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Static And Modal Investigation Of A Quadcopter Frame Using Solidworks

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Abstract:
This paper examines the structural model analysis of a locally made quadcopter using SolidWorks, a comprehensive computer-aided design and engineering software. The aim is to ensure the stability of the quadcopter during flights and landing. The study focuses on the design and materials used for the quadcopter and their effects on its performance. Modal analysis is carried out on the quadcopter to determine the vibration characteristics of the structure of the quadcopter. This analysis helps to point out the level of vibration that can affect the integrity of the structure of the quadcopter. Static analysis was also conducted for the landing gear and entire structure of the quadcopter. Using this, we can improve the integrity of the structure of the quadcopter under certain operating conditions.

Keywords: *Quadcopter, Modal analysis, Static analysis, Modelling, SolidWorks*

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I. Introduction

In recent years, the industry of Unmanned Aerial Vehicles (UAVs) has been transformed by the introduction of first-person view (FPV) drones, which have found applications in various fields [1-2]. However, the design and construction of these drones for various applications require careful attention to ensure safety, stability, and durability [3-4]. A critical aspect of drone design is the determination of the structural integrity of the drone frame, which directly affects the drone's performance, durability, and safety. Achieving the structural stability is a key challenge in the design [5] and this can be addressed through structural analysis of the model as demonstrated by [1] and design optimization detailed in [6]. A comprehensive structural analysis of a prototype quadcopter frame will be examined in this paper using SolidWorks software [7]. The use of SolidWorks in the structural investigation of quadcopter frames has proven to be a valuable approach in enhancing the performance, safety, and reliability of UAVs through material selection according to Kayacan, et al, [8], finite element analysis, load analysis, and design optimization, researchers can develop frames that meet the stringent requirements of various applications [9]. The analysis conducted in this paper includes both modal analysis of the frame and the static analysis of the landing gear and bottom part of the quadcopter. The aim is to determine if a frame produced by rapid prototyping is suitability for use a drone structure. The materials used and mesh type will be described, as well as the role of modal and static analysis in determining the integrity of the structure of the quadcopter.

Problem Definition:

The operational demands of the quadcopter drone require that its frame satisfy some basic conditions, the key factors to be considered for the design of the frame include:

- The ability of the frame to support various loads such as the weight of the drone components (motors, battery, speed controller, etc.) and the attendant aerodynamic forces experienced in flight. To ensure stability these loads must be distributed hence the requirement for symmetry in the geometry of the drone frames; additionally, the frame must provide load bearing ability for the weight considered without significant deformation.
- The drone frame must be able to provide stability against vibration forces induced by mass imbalance in the propellers. These vibrations can distort the accuracy of cameras or sensors mounted on the structure. More catastrophic is the ability to induce resonance in the entire system.
- Weight to strength consideration of the drone frame.

II. Methodology

The structural analysis of the quadcopter frame follows the process depicted in figure 1:

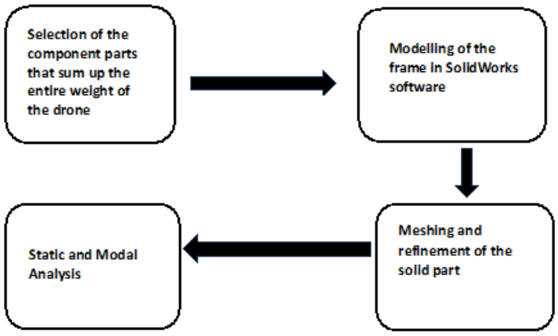


Fig.1: Methodology diagram

Static analysis is performed to determine the stress, strain and displacement experienced by the frame under load conditions. The overall weight of the drone is assumed 4kg and distributed as shown in the Table 1:

Table 1: Drone Component and Weight

S/N	Component	Quantity	Mass (g)
1	Quadcopter Frame	1	325
2	Propellers	4	168
3	Brushless Motors	4	211
4	Electronic Speed Controllers	4	100
5	Power Distribution Board	1	8
6	Flight Controller	1	306.2
7	Harness	NA	200
8	Battery	1	380
9	Payload	1	1300
10	Screws	20	1000
	Total		**3998.2**

Model Development

The first step was to develop the model of the quadcopter using a computer aided design software called SolidWorks. The frame consists of the upper part, the bottom part and the landing gear. The frame is modelled after the DJI Phantom 2 structure [10] where the arms are not separate parts but rather are an integral part of the body. The landing gear is modelled separately and attached to the under parts of the quadcopter.

The landing gear, body and frame of the quadcopter were developed and analyzed using SolidWorks. The Finite Element Analysis (FEA) computation method is used to predict the response of the structure to external disturbances such as vibration, forces, heat etc. To study the quadcopter frame mesh was generated for the structure using SolidWorks. A solid mesh with a maximum element size of 2.33cm and a minimum element size of 0.46cm was utilized. ABS plastic (Acrylonitrile Butadiene Styrene) was selected as the material used for the CAD model. The material properties for the quadcopter were specified based on what was used to construct the quadcopter. ABS (Acrylonitrile Butadiene Styrene) plastic was used for modeling the main frame with the following properties:

Table 2: Material Properties of ABS

Material Property	Value
Mass density	1020 kg/m^3
Elastic modulus	2e+009 N/m^2
Tensile strength	3e+007 N/m^2
Shear modulus	3.189e+008 N/m^2
Poisson's ratio	**0.394**

The mass of the frame was determined from the mass function of the software to be 0.326 kg. The details of the component parts of the drone frame are summarized in Table 1 indicating the various weights and volume of the parts.

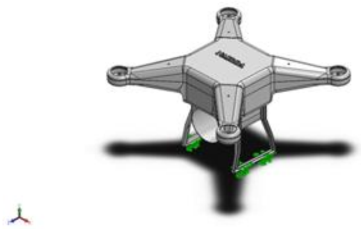
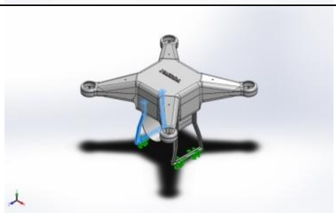
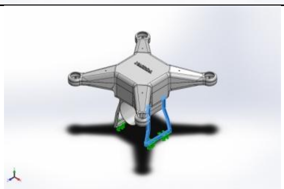


Fig2: CAD Model of Quadcopter Drone Structure

The component mass of the various components used in the analysis is presented in Table 1 and the properties of the material used for prototype development is also given in Table 2. A factor of safety of 2 is assumed for the load applied in the static analysis. Table 3 shows the different parts of the drone structure and their physical properties.

Table 3: Quadcopter Frame Parts

PARTS	Volumetric Properties	Document Path/Date Modified
	**Mass:0.220611 kg** **Volume:0.000216286 m^3** **Density:1020 kg/m^3** **Weight:2.16199 N**	**DRONE BUTTOM.SLDPRT**
	**Mass:0.0854599 kg** **Volume:8.37843e-005 m^3** **Density:1020 kg/m^3** **Weight:0.837507 N**	**DRONE TOP.SLDPRT**
	**Mass:0.00989497 kg** **Volume:9.70095e-006 m^3** **Density:1020 kg/m^3** **Weight:0.0969707 N**	**LANDING GEAR LEG1.SLDPRT**
	**Mass:0.00989497 kg** **Volume:9.70095e-006 m^3** **Density:1020 kg/m^3** **Weight:0.0969707 N**	**LANDING GEAR LEG2.SLDPRT**

Analysis

The integrity of the structure was tested for both the Modal and Static analysis using SolidWorks.

Static analysis for bottom part

The static analysis is performed to determine the magnitude of stress at various points on the structure with particular attention to stress concentration points along the frame, We also determine the magniture of strain and displacement experienced by the structure during operation. A total force of 8N was applied, axially concentrated as 2N at each of the arms as shown in figure 3. Since the weight of the motors and propellers rest on the arms attached to the bottom part it is taken as the point of application of the axial force. Figure 4 shows the bottom part of the drone structure after application of mesh.

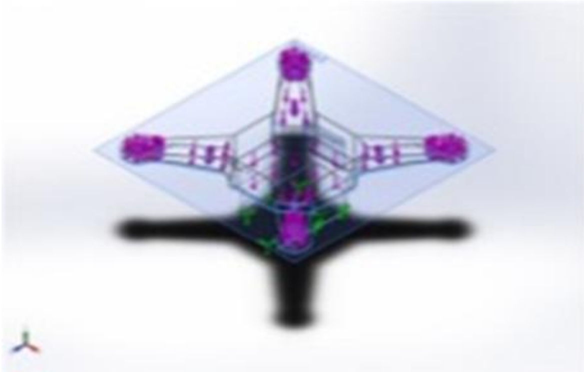


Fig 3: Drone bottom showing points of load application

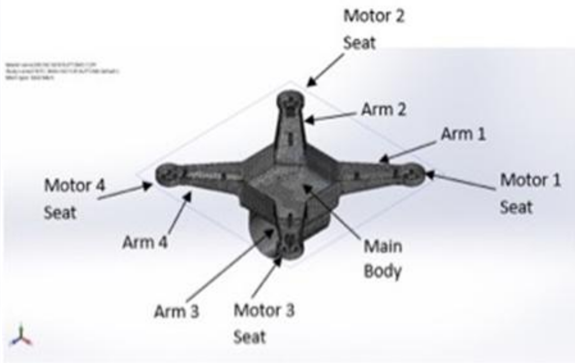


Fig 4: Bottom part after meshing

Static analysis for landing gear

Static analysis was also performed for the two legs of the landing gear as shown. The landing gear bears the entire weight of the drone hence the weight of 8N was applied axially at the landing gear point as shown in figure 5. The static analysis is to ascertain the capacity of the landing gear to withstand twice the total weight of the drone. The landing gear after application of mesh is shown in figure 6.

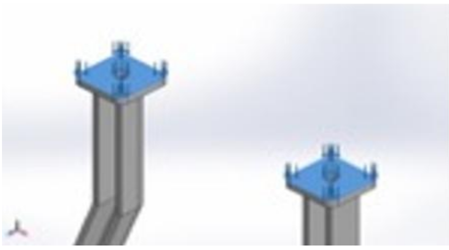


Fig 5: Axial load application

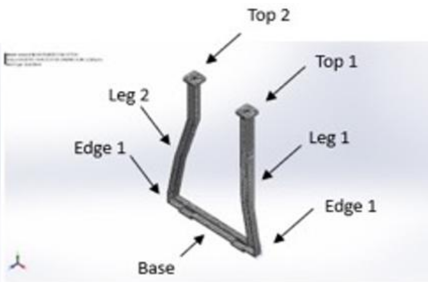


Fig 6: Meshed landing gear

III. Results

The simulation results using SolidWorks is presented in the following sections for both the static and modal analysis of the quadcopter frame. The resultant reaction force and moment experienced by the bottom part and the landing gear is presented in Tables 4 and 5.

Table 4: Reaction force at bottom part

Components	X	Y	Z	Resultant
Reaction force (N)	-0.000163435	71.5747	-3.13018e-005	71.5747
Reaction Moment (N.m)	0	0	0	0

The static analysis results for the parts of the drone structure are presented in Figures 7–13. The Von Mises stress for the bottom part and landing gear is shown in Figures 7 and 11. The displacement is shown in Figures 8 and 12. Figures 9 and 13 represent plots of the equivalent strain. The deformation of the bottom part is as seen in Figure 10.

Static Analysis Result for Bottom Part

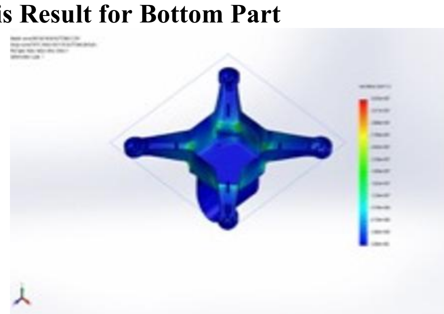


Fig 7: Von Mises Stress Bottom
Min:5.05382e-05 N/m^2, Max:3.67795e+07 N/m^2

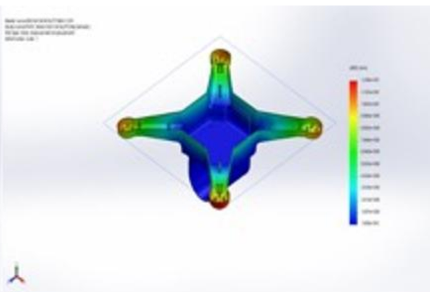
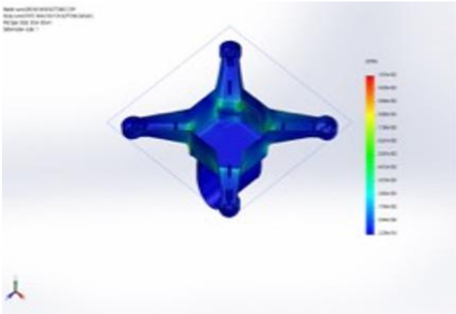


Fig 8: Displacement Bottom
Min: 0mm, Max:12.0795mm



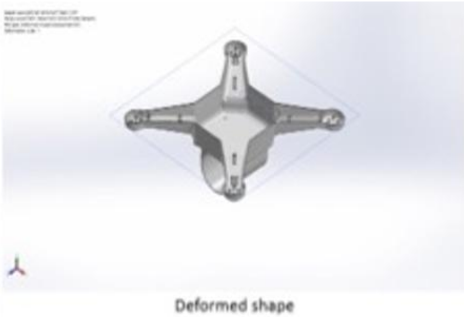


Fig 9: Equivalent Strain Bottom
Min:2.23875e-014, Max:0.0107332

Fig 10: Deformed Shape

Static Analysis Result for Landing Gear

Table 5: Reaction force at landing gear

Components	X	Y	Z	Resultant
Reaction force (N)	0.000714332	15.9999	-0.000225633	15.9999
Reaction Moment (N.m)	0	0	0	0

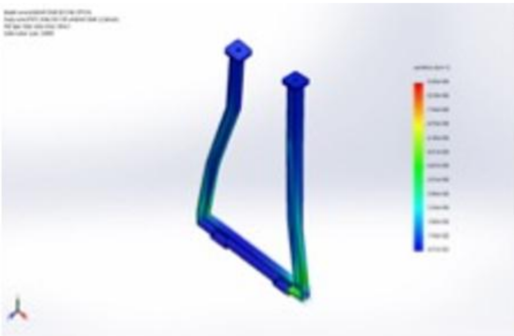


Fig 11: Von Mises Stress Landing Gear
Min: 487.749 N/m^2, Max:9.29316e+06 N/m^2

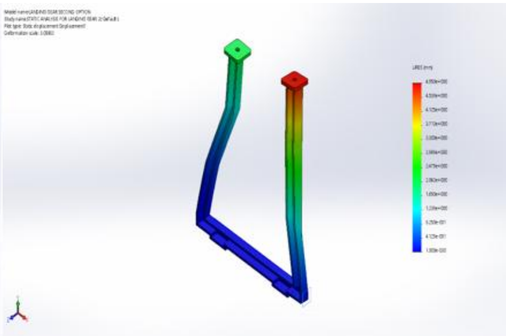


Fig 12: Displacement Landing Gear
Min: 0 mm, Max:4.9002mm

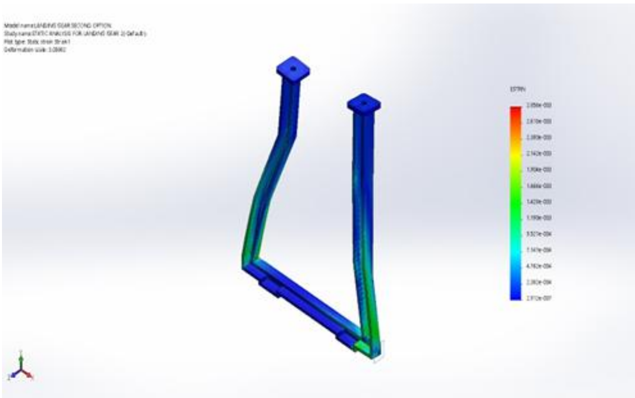


Fig 13: Equivalent Strain Landing Gear
Min: 2.91164e-07, Max:0.00285571

Modal Analysis

To study the dynamic characteristics of the drone frame modal analysis was performed . The results following show the natural frequencies and amplitude plots for the various mode of the designed drone structure. The modal analysis results indicates five mode shapes during the vibration. Figures 14, 15 , 16, 17 and 18 represent Modes 1, 2, 3, 4 and 5 respectively. The expected deformation is shown in Figure 18.

Modal Analysis Results

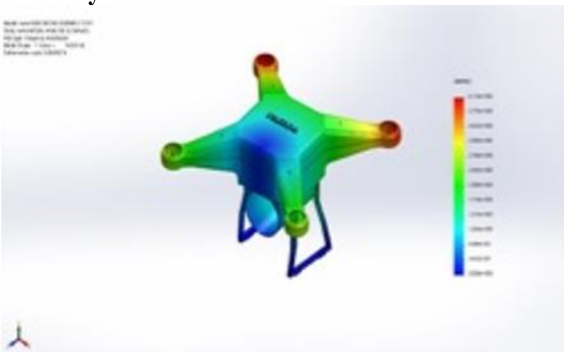


Fig 14: Amplitude Plot for Mode Shape 1 (Value = 16.538 Hz) Min: 0, Max: 4.11849

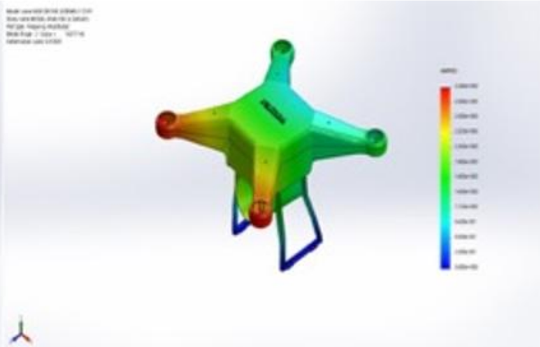


Fig 15: Amplitude Plot for Mode Shape 2 (Value = 16.9168 Hz) Min: 0, Max: 3.36

Fig 16: Amplitude Plot for Mode Shape 3 (Value = 27.6346 Hz) Min: 0, Max: 2.20499

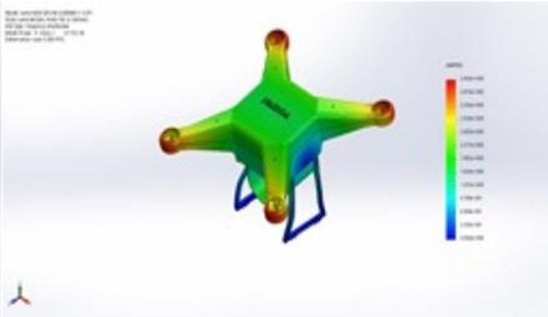


Fig 17: Amplitude Plot for Mode Shape 4 (Value = 67.7416 Hz) Min: 0, Max: 3.90335

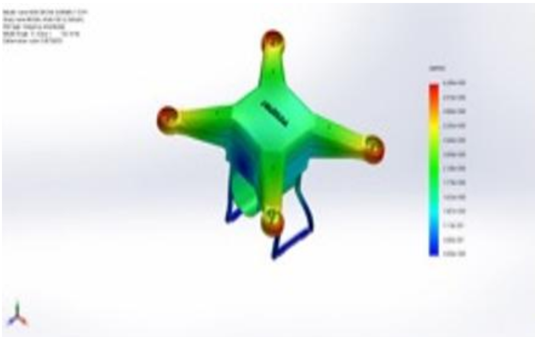


Fig 18: Amplitude Plot for Mode Shape 5 (Value = 102.139 Hz) Min: 0, Max: 4.26937

Fig 19: Deformed Shape

The result of the structural analysis test showing the five modes of vibration and their attendant amplitudes is presented in Table 6.

Table 6: Mass Participation (Normalized)

Mode Number	Frequency (Hertz)	X direction	Y direction	Z direction	Seconds
1	16.538	0.27763	1.2581e-006	0.00058636	0.060467
2	16.917	0.69354	4.2477e-007	6.1501e-006	0.059113
3	27.635	0.00012921	4.4821e-006	0.9371	0.036186
4	67.742	5.0858e-009	0.00059659	0.031222	0.014762
5	102.14	0.0026131	0.0014895	2.1332e-005	0.0097905
		Sum X = 0.97392	Sum Y = 0.0020923	Sum Z = 0.96894	

The drone structure produced by rapid prototyping can be seen in figure 20 below.

Fig 20: Final Frame Produced by Rapid Prototyping

IV. Discussion And Conclusion

The structural test of the bottom part suggests that the frame's arms and the point where the arms connect to the body are the most stressed and strained parts, while the motor seats and main body experience minimal stress and strain. The significant displacement in motor seats could be a point of concern and may require further examination for structural integrity. The overall reaction forces indicate a primary load in the Y-direction with no rotational moments.

Under a static loading of twice the weight of the quadcopter the Von Mises stress results of the Landing gear indicate that the majority of the structure (Top1, Top2, Leg1, Leg2, Base) shown in Figure 6 experiences a relatively low stress of approximately 487.749 N/m². However, Edge1 and Edge2 experience significantly higher stress of about 5.421e+06 N/m² indicating a stress concentration point, as expected, the edges have the maximum equivalent strain of 1.428e-03. This problem can be resolved by increasing the fillet at the edges. The displacement results in figure 12 show varying levels of displacement across different parts of the landing gear with a maximum value of 4.95 mm at Top 1. Leg1 and Leg2 have moderate strain values (2.382e-04), while Top1, Top2, and the Landing Base have minimal strain (2.912e-07). The reaction forces shown in Tables 4 and 5 indicate that the primary load is vertical, with minimal forces in other directions. The absence of reaction moments in Table 5 suggests no significant rotational forces on the landing gear.

The Modal Analysis test of the entire structure yielded five modes of vibration, each presenting unique characteristics in terms of frequency and directional responses, refer to figures 14-18. Mode 1 at a frequency of 16.538 Hz indicates a primary response in the X-direction with minimal movement in the Y and Z directions. Mode 2 at a frequency of 16.917 Hz indicates dominant movement in the X-direction, with a higher amplitude compared to Mode 1, with negligible Y and Z responses. Mode 3 at a frequency of 27.635 Hz indicates a significant response in the Z-direction, indicating a different mode of structural behavior compared to the first two modes. Mode 4 at a frequency of 67.742 Hz with minimal response in the X-direction, with the Y and Z directions showing slightly higher but still low amplitude responses. Mode 5 at 102.14 Hz is the highest frequency mode but the response across the three directions is low and evenly distributed. The structural analysis indicates that the structure exhibits varying dynamic behaviors at different frequencies, with notable directional responses. Modes 1 and 2 are predominantly influenced by the X-direction, Mode 3 shows a major response in the Z-direction, while Modes 4 and 5 demonstrate lower amplitude movements with Mode 5 showing more balanced directional influences. Figures 10 and 19 show negligible overall deformations in the structure indicating it as feasible for use as a quadcopter drone’s structure. The final frame produced via rapid prototyping can be seen in figure 20.

Abbreviations

UAV - Unmanned Aerial Vehicles
ABS - Acrylonitrile Butadiene Styrene.
CAD - Computer Aided Design.

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Author’s Contributions

All the authors read and approved the manuscript.

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