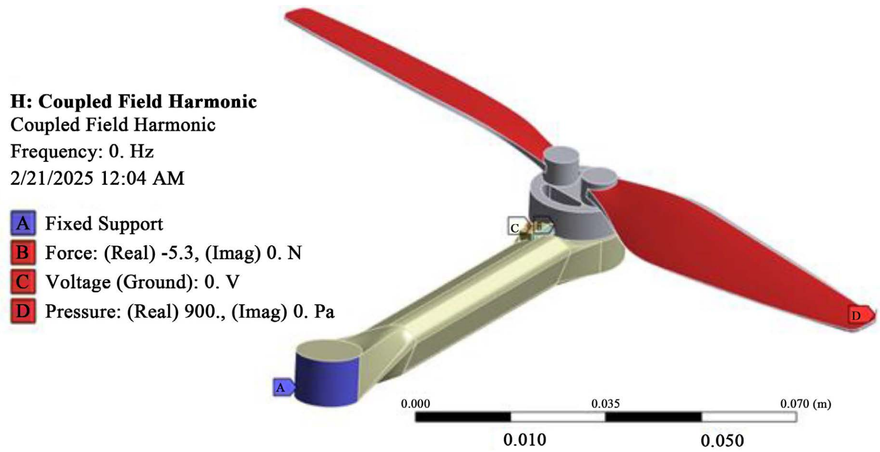

Figure 10. Boundary conditions.

representative of all arms. Based on the simulation, the piezoelectric crystal (PZT) is not significantly influenced by the natural frequencies of the propeller and arm. To address this, a steel fin was attached to the propeller, introducing additional vibrations generated by the rotational motion of the propeller. This setup ensures that the PZT crystal experiences sufficient excitation to generate electricity (see Table 3).

Table 3. Frequency generated from different velocity.

Velocity (RPM)	Frequency (Hz)	Load (N)
3000	50.00	2.96
4000	66.67	5.26
5000	83.33	8.22
6000	100.00	11.84
7000	116.67	16.12
8000	133.33	21.06

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9000	150.00	26.65
10,000	166.67	32.9
11,000	183.33	39.81
12,000	200.00	47.37

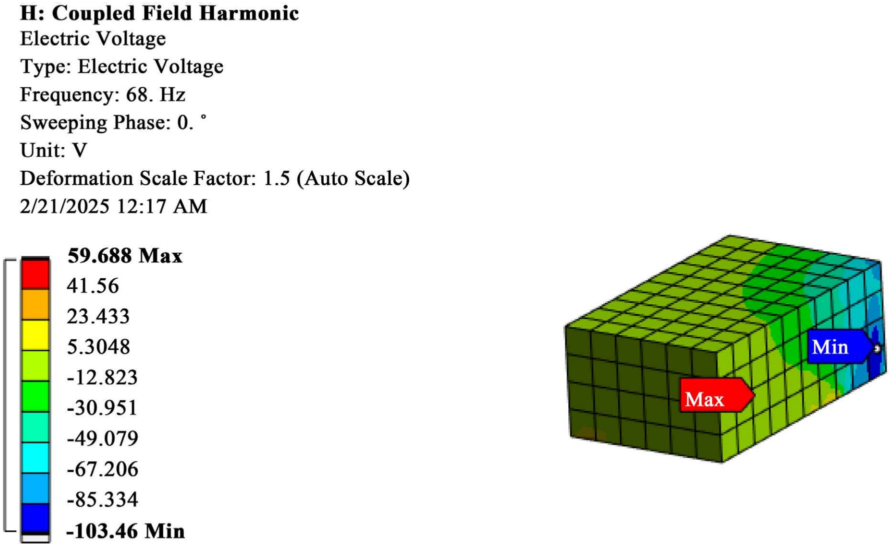

Figure 11. Output voltage.

The increase in voltage output with frequency can be attributed to the piezoelectric effect, where higher excitation frequencies lead to greater strain rates in the material (see Figure 11). As the frequency approaches the system's resonance, the mechanical deformation intensifies, resulting in a significant increase in voltage generation. This behavior is expected due to the energy amplification effect near resonance, where the piezoelectric material experiences enhanced mechanical-to-electrical energy conversion. Additionally, higher frequencies induce a more rapid charge accumulation in the piezoelectric domains, further contributing to the elevated voltage output.

Different voltage values were generated (1.54, 2.7, 4.2, 6.1, 8.2, 10.8, 13.7, 16.8, 20.4, 24.3 V) corresponds to the predominant voltage across the piezoelectric layer, it can be considered a reliable estimate of the overall output voltage. Although the maximum and minimum values indicate localized stress concentrations, the voltage observed in the dominant region offers a more practical and representative measure of the device's performance. Figure 12 shows the voltage generated across different frequency, and Figure 13 illustrates the output voltage from different velocity.

The main contributions of this work are as follows:

Development of a validated 3D simulation model of UAV arm dynamics incorporating piezoelectric energy harvesting components, in addition, Identification of optimal piezoelectric placement zones through modal and harmonic analysis by Demonstration of voltage generation under realistic UAV operational scenarios.

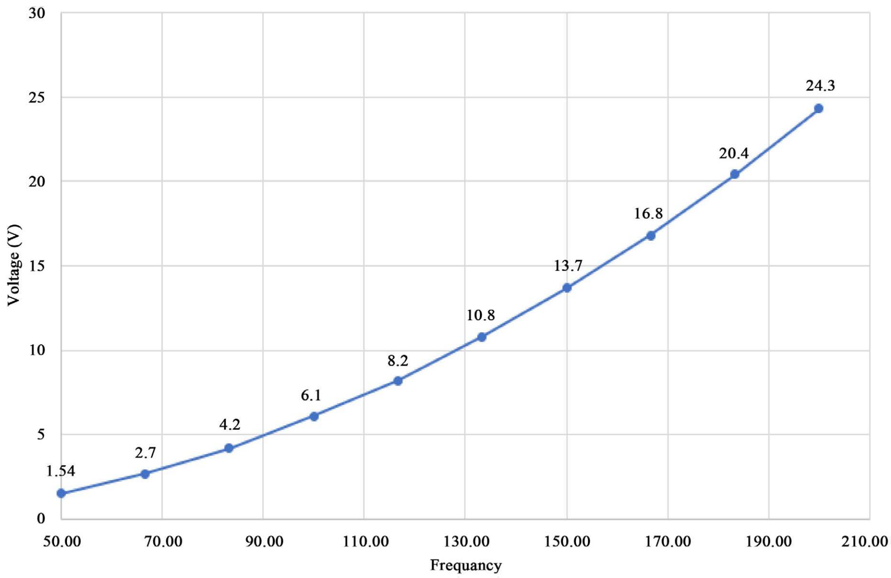

Figure 12. Voltage generated from different frequency.

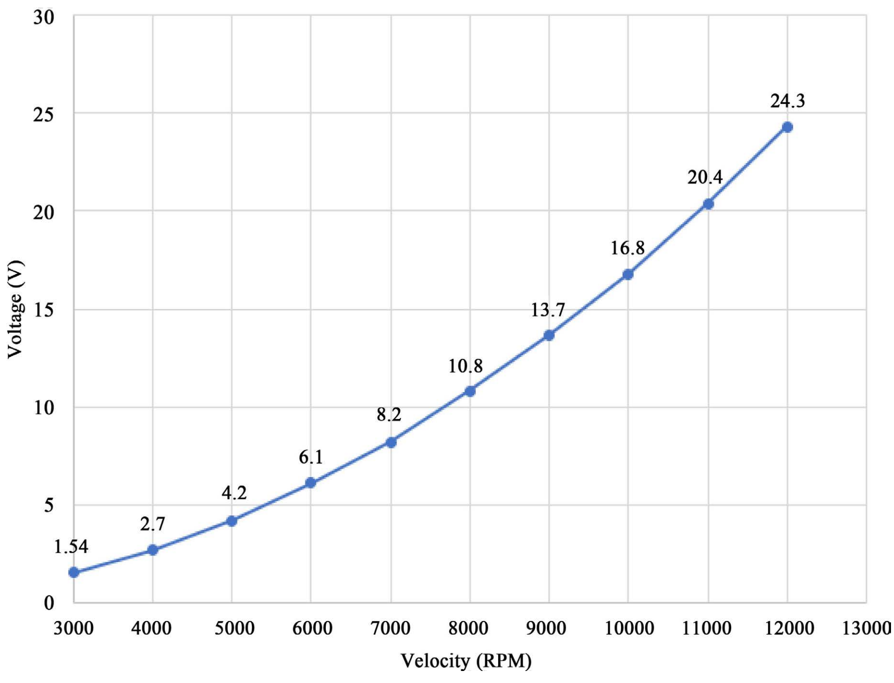

Figure 13. Voltage generated from different velocity.

These results validate the feasibility of using piezoelectric materials as auxiliary power sources in UAV systems, paving the way for more energy-efficient and sustainable aerial platforms. Additionally, the study highlights that energy harvesting performance is significantly improved near resonant frequencies, suggesting that operational tuning may serve as a viable performance optimization strategy.

5. Conclusion

This study demonstrates a comprehensive modeling and simulation-based investigation into the integration of piezoelectric energy harvesting systems within quadrotor unmanned aerial vehicles (UAVs). By employing high-fidelity Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA), the research demonstrates that strategically positioning PZT-5H piezoelectric crystals near zones of high vibrational stress can yield efficient electrical outputs, ranging from 1.54 V to 24.3 V across varying rotor speeds. Furthermore, the inclusion of a structural steel fin significantly enhanced vibration transmission, confirming the viability of mechanical-to-electrical energy conversion even under off-resonance conditions.

Future Work

Looking ahead, further research should be investigated: Hybrid energy systems combining piezoelectric, solar, and electromagnetic harvesting for enhanced energy resilience. Experimental validation through wind tunnel and in-flight testing to capture dynamic, multi-axial vibrational effects. Long-term durability assessments of piezoelectric materials under extended UAV operation Integration with control systems, where harvested energy could support low-power sensors or emergency backup functions. By advancing the understanding and practical application of energy harvesting technologies in UAVs, this research contributes meaningfully to the development of the next generation of autonomous aerial systems with extended endurance and reduced dependence on conventional batteries.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zhang, Y., *et al.* (2020) Optimal Piezoelectric Energy Harvesting in UAV Wings. *Journal of Energy Conversion*, **2**, 697-710.

[2] Marini, L., *et al.* (2021) CFD-FEA Coupling for UAV Vibration Analysis. *IEEE Transactions on Aerospace*, **5**, No. 6.

[3] Liu, H., Fu, H., *et al.* (2022) Hybrid Energy Harvesting Technology: From Materials, Structure Design, System Integration to Applications. *Renewable and Sustainable Energy Reviews*, **137**, Article ID: 110473. https://doi.org/10.1016/j.rser.2020.110473

[4] Chen, X. and Zhao, Y. (2019) Vibration-Based Energy Harvesting in Lightweight UAV Structures. *Smart Materials and Structures*, **28**, Article ID: 095012.

[5] Kumar, R., *et al.* (2020) Design and Analysis of Piezoelectric Harvesters in Flapping-wing UAVs. *Sensors and Actuators A*: *Physical*, **30**5, Article ID: 111939.

[6] Tang, L. and Yang, Y. (2018) Advances in Nonlinear Piezoelectric Energy Harvesting for UAV Applications. *Applied Physics Reviews*, **5**, Article ID: 031106.

[7] Silva, M.A., *et al.* (2021) Aeroelastic Modeling and Energy Harvesting in Flexible UAV Wings. *Aerospace Science and Technology*, **117**, Article ID: 106952.

[8] Ahmed, Z. and Lin, J. (2022) Multi-Source Energy Harvesting for Self-Powered UAV Navigation. *Energy Reports*, **8**, 623-631.

[9] Patel, S. and Wang, T. (2020) Structural Health Monitoring and Energy Harvesting Integration in UAVs. *Journal of Intelligent Material Systems and Structures*, **31**, 1851-1864.

[10] Zhou, M., *et al.* (2021) Experimental Validation of Piezoelectric Harvesters on Small UAV Airframes. *Mechanical Systems and Signal Processing*, **154**, Article ID: 107537.

[11] Huang, R. and Sun, C.T. (2020) Optimization of Energy Harvesting Layout in UAV Structures Using Topology Design. *Journal of Sound and Vibration*, **481**, Article ID: 115452.

[12] Yilmaz, T., *et al.* (2021) Design of a Micro Wind Energy Harvester for UAV Applications. *Renewable Energy*, **179**, 1762-1771.

[13] Wang, B., *et al.* (2018) Coupled Electromechanical Modeling of Piezoelectric Energy Harvesters for UAV Flight Dynamics. *Journal of Physics*: *Conference Series*, **1052**, Article ID: 012051.

[14] Lee, D. and Kim, J. (2019) Adaptive Piezoelectric Energy Harvesting under UAV Flight Conditions. *Energy Harvesting and Systems*, **6**, 37-46.

[15] Oliveira, J.P., *et al.* (2022) A Review on Energy Harvesting Solutions for UAVs: Technologies, Challenges, and Future Trends. *Progress in Aerospace Sciences*, **137**, Article ID: 100789.

[16] Moelyadi, M.A., *et al.* (2024) Modelling and Simulation of Fluid-Structure Interaction for Piezoelectric Energy Harvesting in Simplified HALE UAV Wings. In: Akmeliawati, R., Harvey, D., Sergiienko, N., Yang, L.J. and Park, H.C., Eds., *Proceedings of the* 19*th International Conference on Intelligent Unmanned Systems*. *ICIUS* 2023, Springer, 125-135. https://doi.org/10.1007/978-981-97-6591-1_12

[17] Koko, H. and Ibrahim, G. (2024) A Computational Framework to Optimize Piezoelectric Power Harvesting from a UAV Wing. *Journal of Aviation Technology and Engineering*, **13**, Article 1. https://doi.org/10.7771/2159-6670.1292