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Unravelling quadcopter frame dynamics: A study on vibration analysis and harmonic response

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Abstract: Quadcopters are widely used rotorcraft members of the UAV family. Since they have four motors and four propellers, they are exposed to dynamic loads and vibratory motion. This study presents vibration analysis of a well-known F450 quadcopter frame. Modal analysis was performed to identify the natural frequencies and mode shapes, followed by harmonic response analysis to observe the dynamic behaviour under a periodic force. Harmonic response analysis frequency range covered all critical frequencies obtained by modal analysis. Two additional axes in addition to hovering direction were considered in order to simulate the propeller imbalance case. Numerical solution of analysis was performed by finite element method. Critical frequencies were examined in terms of motor angular velocities and compared with real life motor rpm values. Harmonic response analysis for Y-axis displacements revealed significant peaks near 222 Hz and 410 Hz, corresponding to motor speeds of approximately 12,000–24,000 RPM. For an unbalanced propeller simulated along the X-axis, significant response peaks were observed near 277 Hz and 620 Hz, corresponding to motor speeds of approximately 15,000–360,000 RPM. Similarly, for the Z-axis, peaks were observed near 200 Hz and 420 Hz, also corresponding to motor speeds of approximately 15,000–360,000 RPM. These results indicate potential risks of structural resonance during quadcopter operation, particularly under high throttle or unbalanced loading conditions.

Keywords: modal analysis; quadcopter vibration analysis; harmonic response; structural vibration

1. Introduction

Unmanned aerial vehicles, especially quadcopters, are susceptible to structural vibrations that can compromise flight stability and sensor performance. Analysing the dynamic behaviour of the frame components is critical in enhancing durability and performance. Faraz Ahmad et al. investigate the vibration characteristics of a quadcopter propeller. They design the 3D model of the propeller in Creo 2.0 and analyse it using Ansys. They compare the vibration behaviour of different materials (G-10, aluminium and CFRP) and determine the first 6 natural frequencies and mode shapes by modal analysis. As a result, they find that CFRP material exhibits higher frequency values and is more suitable for heavy loadings[1]. Bhandari et al. deal with modelling and vibration analysis of the quadcopter body frame by changing boundary conditions. Thus, the failure frequency range can be controlled. Simulation results help researchers to design quadcopter frames for heavy-duty applications[2].

Chen et al. study the structural vibration problems of multi-rotor drones in order to solve the structural damage problem of large multi-rotor manned drones. From this study, researchers find that the main vibrations of a large multi-rotor manned drone arm are low-frequency vibrations below 200Hz, and the vibrations mainly produce torsional and bending modes[3]. Kuantama et al. performed vibration analysis using the finite element method. In this analysis, it was investigated that the existence of rotational speeds in each propeller flow field will significantly affect the thrust efficiency, which may cause flight instability or body frame vibration[4]. Lostaunau et al. perform an analysis of the measured vibration of a quadcopter during hovering under varying propeller speeds and track compliance. To collect data, four accelerometers are mounted on the drone's arm. The collected data are analysed using time domain plots and spectrograms obtained from the Gabor transform[5]. Kalay and Özkul[6] investigated the role of vibrations in Unmanned Aerial Vehicles (UAVs), efficiency measurement techniques, and their effects on

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performance; using theoretical and experimental methods such as frequency analysis, mode analysis, and finite element analysis, they understood the vibration dynamics of UAVs and achieved higher performance, longer operational life, and increased precision. Lalem et al.[7] investigated AI and vibration signal processing for anomaly detection in quadcopter systems; they demonstrated the effectiveness of the combination of AI and the Internet of Things (IoT) to improve fault detection and problem diagnosis in UAVs by obtaining 97.78% accuracy with Random Forest and Support Vector Machine (SVM) classifiers by extracting features from accelerometer data. Salem et al.[8] investigated the vibration analysis using multilayer perceptron artificial neural networks (MLP-ANN) to detect rotor imbalance in quadrotor UAVs, trained the MLP-ANN model by extracting time, frequency, and time-frequency domain features from accelerometer data, and detected rotor imbalance with a high accuracy of up to 99.1%.In this study, Geronel et al.[9] investigated the vibration analysis of a load connected to a quadrotor-type UAV with a shape memory alloy (SMA) spring; by analysing the natural frequencies and damping properties of the load, they evaluated the vibration isolation and adaptive damping potential of SMA springs. When the literature is examined, it is easily seen that there are not many studies on quadcopter vibration analysis. In this study, the solid model of the well-known F450 coded (▶**Figure 1**) quadcopter frame is prepared, and ABS material is assigned to the prepared model.

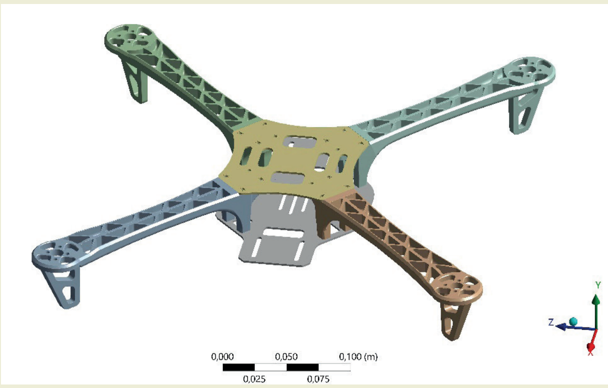

Figure 1. F450 quadcopter frame

The frame has a cross length of 450 mm and an arm length of 210 mm. ABS material has a density of 1050 kg per cubic meter volume, an elastic modulus of 2.4 GPa and a shear modulus of 0.8 GPa. Boundary conditions are determined for the model and vibration and harmonic response analysis are performed. As a result of these analyses, the critical natural frequencies and harmonic responses for the frame are determined. At the end of the study, the mode shapes related to natural frequencies and the critical frequencies obtained as a result of the harmonic response are interpreted. In addition to these, the connection between the harmonic response critical frequencies and the motor speed relations is also mentioned.

2. Materials and Methods

2.1. Modal Analysis

Modal analysis examines the dynamic properties of a structure or system in the frequency domain. Its main purpose is to determine the natural vibration frequencies of the structure and the mode shapes corresponding to these frequencies. This analysis is critical for understanding how a system or a structure will respond to external forces or vibratory motions.

If one of the natural frequencies of a structure matches the frequency of the applied external force, resonance occurs. This can lead to excessive vibrations and structural damage. Modal analysis identifies these potential resonant frequencies, allowing design changes to be made.

$$[M]\ddot{u}(t) + [K]u(t) = 0 \tag{1}$$

Modal analysis solves the mathematical free vibration equation (Equation 1). and solving the eigenvalue problem Equation 2 gives natural frequencies and mode shapes corresponding to natural frequencies[10].

$$([K] - \omega_n^2[M])\phi_n = 0 \tag{2}$$

ANSYS uses the finite element method in order to discretize geometry into smaller elements. This discretization enables a numerical solution of the structural dynamic equations[11].

Modal analysis in ANSYS begins with preparing the geometry of the quadcopter frame. Since the quadcopter frame is symmetric, a single arm of the frame is sufficient enough to perform modal analysis. Single-arm geometry is isolated, and in the modal analysis section, boundary conditions are applied. Fixed support is assigned in ▶**Figure 2** in order to model connection single arm to middle body plates.

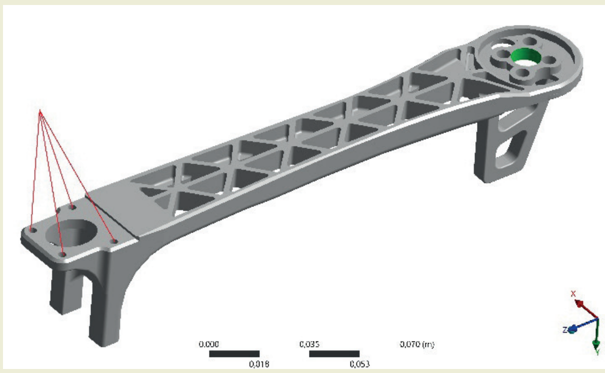

Figure 2. Fixed support locations

The main purpose of modal analysis is to obtain the natural frequencies of single arm. Therefore, external force is not applied. A total of 38135 elements and 68200 nodes are generated at the end of the meshing operation (▶Figure 3). Skewness is selected as a mesh quality indicator. Average value of skewness is obtained as 0.42 and this value is sufficient enough to perform modal analysis.

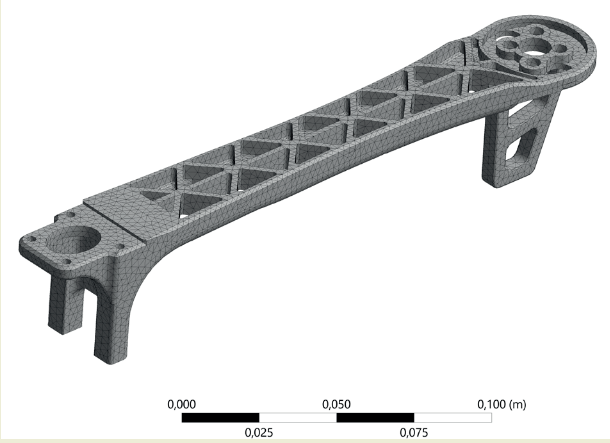

Figure 3. Mesh view

First six natural frequencies in ▶Table 1 and mode shapes corresponding to natural frequencies are obtained.

Table 1. Modal analysis results

Mode	Frequency (Hz)
1	47.018
2	135.06
3	237.77
4	270.09
5	547.44
6	761.69

In this mode, the structure essentially makes an upward-downward bending movement (▶Figure 4). This mode represents the first frequency at which vertical vibrations from engines or external factors during flight can cause resonance. Entering this frequency range, especially during take-off or landing, can lead to vibration growth.

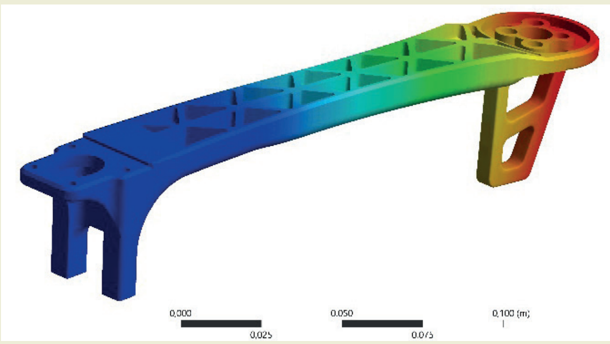

Figure 4. First mode shape

In the second mode, the structure exhibits bending behaviour in the horizontal plane (▶Figure 5). This mode represents the natural frequency that can occur in side-slip manoeuvres. It is important to understand the lateral vibrations of the body.

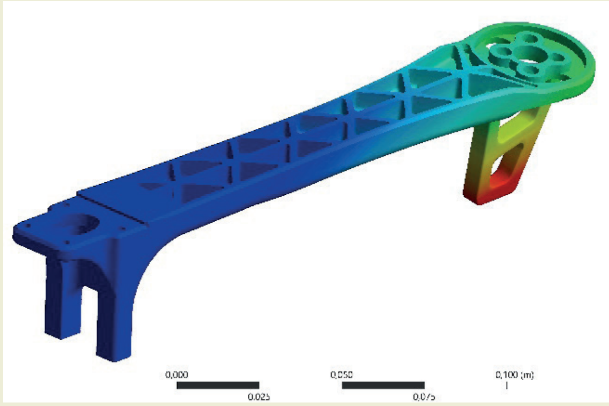

Figure 5. Second mode shape

In this mode the structure exhibits transverse torsional motion (▶Figure 6). Torsional modes can often be triggered by propeller imbalance or engine vibrations. Therefore, engine speeds close to the frequency of the third mode should be avoided.

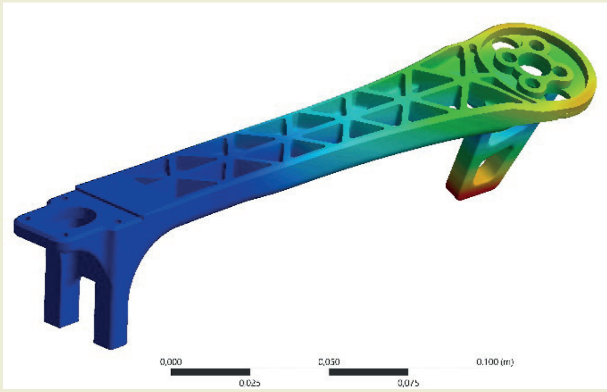

Figure 6. Third mode shape

This mode acts as a combination of the previous bending modes, with a combined bending tendency in different planes (▶Figure 7). When engines operate at high speeds, these modes can also be excited, creating simultaneous vibrations in various axes of the structure.

In the fifth mode, there is more pronounced torsion and asymmetric bending (▶Figure 8).

In this mode, a more complex vibration pattern is observed in the upper part of the structure and in the propeller mounting area (▶Figure 9).

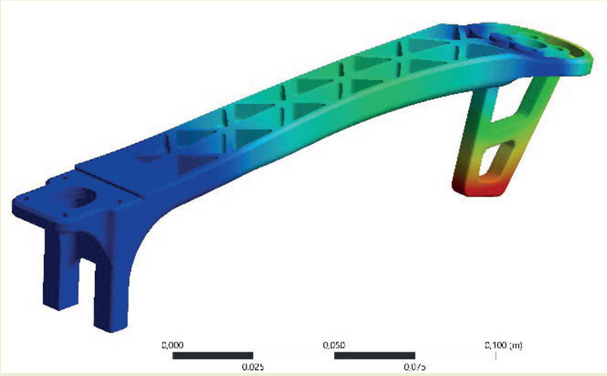

Figure 7. Fourth mode shape

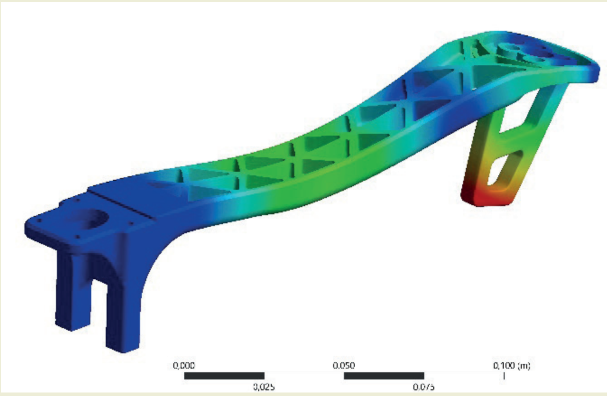

Figure 8. Fifth mode shape

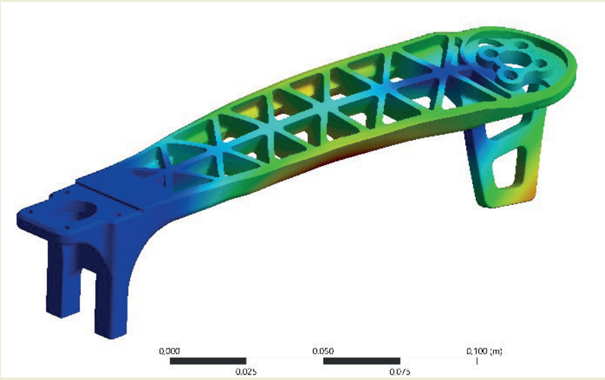

Figure 9. Sixth mode shape

2.2. Harmonic Response Analysis

Harmonic response analysis is a type of analysis used to determine the steady-state dynamic response caused by sinusoidally varying loads applied to a structure or system. This analysis is critical for understanding the structure's forced vibration behaviour at specific frequencies, determining resonant frequencies and amplitudes, and assessing structural integrity. Harmonic response analysis for a forced vibration system is modelled as in Equation 3[12].

$$[M]\ddot{u}(t) + [C]\dot{u}(t) + [K]u(t) = F(t) \tag{3}$$

Force is modelled as a constant amplitude sine wave (Equation 4).

$$F(t) = F_0 \sin(\omega t) \tag{4}$$

System response under constant amplitude harmonic force is given in Equation 5.

$$u(t) = U\sin(\omega t + \phi) \tag{5}$$

The response amplitude is calculated using the expression in Equation 6.

$$|U| = |([K] - \omega^2[M] + i\omega[C])^{-1}F_0| \tag{6}$$

Since the frequencies to which the system responds are important rather than the magnitude of the response given by the system in the harmonic response analysis, a force of 1 N magnitude is applied as in **►Figure 10**. In harmonic response analysis, the 1 N load is a standardization tool to determine the frequency-dependent behaviour of the system against a unit load. This allows the results obtained to be easily scaled to other loading cases and provides a clearer understanding of the dynamic properties of the system, such as resonance, damping, and amplitude. The force applied in this direction will be used to obtain the vibration behaviours that the quadcopter will be exposed to during take-off and landing.

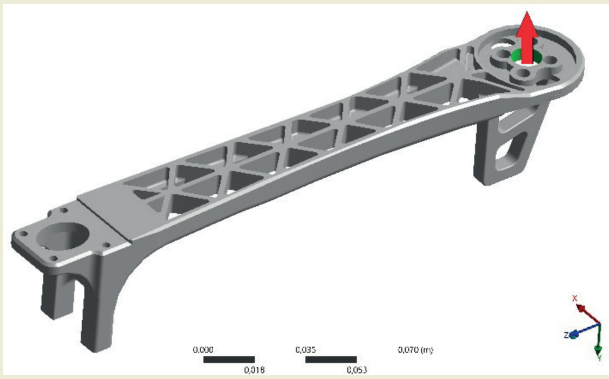

Figure 10. Force applied in the Y axis

The frequency range to be scanned in the harmonic response analysis should be selected to include the frequencies obtained as a result of the modal analysis. Therefore, the frequency range is assigned as between 20 Hz and 800 Hz. In order to determine the vibration response of the propeller due to the inhomogeneous mass distribution caused by production and the unexpected forces that will occur in the propeller imbalance situation, harmonic response analysis is performed again by applying force in the Z direction shown in **►Figure 11**.

In a similar way harmonic response analysis is performed again by applying force in the Z direction shown in ▶Figure 12.

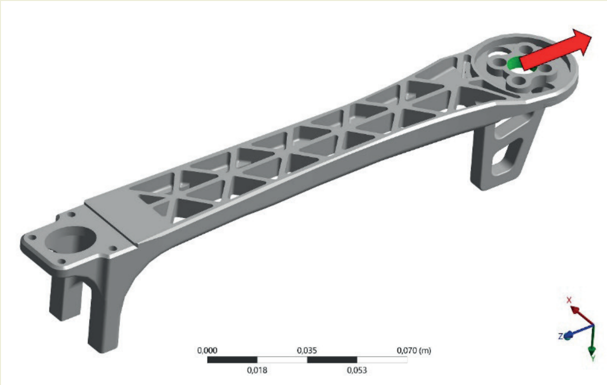

Figure 11. Force applied in the Z axis

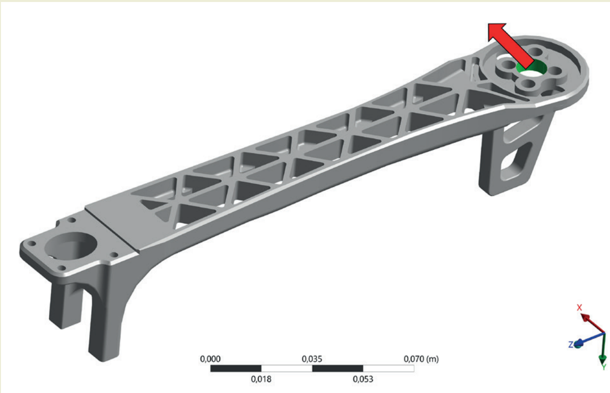

Figure 12. Force applied in the X axis.

3. Results and Discussions

The modal analysis revealed the first six natural frequencies of the isolated F450 arm made of ABS material. These modes include bending, torsional, and coupled vibration shapes, with the first mode appearing at approximately 47 Hz and the sixth mode at 761 Hz. The distribution and symmetry of mode shapes are consistent with cantilever-like boundary conditions and suggest that excitation in certain frequency bands can lead to dynamic amplification. The harmonic response analysis focused on Y-axis displacements, which are critical for vertical stability in flight (▶Figure 13). Significant response peaks were observed at frequencies near 222 Hz and 410 Hz. These correspond to motor speeds of approximately 12,000–24,000 RPM. If the quadcopter operates in this regime, resonance phenomena could amplify structural vibrations, potentially affecting flight control systems or inducing fatigue.

An unbalanced propeller scenario was simulated along the X-axis to investigate lateral vibrational effects. Significant response peaks were observed at frequencies near 277 Hz and 620 Hz (▶Figure 14). These correspond to motor speeds of approximately 15,000–360,000 RPM. This result indicates that lateral vibrations may still influence the camera payload or sensor accuracy during high-speed manoeuvres.

In a similar way, an unbalanced propeller scenario was simulated along the Z-axis to investigate vibrational effects. Significant response peaks were observed at frequencies near 200 Hz and 420 Hz (▶Figure 15). These correspond to motor speeds of approximately 15,000–

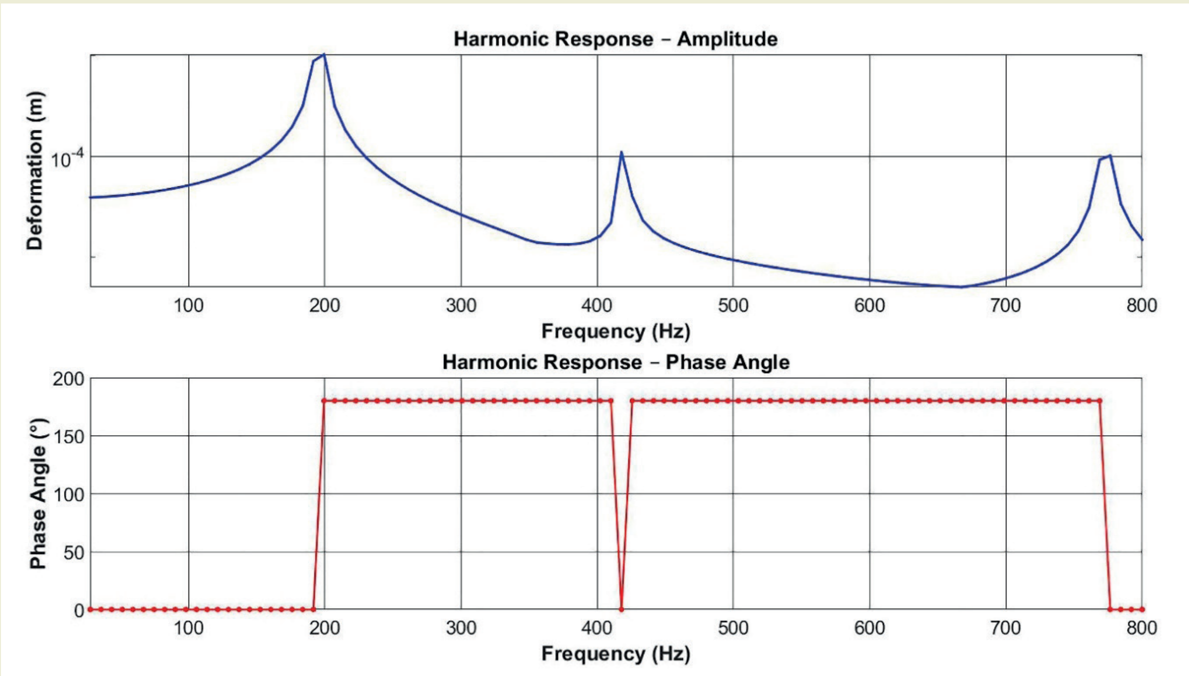

Figure 13. Harmonic response for Y direction

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360,000 RPM.

It is observed that the y data results and the z data results are very close except for the phase angle. The phase angle at the peaks of the y-axis is 0 degrees, while the phase angle on the z-axis is 180 degrees. The phase angle is the angle between the applied force and the deformation.

4. Conclusions

This study conducted a detailed modal and harmonic response analysis of a single ABS arm of the F450 quadcopter frame using ANSYS. Modal results revealed key frequencies susceptible to resonance, while harmonic analysis showed significant amplitude peaks in the Y-direction within common motor speed ranges. These results indicate potential risks of structural resonance

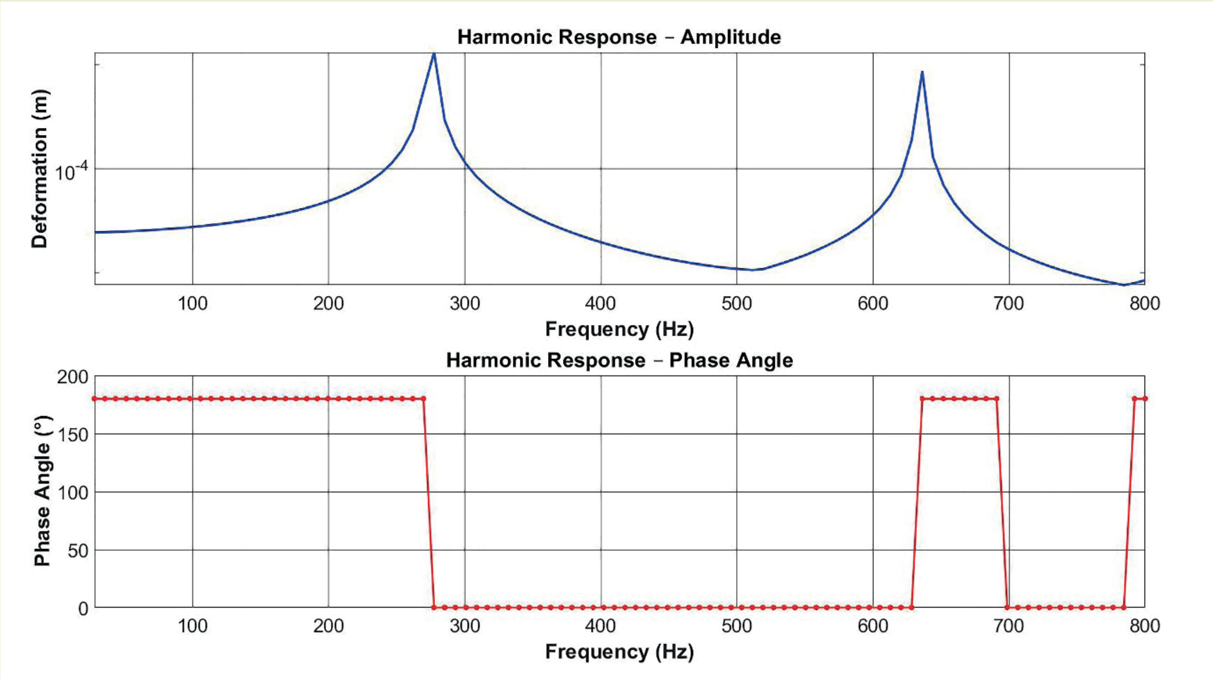

Figure 14. Harmonic response for X direction

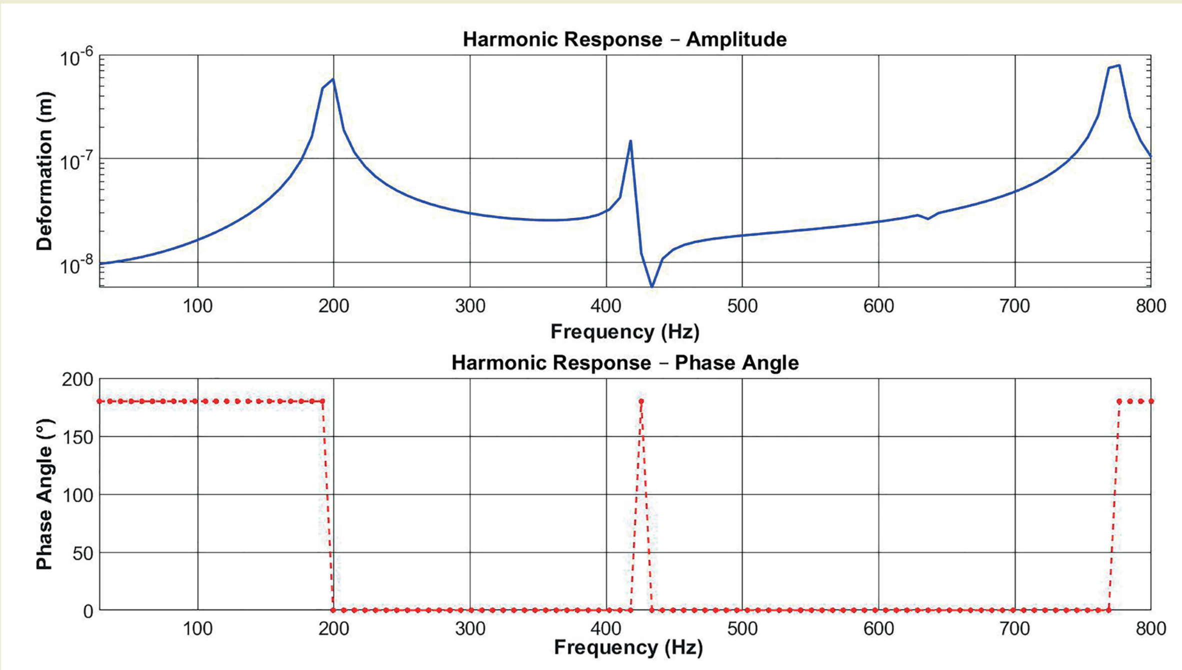

Figure 15. Harmonic response for Z direction

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during operation, especially under high throttle or unbalanced loading.

Future studies may explore full-frame analysis, incorporate motor and propeller coupling effects, and validate results with experimental modal testing. Optimizing the frame geometry or integrating vibration-absorbing materials could further improve performance and durability.

Research ethics

Not applicable.

Author contributions

The author solely conducted all stages of this research.

Competing interests

The author states no conflict of interest.

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Data availability

Not applicable.

Peer-review

Externally peer-reviewed.

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References

[1] Ahmad, F., et al. (2019). Modeling and mechanical vibration characteristics analysis of a quadcopter propeller using FEA. IOP Conference Series: Materials Science and Engineering. IOP Publishing.

[2] Bhandari, A., et al. (2019). Design and vibration characteristics analysis of quadcopter body frame. International Journal of Applied Engineering Research, 14(9), 66–70.

[3] Chen, K., et al. (2023). An investigation on the structural vibrations of multi-rotor passenger drones. International Journal of Micro Air Vehicles, 15, 17568293231199097.

[4] Kuantama, E., Craciun, D., & Tarca, R. (2016). Quadcopter body frame model and analysis. Annals of the University of Oradea, 71–74.

[5] Lostaunau, O., et al. (2024). Analysis of quadcopter body frame vibration during hovering flight with variable rotor speeds. In 2024 8th International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT). IEEE.

[6] Kalay, E., & Özkul, İ. (2024). İnsansız hava araçlarında titreşimlerin rolü, verimlilik ölçüm teknikleri ve performans etkileri. Turkey Unmanned Aerial Vehicle Journal / Türkiye İnsansız Hava Araçları Dergisi, 6(2).

[7] Lalem, M. S. E. I., Ouadah, M., & Touhami, O. (2024). Anomaly detection in quadcopter systems using AI and vibration signal processing.

[8] Abdullah Salem, B. T. S., et al. (2025). Vibration analysis using multi-layer perceptron neural networks for rotor imbalance detection in quadrotor UAV. Drones, 9(2), 102.

[9] Geronel, R. S., Bueno, D., & Botez, R. M. (2022). Vibration analysis of a payload connected to quadrotor-type UAV by SMA spring. In AIAA SciTech 2022 Forum.

[10] Rao, S. S., & Yap, F. F. (1995). Mechanical vibrations (Vol. 4). Addison-Wesley.

[11] Bhavikatti, S. (2005). Finite element analysis. New Age International.

[12] Rao, S. S. (2019). Vibration of continuous systems. John Wiley & Sons.