Modeling and Analysis of Quadcopter F450 Frame

Conference Paper · February 2020

DOI: 10.1109/IC3A48958.2020.233296

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***Abstract*- Quadcopters have a unique characteristic unlike the other conventional flying objects like vertical takeoff and landing (VTOL), and has a leading aspect in multiple applications like war fare, traffic updates, surveillance, festival places and mostly dense areas. Design of a quadcopter is an important aspect for its aerodynamics of which modeling and analysis are two key areas invol.ved in its manufacturing. This paper focuses on the modeling and structural analysis of quadcopters frame. Modeling is carried out in AutoCAD 2016 software and analysis of various parts is performed using ANSYS 17.0 software. Results obtained are compared to sustain the loads generated in the quadcopter. It is found that the proposed design is safe as very small deformations occurred on the plates.**

Keywords: Quadcopter; UAV; Aerodynamics; Structural Analysis.

I. INTRODUCTION

The need of unmanned aerial vehicles/quadcopters is widely increasing in the field of aerospace industry. It is necessary to make them tough and robust in order to operate them in potentially tough environments to overcome the failures in flying. The role of design principles and modeling of physical structure plays a vital role in unmanned aerial vehicle (UAV) or Quadrotor because of its capability to hover in small areas and vertical takeoff and landing. Quadcopters are equipped with four motors and locked propellers to generate lift. The four motors which drive the propellers are attached on the end beam in the frame that often is made like a cross, made from two beams. In quadcopters two motors fixed in the opposite direction rotates in clockwise direction and other two motors rotates in counter clockwise direction in order to lift from the ground. Every fixed motor will generate required amount of thrust and torque in rotational motion and such forces are used to move and hover the quadcopter properly. Co-ordination of these motors with respect to their direction of revol.ving will cancel all the forces and maintains the speed to be same. During hovering of a quadcopter, in order to rotate it in the required direction certain points has to be remembered. If the speed of the motors on the either sides (left/right on frame) are changed remaining the direction of other two motors same then it generates 'Yaw' in direction. Accordingly, other two movements i.e. 'Roll' & 'Pitch' is generated by interchanging the speed of motors [1]. Schematic arrangement of a quadcopter is shown in *Fig. 1*.

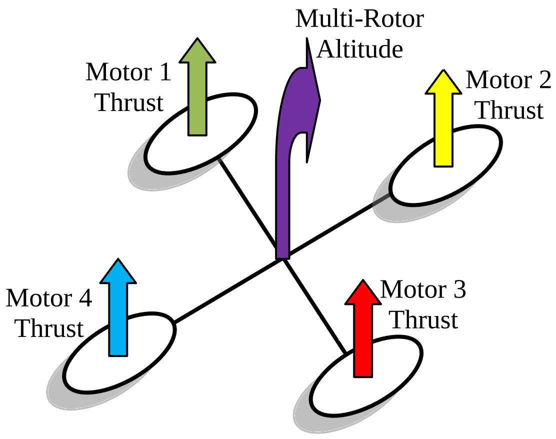

Fig. 1. Schematic arrangement of quadcopter [3]

II. LITERATURE REVIEW

Jeong et al. [2] discussed the omni-directional flying four wheel drives with inbuilt fans. This drive having an ability of hovering in the air and maneuver on field. The signals stability is controlled by Kalman filter then fed to PID controllers. Lim et al. [4] discussed the designing and controlling effect of flying robot having landing frame with double operated rotors. The altitude and the orientation of the situation are sensed by the ultrasonic and gyro-sensor. H8/3694F microcomputer was used for all computations to control the robot. Javir et al. [5] discussed the amount of thrust required during different maneuvers of quadcopter. The study of the gravitational force, self weight of frame and attached components, deformation, stress, natural frequency is done by ANSYS software to ensure the safe design. Kumar et al. [6] discussed an exclusive type UAV having an ability of vertical takeoffs with smooth landing. In this model the direction is changed by manipulating the individual propeller's speed without the cyclic & collective pitch control. Abishini et al. [9] has developed a quadcopter for aerial surveillance as well as underwater ship wrecks, crashes and other applications. It is also stated that for developing such models certain aspects are considered to be important alike buoyancy and floatability for the power requirements and integrity of the quadcopter. The study explains the modeling of the frame in CATIA and later design is validated through stress analysis and compared with other materials.

Prajwal et al. [10] developed a quadrotor for lifting the maximum payload capacity. The study explains about the modeling of frame in CATIA V5 R19 and ANSYS workbench is used for the dynamic and static analysis. CFD analysis is also performed on the frame in order to calculate the maximum stress and deformation. The results obtained were within the limits and safe.

III. MAIN OBJECTIVES OF MANUSCRIPT

i. To study quadcopter flight aerodynamics.
ii. Modeling of quadcopter frame with F450 and AUVSI standards (Association for Unmanned Vehicle Systems International) using AutoCAD 2016.
iii. Carrying out structural and total deformation analysis on quadcopter frame in ANSYS software.

IV. HARDWARE COMPONENTS OF QUADCOPTER

The different components mounted on quadcopter [*Fig.2*] with their specifications are discussed as:

A. DC Motors

Brushless DC motors (BLDC) are widely used in quadcopters. These consists of a permanent magnet which rotates around a fixed armature and has many advantages over brushed DC motors like more torque, reduced noise, high reliability, longer battery life and increased efficiency for less power and low weight. BLDC motors are rated in kV where it rotates 1000 RPM per 1V supplied to it if its rating is 1 kV. Each BLDC motor is capable of producing 750 g of thrust force depending on kV rating. Motors are selected based upon their kV rating.

B. Propellers/ Fans

Propeller/fans generate the thrust for the quadcopter to lift. They are classified depending on their diameter and pitch and are represented in the form of product of diameter and pitch. The diameter of propeller indicates the virtual circle that the propeller generates whereas the pitch indicates the amount of travel per single rotation of propeller. To counter the motor torque, quadcopter requires two clockwise (CW) and two anticlockwise (CCW) rotating propellers. Many motors are available with propeller specifications to have optimum power consumption. If propeller specifications are not identified, then trial and error method must be used. 10x4.5 propellers black CW, CCW of 4 pieces is used as per the requirements.

C. Electronic Speed Controllers (ESC's)

The function of ESC is to control the speed of the motors by receiving the Pulse Width Modulation (PWM) signal from the APM board. The input signal is varied by receiving the power from battery. It has a vol.tage reducer sensor which supplies required vol.tage output from battery to the FS-i6 receiver and APM board.

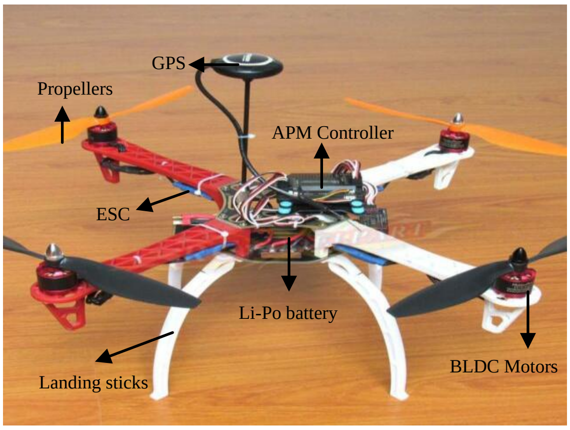

Fig. 2. Components of quadcopter

BLDC motors are connected to the female pins of ESC in order to receive the power. Selection of ESC's depends on the current rating of the BLDC motors. ESC's acts as step-down devices by reducing the input vol.tage from the battery to receivers. The speed of BLDC motor is controlled by the ESC's with the input of PWM signals from the flight controller. The signal and power wires from the BLDC motors are connected to ESC's and the remaining two wires from the other end of ESC's are soldered to the PCB boards for powering up. Four 20A ESC's (electronic speed controllers) are used in proposed quadcopter prototype. In this project 20A ESC's are used so the maximum current it can handle is 13A. ESC's takes the signal from throttle channel of receiver, and supplies 3 phased AC vol.tages to motor. An important benefit of ESC for aircrafts is to cut the power of motor when the battery is low and keep the controls for ailerons, elevator and rudder on so the quadcopter can glide down safely.

D. Lithium Ion Polymer (LiPo) Battery

Lithium Ion Polymer (LiPO) batteries are used in quadcopters. The cells in batteries are 3.7V per cell and can produce enormous amount of current for the BLDC motors. These batteries are rated based on their C-ratings. It takes completely two hours for full charging. A fully charged battery can be used for 20 minutes in quadcopter depending upon the payload as shown in Fig.8. So maximum source power it can provide is 75A. LIPO batteries cannot be used below 80% of the maximum capacity.

E. Radio transmitter and receiver

The Flysky FS-IA6B is a 6-channel receiver with 2.4 GHz frequency. It is connected to the control board of quadcopter (APM 2.6 Arducopter). This receiver consists of six channel receiver pins and a 5V pin for switching on. The four channel (*CH1, CH2, CH3,* & *CH4*) pins of receiver are connected to the controller *(1, 2, 3, 4)* input pins by jumper wires. The function of this receiver is to send the signal to the controller according to the stick movements of radio control transmitter by which the motion of the quadcopter can be controlled according to the requirement. The weight of the mounted components on quadcopter is listed in *Table I.*

TABLE I. LIST OF COMPONENTS

Sr.No.	Components	Weight(gm)
1.	APM 2.8 controller	50
2.	GPS module	25
3.	BLDC motors (920kv)	235
4.	Electronic speed Controller(ESC)	100
5.	Propeller (1045)	45
6.	Li-Po battery	265
7.	Landing frame	75
	Total Weight	**795**

F. APM controller

APM ardupilot controller is considered as one of the best and stable flight controllers for quadcopters. It has multiple I/O pins for connecting more number of channels. This flight controller also supports the GPS system for finding the location of quadcopter in mission planner software. Apart from this it has many pins for mounting the additional sensors/components for multipurpose use. Programming APM controllers is user friendly and easy to load the values.

V. DYNAMIC MODELING OF QUADCOPTER

A quadcopter with four fixed rotors and pitch angle is an under actuated aircraft. Modeling of quadcopter is a crucial task in the field of aircrafts. The main objective of the paper is to develop a model of quadcopter with more realistic parameters.

A typical quadcopter has four input forces and required thrust provided by the propellers as shown in *Fig.3*. Most of the quadcopter design are in the form of ‘X’ and ‘+’. From the design point of view the ‘X’ configuration is considered to be more stable and perfect while hovering when compared with the ‘+’ configuration mode [8].

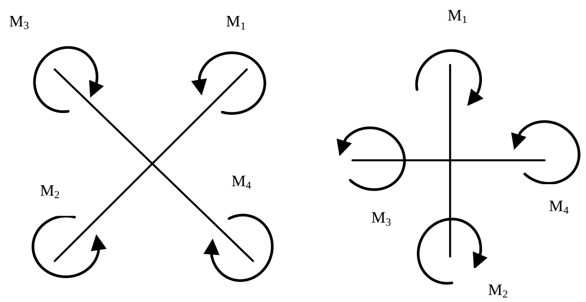

Fig. 3. ‘X’ and ‘+’ configuration

The improvement of quadcopter has become little difficult due to their algorithm of control on four motors and it has become very hard to maintain the same speeds of motors without the help of electronics. In order to achieve six degrees of freedom, three rotational and translational motions are coupled together as shown in *Fig.4*. With this six DOF and four inputs the control of motors speed has become easy for the operator to tilt the quadcopter in required direction.

The four input forces of quadcopter which affects the hovering are U_1, U_2, U_3, & U_4. The change in altitude of the quadcopter is done by U_1 and change in rotation of roll angle is done by U_2, the pitch angle is affected by U_3 and the yaw angle is controlled by U_4. These input forces will help the operator to move the quadcopter in all directions. Each input force is calculated by an equation as shown in (1). [1].

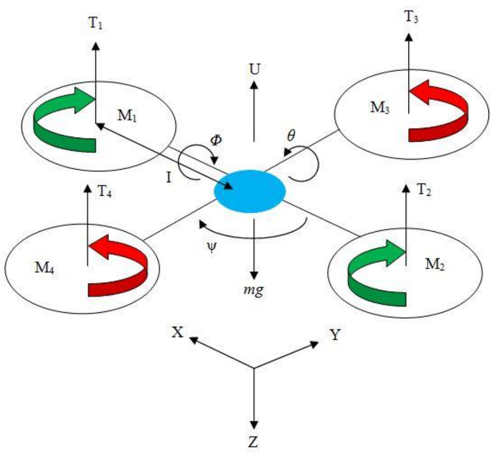

Fig. 4. Quadcopter with six degrees of freedom [1]

$$U = \begin{cases} u_1 = (T_1 + T_2 + T_3 + T_4)/m \\ u_2 = l.(-T_1 - T_2 + T_3 + T_4)/I_1 \\ u_3 = l.(-T_1 + T_2 + T_3 - T_4)/I_2 \\ u_4 = l.(T_1 + T_2 + T_3 + T_4)/I_3 \end{cases} \tag{1}$$

where,

U = Sum of the thrust of all motors;
T_1= Thrust generated by front motor *(M1);*
T_2= Thrust generated by rear motor *(M2);*
T_3= Thrust generated by right motor *(M3);*
T_4= Thrust generated by left motor *(M4);*
m = Mass of quadcopter;
I= Moment of Inertia;
l = Half length of the quadcopter;
x, y, z = Three positions of quadcopter.

A. *Calculating the Thrust*

Thrust is defined as the force required for driving or supplying the motion to the propeller of quadcopter. It is generated by the motor which spins at certain angular velocity. Thrust developed by a rotor is shown in (2). [1].

$$T = \rho A V r^2 \tag{2}$$

where, ρ is real-time air density *(Kg/m*^{3}*); A* is propellers cross sectional area; V_r is an instantaneous peripheral velocity of rotors *(r =1, 2, 3...)*.

Maximum power of motor is calculated as shown in (3).

$$P = V * I \tag{3}$$

where, vol.tage *(V) = 11.1v* and *I= 3.5* Amp is the current rating of Li-Po battery.

P= 38.85 Watts.

Selection of ESC’s [10] is based on (4).

(Number of ESC’s ×Ampere rating of ESC) > (C×I) (4)

where, the discharge rate of Li-Po battery is denoted with C.

4×30A>25×3.5

Propeller Sweep Area is calculated as in the (5), where D =10 inch.

$$A = 0.25\,(\pi(D))^2 \tag{5}$$

A = 0.654 ft^2.

Power loading [10] is calculated as in the (6).

$$\frac{P_{in} * \eta}{A_{ft}} \tag{6}$$

Where, Pin is input power (Hp) and η is efficiency of motors.

Pin = 38.85 Watts.

=38.85*1.340*10-3

=0.052 HP.

PL. = 0.052 * 0.70/0.654

PL. = 0.0594 Hp/ft2.

B. Takeoff and Landing Positions

Quadcopters will move in the z-axis (positive direction) while lifting-off from the ground creating a translation motion and it moves in the negative direction of z-axis when it is landing from the air. In order to achieve the stable departure and landing of quadcopter the ratio of throttle given by radio controller plays an important role as it has to be given perfectly so the receiver will understand and maintain the speed of motors to hover properly in z-axis of both directions as shown in *Figs. 5 & 6.*

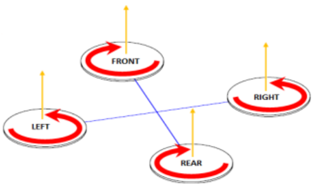

Fig. 5. Take-off motion [9]

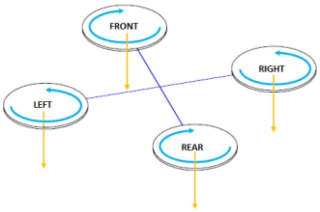

Fig. 6. Landing motion [9]

VI. MODELING OF QUADCOPTER

The standard frame mostly used for the quadcopters are F450 frame because of its light weight and high strength. F450 frame has a shape of 'X' geometry which provides more room space for mounting of additional components in the quadcopter. The modeling of frame is carried in AutoCAD 2016 using the dimensions from F450 frame by taking into considerations the safety requirements, smooth functioning and optimum utilization of propellers, motors and electrical equipments.

The central hub, spars and arms are designed individually and then assembled as shown in *Figs. (7-11)*. The dimensions of quadcopter frame are given in *Table II*.

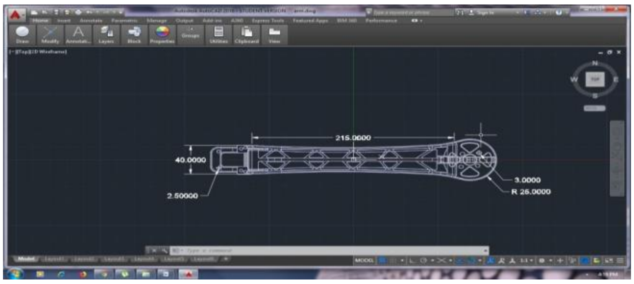

Fig. 7. Sketch of quadcopter arm

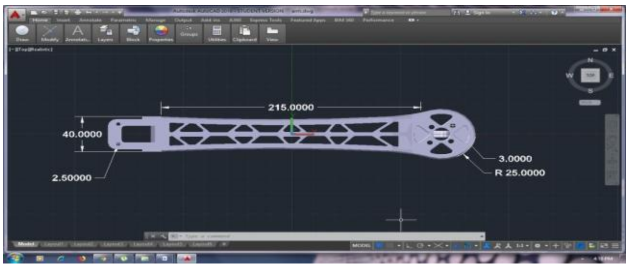

Fig. 8. Model of quadcopter arm in AutoCAD

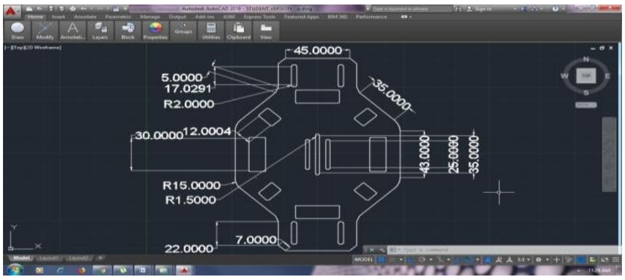

Fig. 9. Sketch of Base plate of quadcopter

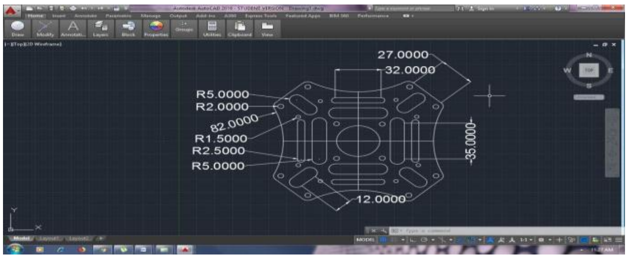

Fig. 10. Sketch of quadcopter top plate

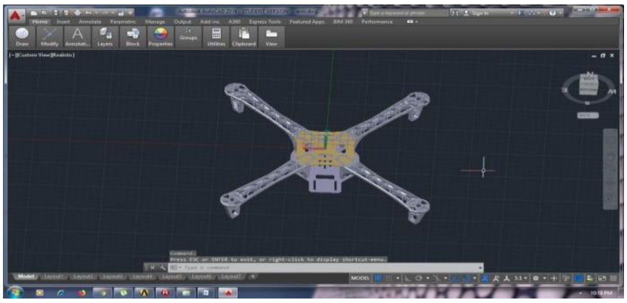

Fig. 11. Assembly of quadcopter frame in AutoCAD

TABLE II. DIMENSIONS OF QUADCOPTER FRAME

S. No.	Quadcopter Components	Specifications(mm)
1	Length of Arm (four arms)	215
2	Dimensions of Arms	40 x 13 x 0.6
3	Base plate dimensions (Length of vertical, horizontal sides, & thickness)	43 x 43 x 2
4	Rectangular drills on base plate	25 x 35
5	Radius of vertical and horizontal sides of top plate , & thickness	82 x 2
6	Radius of circular drill on top plate	1.5 x 2.0
7	Length and breadth of square drill on top	5 x 32 x 35
8	Distance between two motors	455
9	Dimensions of Motor nut & screw	Ø2, 15

A. Weight estimation of Quadcopter

The weight of each component should be taken into consideration for calculating the empty weight and total carrying weight. The calculations of weight estimation [10] are shown in (7).

$$W_T = W_F + W_M + W_{ES} + W_{Batt} + W_{Pay} \quad (7)$$

where, W_T, W_F, W_M, W_{ES}, W_{Batt} and W_{Pay} is take of gross weight, frame weight, motor weight, ESC's weight, battery weight and payload weight respectively.

The empty weight [10] can be calculated as in (8).

$$W_e = W_F + W_M + W_{ES} \tag{8}$$

If the quadcopter is electrically equipped, the take of gross weight will remain constant. So, the total gross weight is as shown in the (9 & 10).

$$W_T = W_e + W_{Batt} + W_{Pay} \tag{9}$$

$$\text{Empty weight fraction} = W_e / W_T \tag{10}$$

VII. STRUCTURAL ANALYSIS OF QUADCOPTER

For a quadcopter, the frame is the main load bearing component. Their ability to bear high tensile and compressive loads makes them more attractive. Structural analysis is carried out on the frame of quadcopter prototype [8] in ANSYS 17.0 software.

A. Von-mises stress analysis of base plate

Structural analysis is carried out on the base plate of quadcopter in ANSYS 17.0 software. The properties for carrying static structural analysis [8] are listed in *Table III*. Meshing resolution used is fine to get the accurate results. The ultimate tensile strength of base plate (PA66GF30) material is 160 MPa [8]. The maximum equivalent stress that is obtained is 5.99 MPa as shown in *Fig.12*. Hence the base plate is safe to withstand the loads.

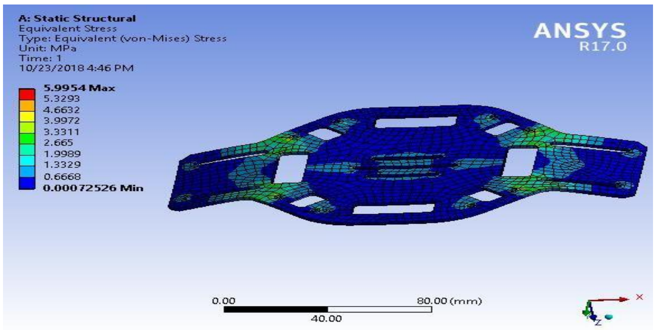

Fig. 12. Von-mises stress analysis for tensile load of 20N on base plate

TABLE III. BOUNDARY CONDITIONS

Material	Density (kg/m^3)	Young's Modulus (MPa)	Tensile strength (MPa)	Poisson's ratio
PA66GF30 Material	1370	15000	160	0.36

B. Von-mises stress analysis of top plate and F450 frame

The ultimate tensile strength of top plate (PA66GF30) material is 160 MPa. The maximum equivalent stress that is obtained is 2.255 MPa as shown in Fig.13. Hence the top plate is safe to withstand the loads. The maximum equivalent stress that is obtained is 23.0 MPa as shown in Fig.14. Hence the F450 frame is safe to withstand the loads.

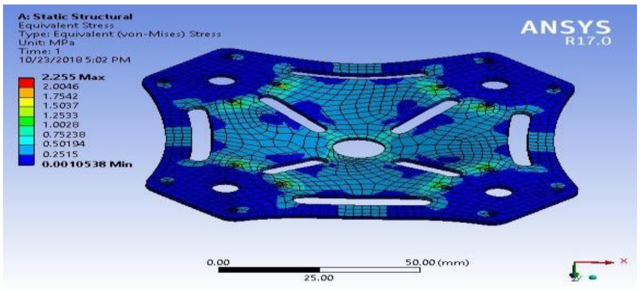

Fig. 13. Von-mises stress analysis for tensile load of 20N on top plate

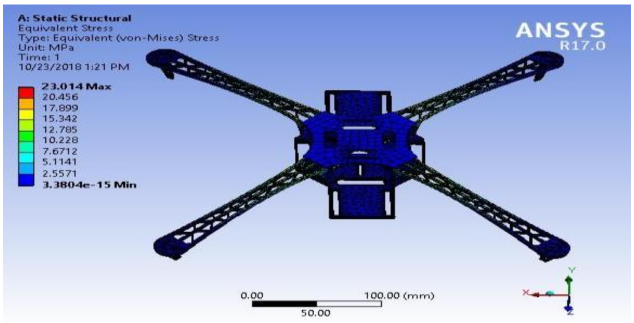

Fig. 14. Von-mises stress analysis for tensile load of 20N on F450 frame

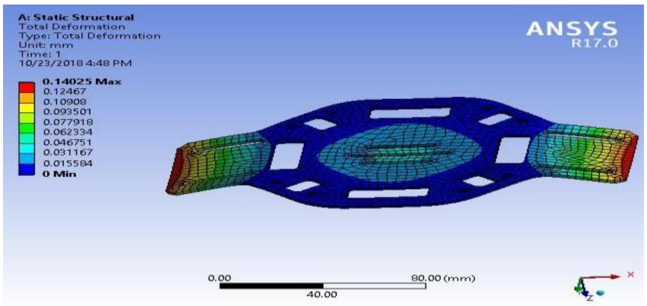

Fig. 15. Total deformation analysis for tensile load of 20 N on base plate

C. Total deformation analysis of base plate

The total deformation obtained for the base plate is minimum 0 mm to maximum 0.14025 mm as shown in *Fig.15*.

D. Total deformation analysis of top plate and F450 frame

The total deformation obtained for top plate and F450 frame is minimum 0 mm and maximum is 0.0097 mm and 4.135 mm as shown in Figs.16&17.

Quadcopter prototype frame (F450) is subjected to static structural analysis to find the deformation when the load is applied on the frame. The results obtained are within the limit when compared to tensile strength of PA66GF30 material. So the frame is safe to use and can with stand the crashes.

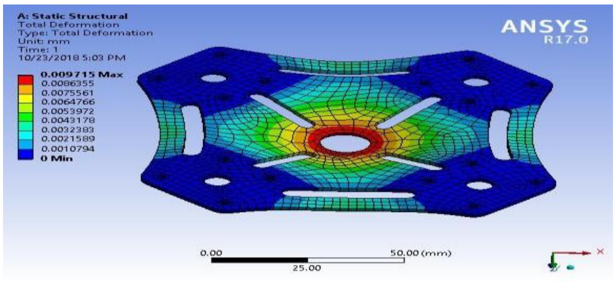

Fig. 16. Total deformation analysis for tensile load of 20 N on top plate

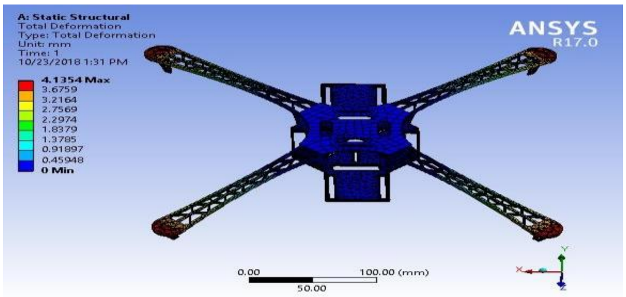

Fig. 17. Total deformation analysis for tensile load of 20 N on F450 frame

VIII. Conclusion

Selection of components is explained to ensure the maximum flight and best control system of quadcopter. Dynamic modeling is presented in order to estimate the motion of quadcopter with parameters of propeller and several components as shown in equations. Modeling and component selection was explained to obtain the weight ratio, mounting of extra sensing equipment, development of craft geometry and to reduce the transition phase of quadcopter prototype. In order to obtain the best results during the flight of quadcopter the standards of AUVSI are implemented in the modeling, thrust and weight estimation of quadcopter and found to be unique in comparison with the literature survey. ESC’s did not provided rotational speed and it was calculated by altering the voltage and mAh ratings of battery. Static air flow of quadcopter is obtained by calculating the thrust. By generating the necessary amount of thrust during the flight of Quadcopter, the value of g, Individual weight of electronic parts assembled on the frame is found to be stable. Deformation and stresses induced are calculated using ANSYS Workbench 17.0. The obtained stress (23.0 MPa) and total deformation (4.135 mm) results for various type of analysis are within the required border. Depending on the results obtained it is stated that modeling of quadcopter frame is safe and can be used for different applications of payload category.

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