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“Structural and Modal Analysis of Quadcopter Frame: Material Optimization for Load-Bearing Efficiency”

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Abstract

Unmanned Aerial Vehicles (UAV), due to the ability of carrying huge payload, have wide applications from military surveillance, medicinal supply to agricultural purposes. To fulfil these applications effectively, the body frame of quadcopter must be able to withstand the various loading conditions. The present study deals with the structural analysis of a quadcopter frame to study the effect of specified loading conditions on the body frame. Further modal analysis was done for material optimization. Four different materials were selected which includes Aluminium alloy, Copper alloy, Carbon fibre, E-glass fibre. From modal analysis six modes with respective frequencies for all four materials were obtained. Based on the results, suitable material was selected which will suit the specified loading conditions.

Keywords- Quadcopter Frame, Load-Bearing Efficiency

1. Introduction

Quadcopter is a multirotor UAV with motor placed in four corners of a cross shaped frame. It is operated by four motors to move in the air as shown in the paper [1]. It’s light weight and high thrust generating capacity of motors that allow it to increase its weight lifting capability which will be more with electronic components placed on it for its operation [2]. Many researches have been done on quadcopter base frame

Kumar, V. Aswin et al. [3] performed structural optimization of a frame of the Multi-Rotor Unmanned Aerial Vehicle through computational structural analysis from which it has been observed that ‘+’ and ‘X’ frame are the best Quadcopter configurations to withstand any kind of external loads. Kumar, Pushpendra et al. [4] studied the dynamics of quadcopter with different frame structures. The dynamic model of the quadcopter is developed based on the Newton-Euler formulation and the lengths of the four arms of the base frame are taken different in the model. The model is verified through simulation in MATLAB and the results were analysed for the balanced vertical motion of the quadcopter with the different frame structure and it is confirmed that the for stable vertical motion symmetry along X and Y axes is necessary, unsymmetrical structures may be very difficult to control due to unbalanced moments.

Sagar, N. V. S. S. et al. [5] performed the multistage mass optimization of a quadcopter frame. Two stage numerical scheme was used for mass optimization of an off-shell UAV model. In the first stage, optimization is done for the shape of the frame using Design of Experiments (DoEs). In the second stage, optimization is carried out for mass using topology optimization. Mass is further reduced in the second stage, i.e. topology optimization. Structural optimization integrated with additive manufacturing technology is realized for designing a lightweight quadcopter structure that can carry an all-up weight of 2Kg. The final redesigned and remodelled geometry yielded a mass of 434 g as against 756 g of initial design.

The main motive of the present study is to understand the effect of the thrust generated by the propellers mounted at the arms and the base plate of the quadcopter body frame through static structural analysis. Further from different literatures four different materials were selected for the manufacturing purpose of quadcopter body frame. Modal analysis was performed for those materials and six modes with respective vibration frequencies for four materials was obtained from the analysis. From this modal analysis we attempted to determine the most suitable material for the manufacturing of the quadcopter frame model. The present paper is divided into following sections: i) Introduction, ii) static structural analysis iii) Modal analysis iv) Conclusion

2. Static Structural Analysis

Static structural analysis of the quadcopter model is performed in Ansys. We attempted to obtain the deformation and equivalent stress contour by applying suitable materials and boundary conditions on the 3D model of the quadcopter frame. We will determine the maximum and minimum deformation and maximum and minimum equivalent (Von-Mises) stress[5-8]

2.1 3D model of a quadcopter body frame

Previous studies have shown that the X and + shaped quadcopter body frame have better performance output than other frames [9]. So for this analysis purpose we have decided to study the X shaped frame. The body frame mainly involves two parts one the base plates and other is the arm. Fig.1 shows the CAD model of the frame which is created in CATIA V5R21. The length of the four arms is kept equal to maintain balanced vertical motion [4]. Fig. 2 shows the mesh model of the body frame. Mesh properties are shown in the table 1.

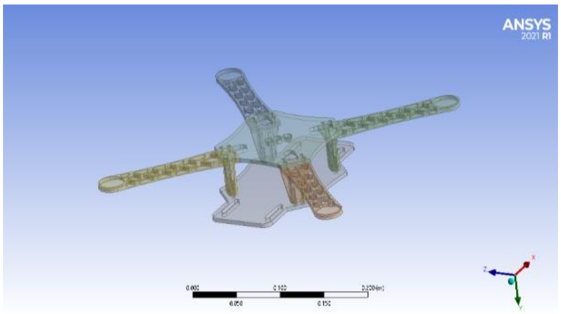


Fig. 1. Quadcopter 3D model.

2.2 Material Properties

For static structural analysis, Polyamide nylon 6 is used for arms of frame and E-glass fibre is used for base plate. Table 2 shows the properties of Polyamide nylon 6 and table 3 shows the properties of E-glass fibre.

2.3 Boundary Conditions

The thrust on each arm due to each rotor mounted on it, is calculated by following equation,

Thrust of each motor = P x D3 x RPM2 x 10-10 oz

Where D is the diameter of the propeller, P is the pitch of the propeller and RPM is the speed of the motor in rotation per minute. The data taken for the analysis purpose is: D = 8-inch, P = 4.5-inch, RPM = 11.1 x 1400 = 15540.

After evaluating the above equation, the calculated thrust of each motor is equal to 15.47N (55.639oz). This thrust in upward direction produced necessary pressure to lift the quadcopter to it's four corners. As shown in the fig. 3 the calculated thrust is applied on the edges of the arms in upward direction

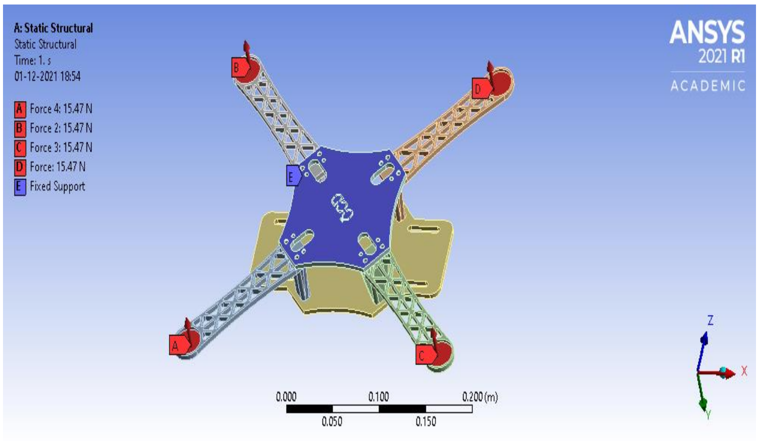


Fig. 3. Boundary Conditions applied on the frame

2.4 Results

The analysis was performed in Ansys to obtain following results. Fig. 4 shows the contour for deformation and Fig. 5 shows the contour for equivalent (Von-Mises) stress.

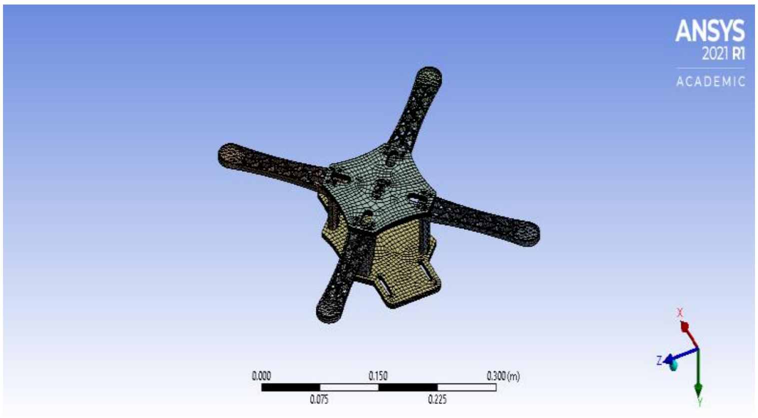


Fig. 2. Mesh of Quadcopter 3D nodel

From Fig. 4 we can see the maximum total deformation 0.0031454 m at the extreme points of each arm shown in red colour while minimum of zero metre deflection is obtained at the base plate. From Fig. 5 we can conclude that the maximum stress of 72.242 MPa is obtained at the joining point of the arms and base plate. The minimum of 0.47107 Pa stress is obtained at the end points of each arm. The static structural analysis performed shows the effect of thrust on the arms and base plate of quadcopter body frame. These results can be used for further structural optimization.

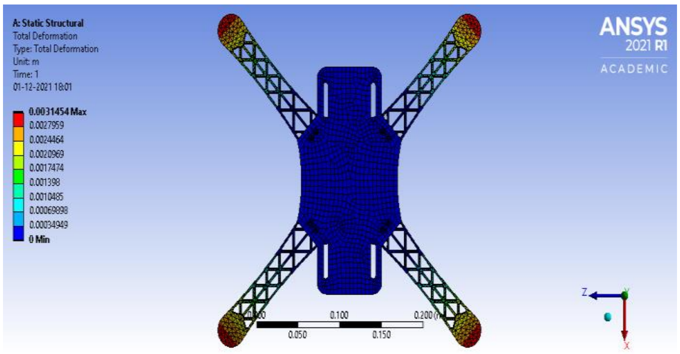


Fig. 4. Total deformation contour for static analysis of quadcopter body frame

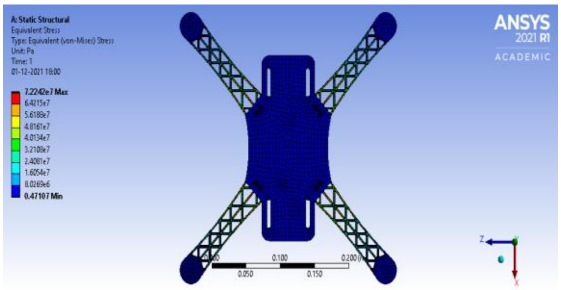


Fig. 5. Equivalent stress contour for quadcopter body frame

Table 1. Mesh properties [10,11]

Span Angle Centre	Coarse
Boundary Box Diagonal	0.44852 m
Average Surface Area	1.5841e-004 m^2
Minimum Edge Length	1.9028e-004 m

Table 2. Material properties of Polyamide nylon-6

Name of the property	Corresponding values
Tensile Yield Strength	1E+08 Pa
Poisson ratio	0.38
Tensile Ultimate strength	9E+07 Pa
Density	1120 kg m^3
Young's Modulus	2.3E+09 Pa

Table 3. Material properties of E-glass fibre

Name of the property	Corresponding values
Shear Modulus	2.0325E+10 Pa
Poisson ratio	0.23
Tensile Ultimate strength	3.0864E+10 Pa
Density	2600 kg m^3
Young's Modulus	5E+09 Pa

3. Modal Analysis

To study the stability of the base frame model of quadcopter and material optimization we used the modal analysis module of ANSYS software through which the vibration frequencies for different modes can be obtained. We used four different materials for this analysis and from the results obtained we tried to determine the suitable material for manufacturing the base frame.

3.1 3D model of the base frame

For modal analysis we used the same model and mesh as that we used in static structural analysis.

3.2 Material properties

In this analysis we used 4 different materials, Aluminium alloy, Copper alloy, Carbon fibre, E- glass fibre. These materials were previously used in quadcopter modelling we will attempt to determine the most suitable of them. Table 4 shows the material properties of these materials.

3.3 Boundary Conditions

For the modal analysis the boundary conditions are same as that we used in static structural analysis.

3.4 Results

the modal analysis is performed on the body frame of quadcopter in ANSYS from which we obtained six modes and corresponding vibration frequencies. Table 4 shows the modes and corresponding frequencies for all four materials. The mode shapes and corresponding natural frequencies for different materials is shown in Fig. 6(for Aluminium alloy), Fig 7(Copper alloy), Fig 8(Carbon fibre) and Fig 9(E-glass fibre).

From Fig. 6 to Fig. 9 we can observe that the vibration frequencies from mode 1 to mode 6 for Aluminium alloy is 148.69 Hz 896.47 Hz, for Copper alloy is 106.92 Hz to 644.67 Hz, for Carbon fibre is 116.67 Hz to 698.36 Hz and for E-glass fibre is from 196.27 Hz to 1182.9 Hz. The resulting modes and frequencies are plotted, as shown in the Fig. 10. The natural frequencies of E-glass fibre are higher than other three so the frame made up of E-glass fibre will have comparatively more strength and hence it will also increase the lastingness of the body frame.

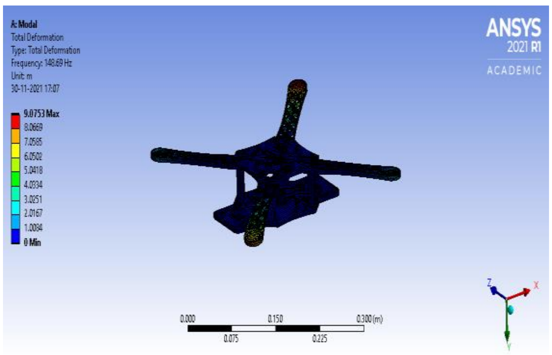
Table 4. Material properties of selected materials

Materials	Density (Kg/m^3)	Young Modulus (Pa)	Poisson Ratio
Copper alloy	8300	1.1E+11	0.34
Aluminium alloy	2770	7.1E+10	0.3
Carbon fibre	1800	2.9E+11	0.4
E-glass fibre	1120	5E+10	.23

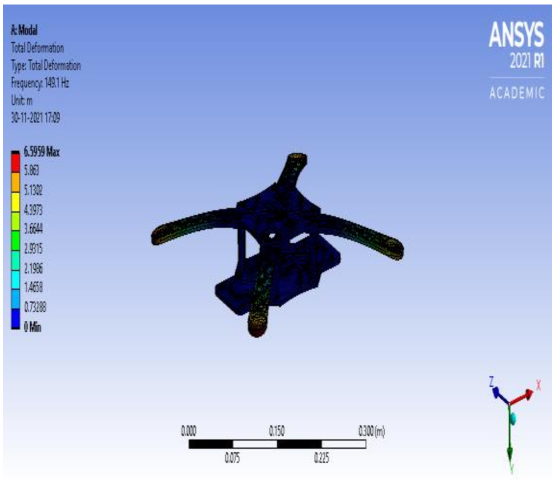
Table 5. modes and corresponding frequencies for selected materials

Modes	Aluminium alloy	Copper alloy	Carbon fibre	E-glass fibre
1	148.69	106.92	116.67	196.27
2	148.7	106.93	117.14	196.27
3	149.1	107.22	117.26	196.82
4	149.24	107.32	117.3	197.01
5	776.51	558.42	603.46	1024.9
6	896.47	644.67	698.36	1182.9

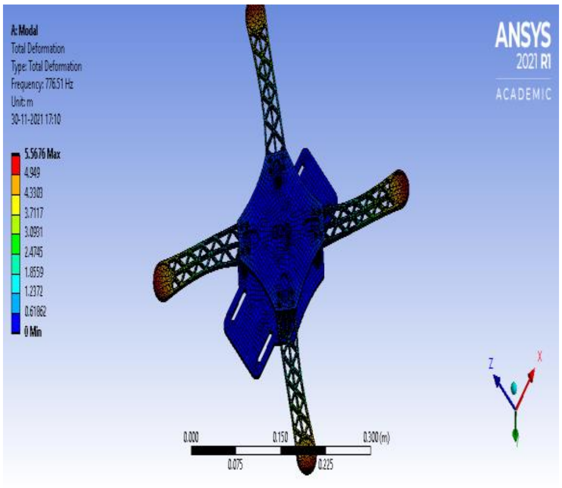
Fig. 6. Mode shapes and natural frequencies for Aluminium alloy



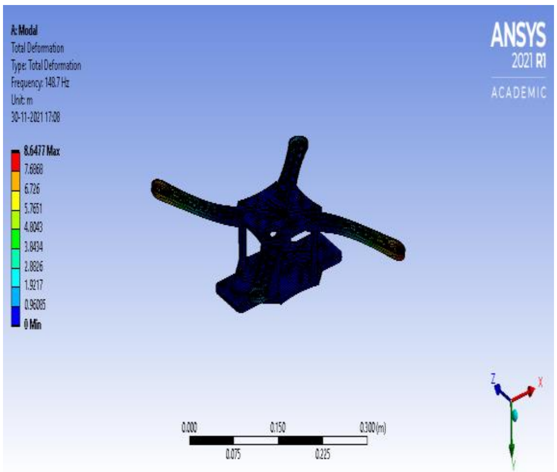
Mode 1 (148.69Hz)



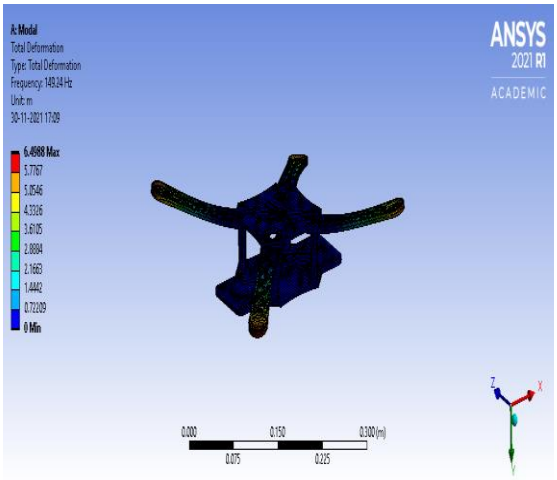
Mode 3 (149.1Hz)



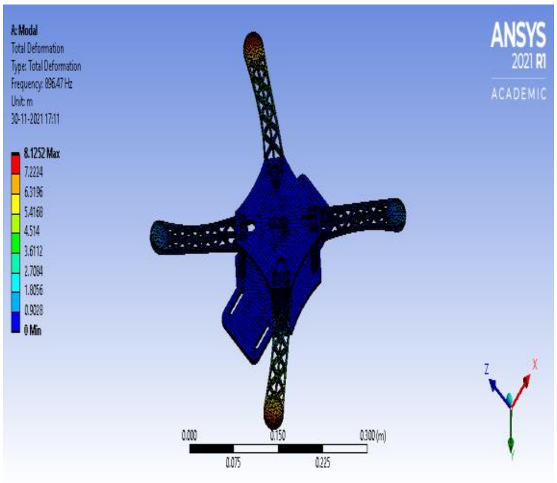
Mode 5 (776.51Hz)



Mode 2 (148.7Hz)

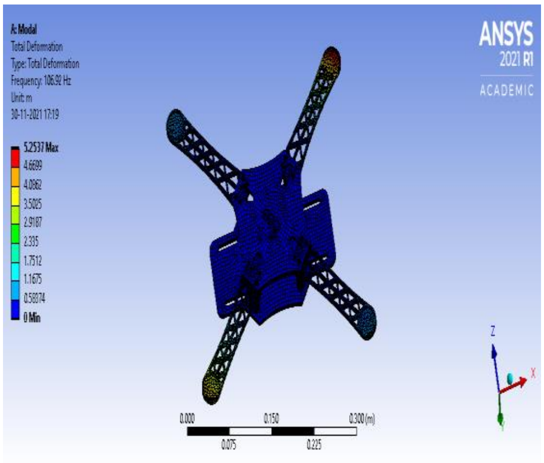


Mode 4 (149.24Hz)

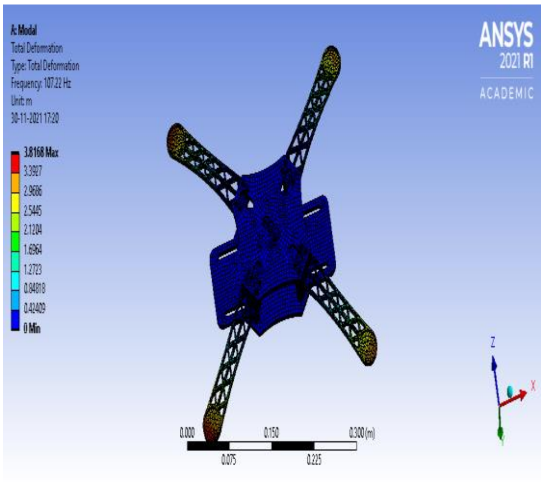


Mode 6 (896.47Hz)

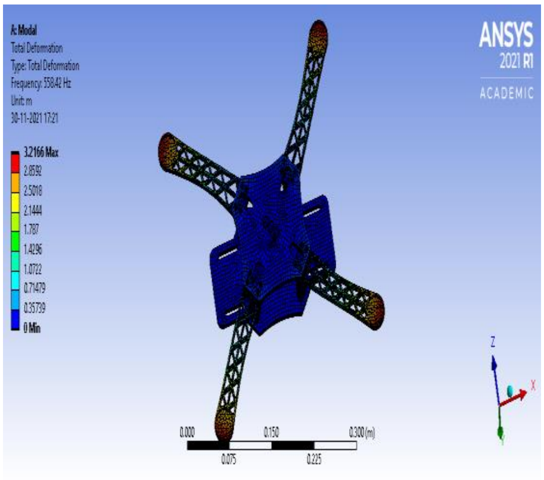
Fig. 7. Mode shapes and natural frequencies for Copper alloy



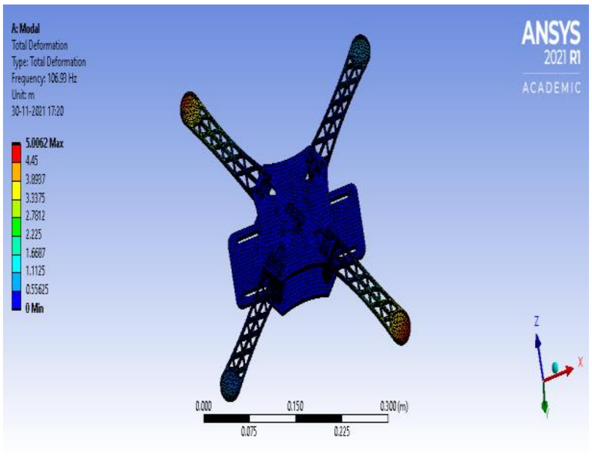
Mode 1 (106.92Hz)



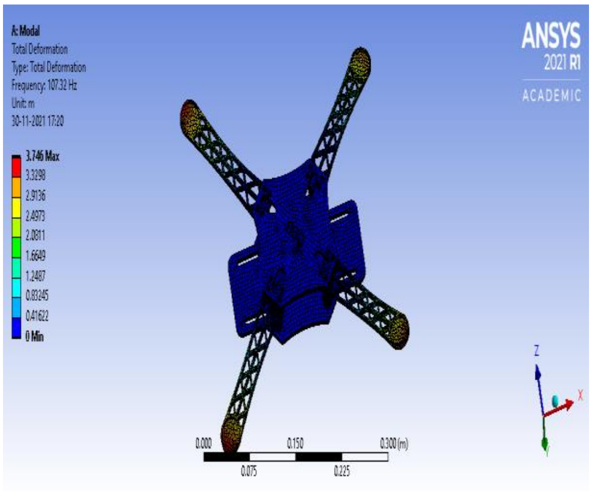
Mode 3 (107.22Hz)



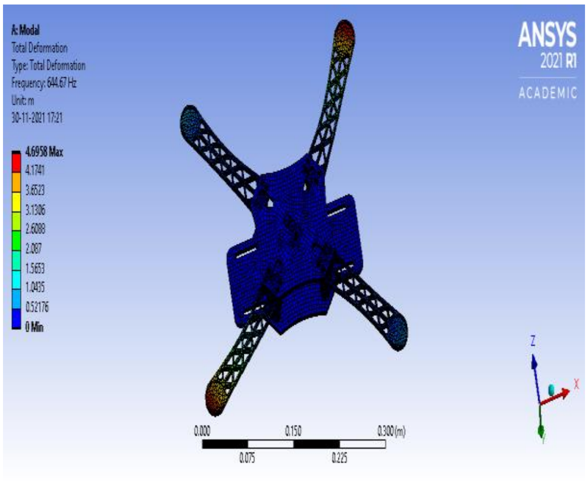
Mode 5 (558.42Hz)



Mode 2 (106.93Hz)

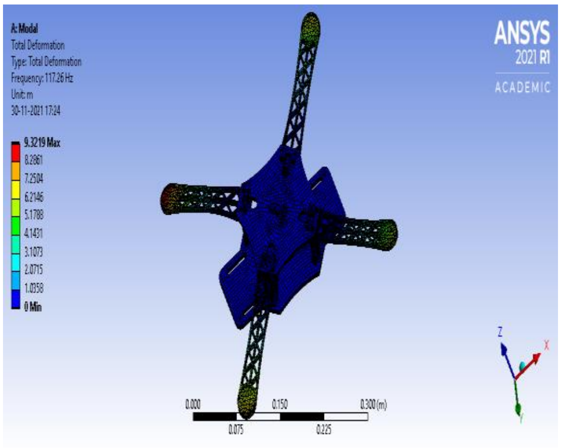


Mode 4 (107.32Hz)

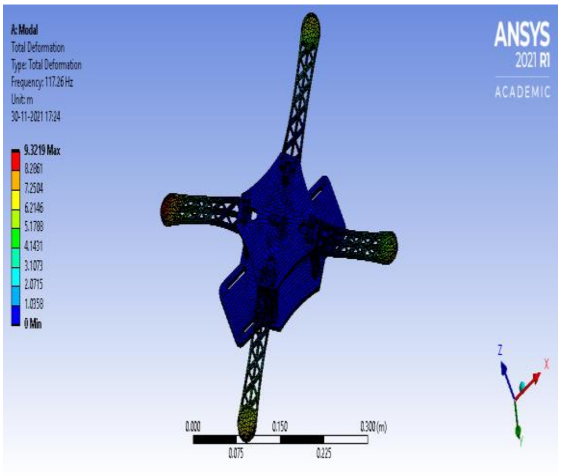


Mode 6 (644.67Hz)

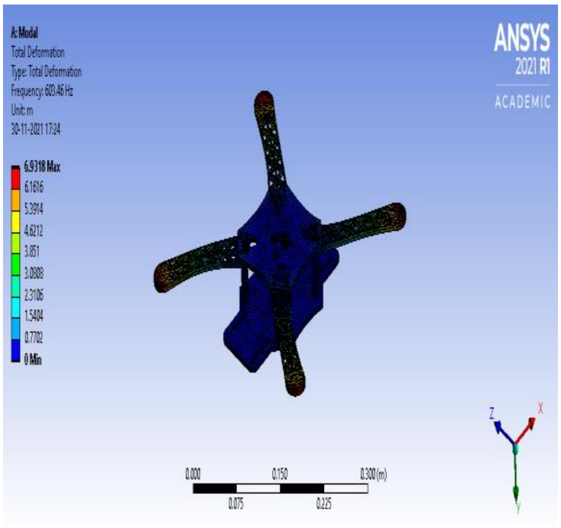
Fig. 8. Mode shapes and natural frequencies for CF



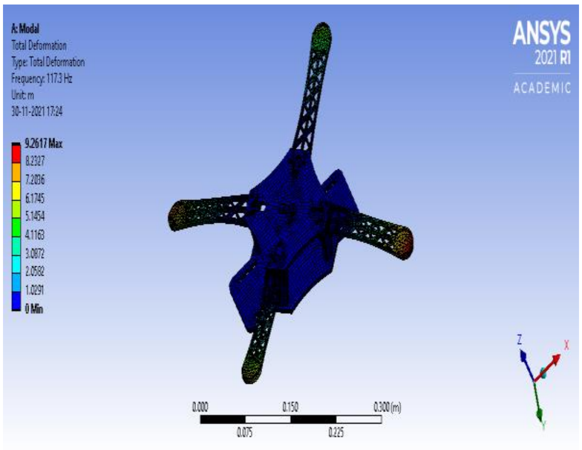
Mode 1 (116.67Hz)



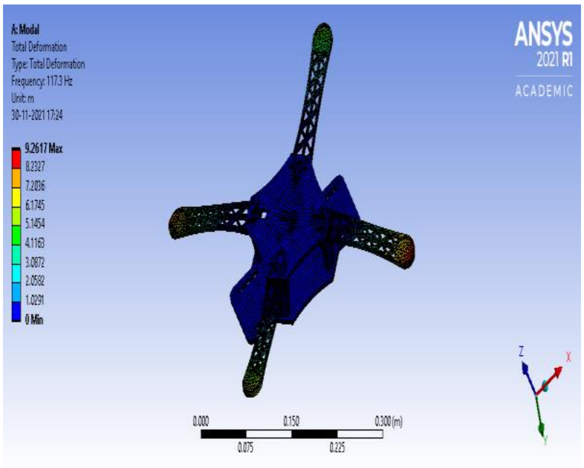
Mode 3 (117.26Hz)



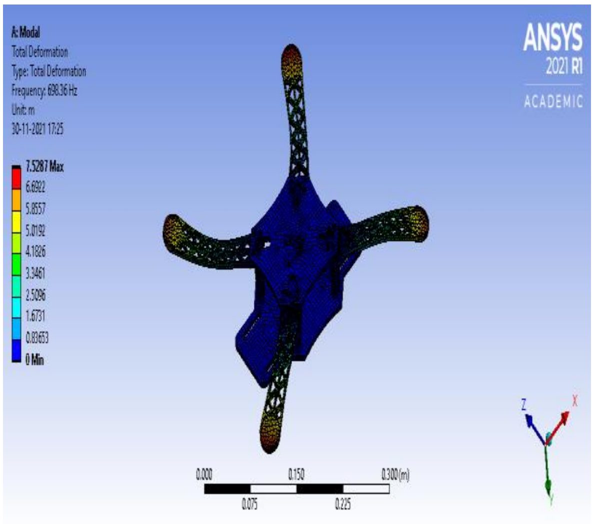
Mode 5 (603.46 Hz)



Mode 2 (117.14Hz)

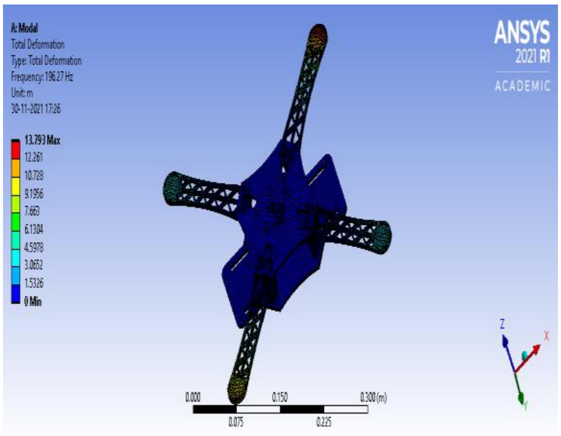


Mode 4 (117.3Hz)



Mode 6 (698.36 Hz)

Fig. 9 Mode shapes and natural frequencies for E-glass fibre



Mode 1 (196.27 Hz)

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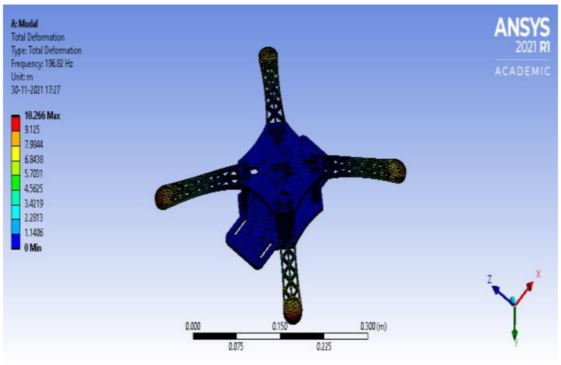
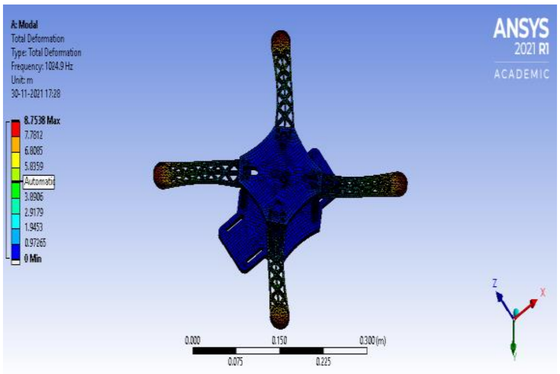
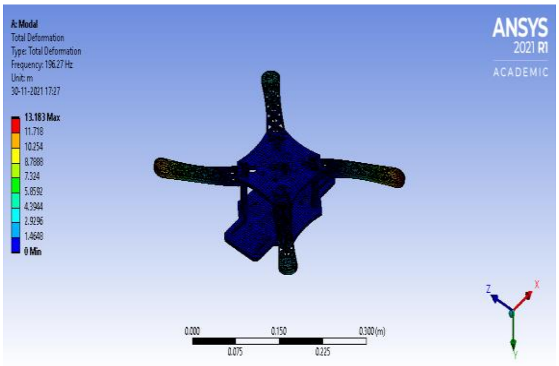


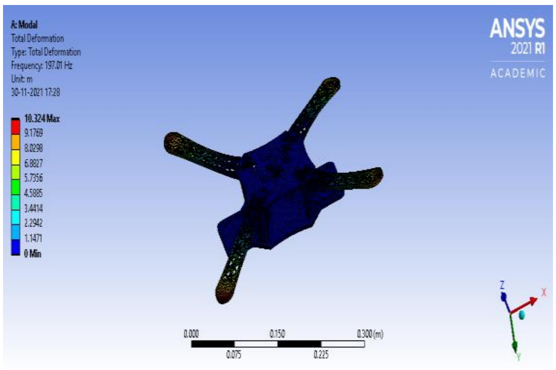
Mode 3 (196.82 Hz)



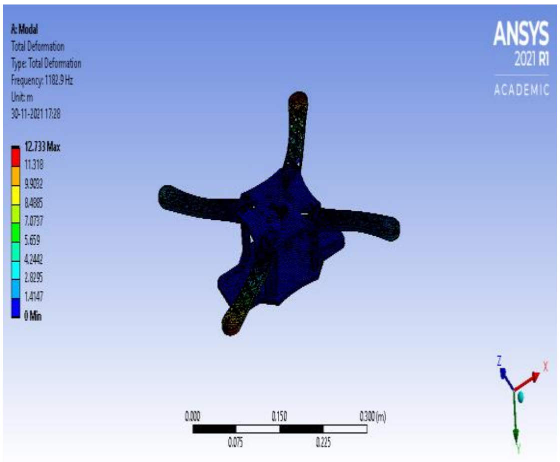
Mode 5 (1024.9 Hz)



Mode 2 (196.27 Hz)



Mode 4 (197.01 Hz)



Mode 6 (1182.9 Hz)

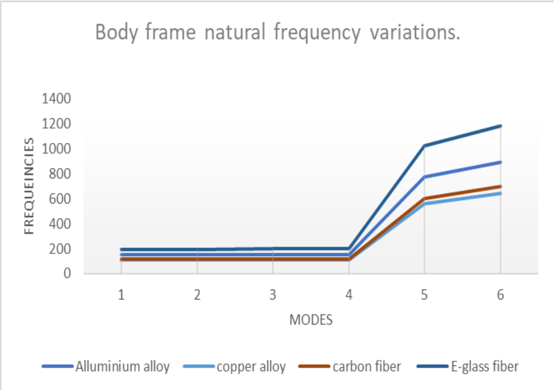


Fig. 10 Frequency vs. mode graph for selected materials

4. Conclusion

In this paper, quadcopter body frame was analysed. A 3D model of the body frame was designed in CATIA V5 software which was then transferred to ANSYS for further analysis. At first static structural analysis was performed from which it can be concluded that the maximum deformations occur at end points of each arm while maximum equivalent stress is observed at the joint of arms and base plates. Using these results further topological optimizations can be performed to reduce the mass of the frame which will increase the performance of quadcopter. Further modal analysis was performed with same loading conditions as used in static structural analysis for four materials (Aluminium alloy, Copper alloy, Carbon fibre, E-glass fibre) selected from literature survey. Six modes with corresponding frequencies were obtained for all four materials. From this result it can be concluded that E-glass fibre has highest failure frequency range than other three materials. So E-glass fibre is a good candidate for manufacturing the body frame of quadcopter

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