Design, optimization and manufacturing of quad copter frame using FDM

Vepa K S, Sagar N V S S

Abstract: This paper explores two important aspects of quadcopter design viz., design optimization using Non-dominated Sorted Genetic Algorithm (NSGA) technique and fabrication of monocoque quadcopter frame. Arm width, arm thickness, thickness of the ring connecting the four arms and dome thickness are the parameters considered for the design of experiments (DoEs). Once the optimized set of parameters is achieved, transient simulation is carried out to test the performance of the quadcopter frame. Mass and thrust-to-weight ratio of the optimized quadcopter frame are compared with that of a commercially available quadcopter frame of the same size. It is observed that there is a significant increase in the thrust-to-weight ratio and a decrease in the mass of the frame. Sensitivity analysis of the DoE results shows that the dome and ring thicknesses have higher influence on the optimized model. Based on the validation of optimized model through static structural analysis, it is concluded that integration of design optimization and additive manufacturing will reduce the usage of material which results in a more budget friendly design. The result of this approach gives a structural frame of new design with monocoque structure of minimum weight with higher performance.

Index Terms: design optimization, design of experiments, sensitivity analysis and quadcopter.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are flying objects that operates without the need of an onboard pilot [2]. UAVs are used in various fields and are considered a valuable asset in the fields like agriculture, topography, sports, surveillance etc. [3-8]. Based on the functionality, UAVs are categorized into different categories viz., multi-rotors, flapping wing, fixed wing and hybrid models. The main differences between these categories are the lift and thrust generation systems [9]. Most popular and widely used model is the multi-rotor type which has a wide range of applications like sports, aerial photography, cargo delivery etc. A multi rotor UAV is given a name based on the number of rotors it uses to operate and the number of rotors range from 1 to 12. In the current work, an UAV with four rotors is used and hence called quadcopter. Configuration of a quadcopter generally consists of a supporting frame with the four rotors placed at the end of the arms of the supporting frame. All the arms of the quadcopter are of same length and make same angle with each other. Fig. 1 shows a typical quadcopter assembly.

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Fig. 1 Typical quadcopter assembly[1]

The key parameters that define the success of a quadcopter are their production cost and structural integrity. To make the quadcopters carry high payloads, it is important to reduce their weight. Hence optimization of quadcopter frame for low weight and high strength is ever evolving. One of the key developments that took the design of low weight quadcopters to the next level is the advent of rapid prototyping. Additive manufacturing, a type of rapid prototyping, has reduced the cost of production so drastically that it is considered a disruptive technology [10] with an estimated global market share of over US$5.1 billion in 2015 [11]. Of all the additive manufacturing techniques available in the market, Fused deposit modelling (FDM) is very popular [12-14] and FDM using thermoplastic polymers has a wide range of commercial applications including that of quadcopter frames [15]. In the current work, Acrylonitrile–Butadiene–Styrene (ABS) which is thermoplastic polymer is used for manufacturing the quadcopter frame. ABS is durable, easy to process and cheap. It's low density and corresponding high strength make it an ideal choice for an optimized quadcopter frame. ABS also has some disadvantages like the need for heated bed while manufacturing and moderate strength [16-18]. Also, choice of process parameters is very important [19-20]. Table I gives the material properties of ABS.

Many components of the quadcopter like arms, body, landing gear, camera mount and protective mount are printed using ABS material and have been already proved to be successful [21-22]. In this paper, the weight of a quadcopter frame is optimized for maximum thrust-to-weight ratio using design of experiments (DoEs). Also, the quadcopter frame is designed as a single piece assembly in this paper.

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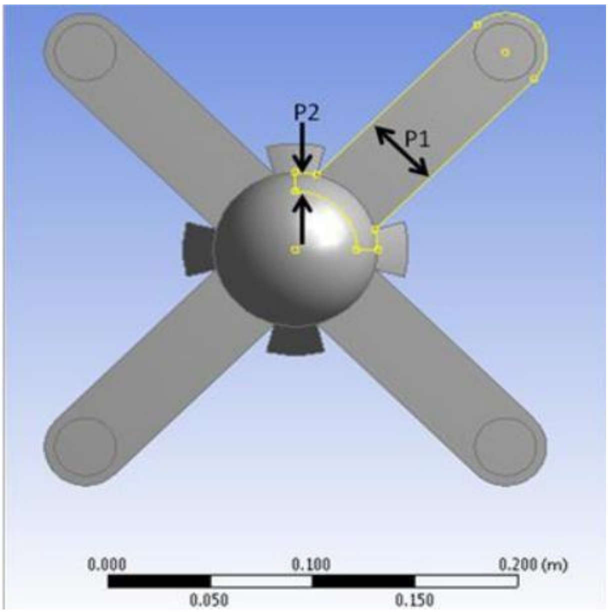
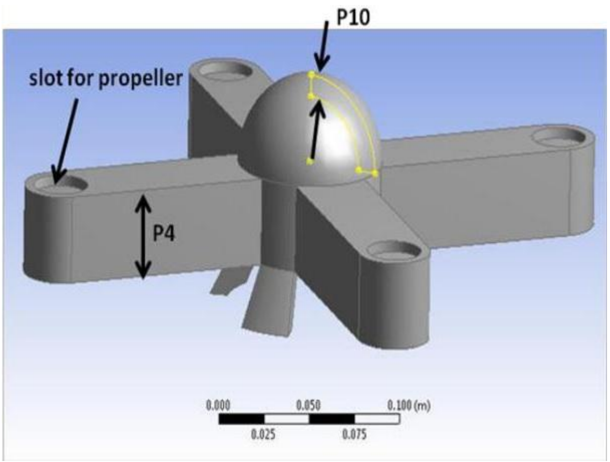
II. Design

Initial design used for optimization is a four-armed copter with an arm height (P4) equal to 0.04 m which is also the height of the leg of a commercially available quadcopter frame. Initial design includes a hemispherical dome of radius 0.04 m and thickness (P10) of 0.01 m as shown in Fig. 2. The initial design also includes slots for placing the propellers as shown in Fig. 2. The initial width of the arm (P1) is 0.04 m and thickness of the ring connecting the four arms (P2) is 0.01 m. Initially, thickness of the ring is same as the thickness of the dome which is centrally located. Arms take the majority of the thrust and centrifugal loads whereas ring and the dome mainly take the payload weight. The goal of this work is to optimize the parameters P1, P2, P4 and P10 for high thrust-to-weight ratio. Another parameter used for the optimization of the frame is the thickness of leg (P11).



(a) Top view



(b) Isometric view

Fig. 2 Initial geometry of the quadcopter

As mentioned earlier, the material used for modeling the quadcopter frame is Acrylonitrile butadiene styrene (ABS).

Table I ABS material properties

Density	1080 kg/m^3
Poison's ratio	0.422
Young's modulus	2.9 GPa
Tensile strength	50 MPa
Compressive strength	69 MPa
Yield strength	44.1 MPa

Initial static structural analysis

An initial static structural analysis has been carried out to check the model for its deformation and stress development behaviour. Following are the boundary and loading conditions (Fig. 3)

Boundary conditions

- Legs of the frame are fixed.

Loading conditions

Thrust force: A thrust force of 9 N is applied at each arm initially but is considered as a variable since the main objective of this optimization is to maximize the thrust-to-weight ratio.

Centrifugal force: Centrifugal force of 15.556 N is applied at each propeller slot.

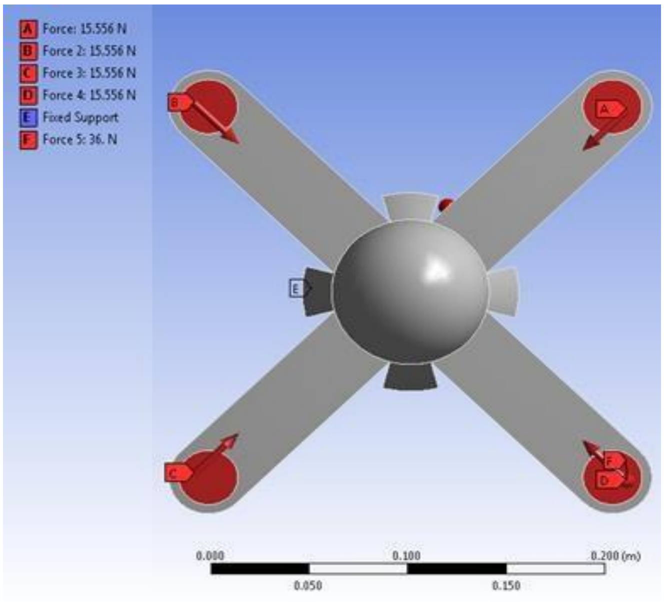


Fig. 3 Boundary and loading conditions

Mesh used for the simulation is a fine tetrahedral mesh with a maximum element size of 0.002 m as shown in Fig. 4. This resulted in a total of 10, 47,776 elements. Initial mass of the frame is 1.006 kg.

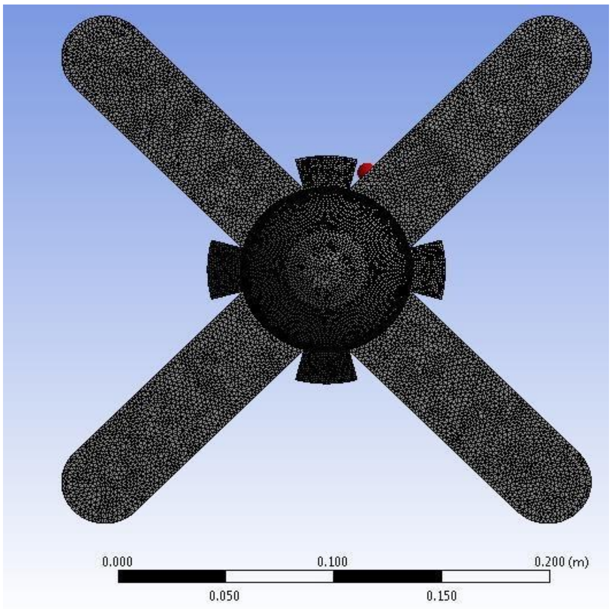
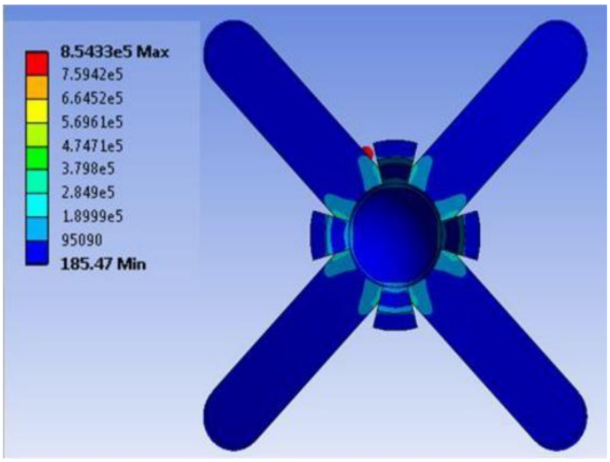
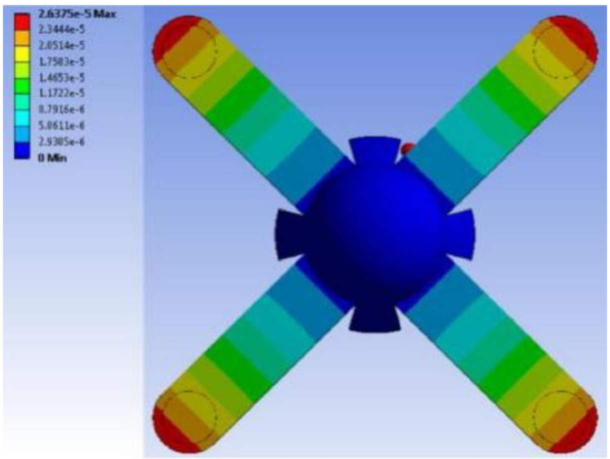


Fig. 4 Meshed geometry of quadcopter

Total deformation and equivalent stress are the two parameters that are studied in the simulation and the results are plotted in Fig. 5.



(a) Deformation



(b) Stress Distribution

Fig. 5 Finite element solutions

The results prove that there is a lot of scope for optimizing the model. Hence the optimization is carried out as described in the next section.

III. Optimization

Optimization of the geometry aims at modifying the input parameters mentioned in the design section, so that the frame has maximum thrust-to-weight ratio and the frame withstands the aerodynamic forces and gravitational pull. Many key parameters like, material properties and geometry play a vital role in reliability and robustness of the UAV during in-service condition. Influence of each of the parameters is studied under sensitivity analysis. Hence, sensitivity analysis for the design of experiments is needed to arrive at an optimum geometry. Design parameters, objective functions and topological constraints for the current quadcopter frame are given in section 3.1.

Table II Design parameters

Parameter	Lower bound	Upper bound
Arm width (P1)	0.02m	0.044m
Arm ring thickness (P2)	0.003m	0.011m
Arm height (P4)	0.003m	0.044m
Dome thickness (P10)	0.003m	0.011m
Leg Thickness (P11)	0.003m	0.011m
Thrust force/propeller (P8)	14N	5N

Objective functions and topology constraints

Objective functions chosen for optimizing the design are:

1. To maximize the thrust-to-weight ratio
2. To limit the maximum possible von Mises stress in the frame. Here a factor of safety of 2 is taken for equivalent von Mises stress and
3. To minimize the deformation of arm.

Topological constraints chosen for optimizing the design are:

1. Maximum possible von Mises stress is limited to 20 MPa and
2. Maximum possible deformation is limited to 5 mm.

IV. Results

Optimization method used for this simulation is an adaptive multi-objective method which is a variant of the popular Non-dominated Sorted Genetic Algorithm which is based on controlled elitism concepts. This method supports multiple objectives and constraints and aims at finding the global optimum. Limitation of this method is that it is applicable to only continuous and manufacturable input parameters. A list of 52 samples with a combination of different input parameters is generated in the first iteration. Based on the results in each of the iterations a set of three combinations are generated by the optimization

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tool that are considered to be the best. Since the priority in this simulation is to identify the sample that yields the best thrust-to-weight ratio, the following sample is chosen as the best possible combination of parameters with the highest possible thrust-to-weight ratio.

Table III Input Parameters

Optimum combination of input Parameters	
P1 (m)	0.032231
P2 (m)	0.005827
P4 (m)	0.042876
P10 (m)	0.009281
P11 (m)	0.0075707
P8 (N)	11.65

Table IV Output Parameters

Resulting output parameters	
Max. stress (Pa)	8.95E+05
Max. deformation (m)	4.45E-05
Thrust-to-weight ratio per unit payload	4.287

The resulting shape after optimization is as shown in Fig. 6. Since the goal is not only to get the best combination for thrust-to-weight ratio but also to design a model that can be 3D printed as a single piece, input parameters are adjusted to three digits after the decimal point. The resulting model is then subjected to a static structural simulation to check the model. Mass of the optimized frame is 108 grams.

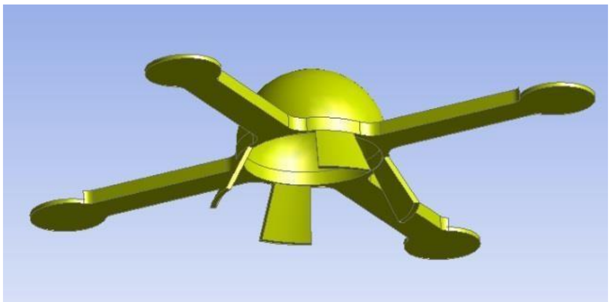
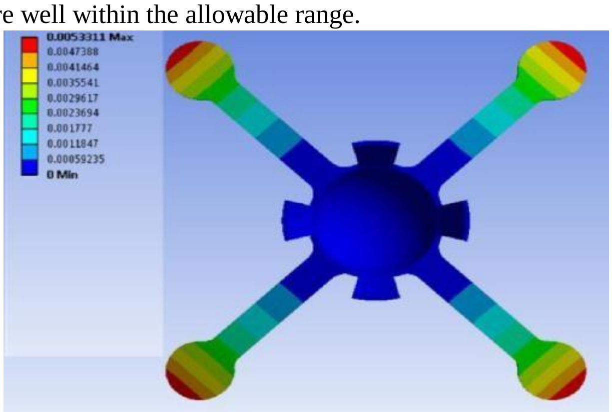
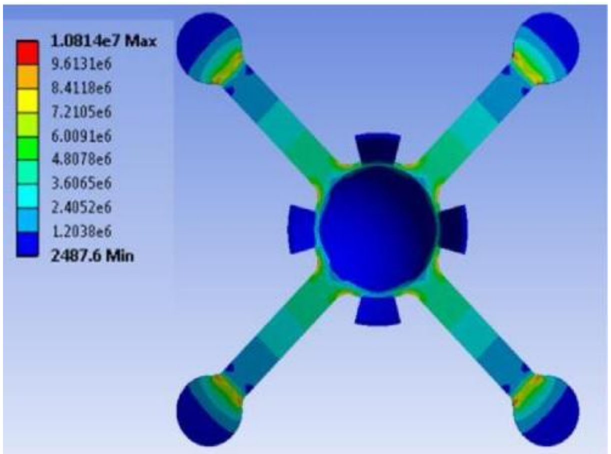


Fig. 6 Optimized shapes that can 3D printed as a single piece

The stress and deformation results are shown in Fig. 7 and are well within the allowable range.



(a) Deformation



(b) Stress Distribution

Fig. 7 Results for the optimized model

It may be observed here that the stress concentration is taking place at the corners of the joints between arms and propeller slot. This can be further reduced by replacing the sharp joints with fillets.

Another aspect of this work is to study the influence of each parameter on the output parameters or in other words, to carry out sensitivity analysis of the input parameters. Fig. 8 shows that parameter P10 i.e., the dome thickness of the quadcopter has a large influence on the output as compared to any other parameter.

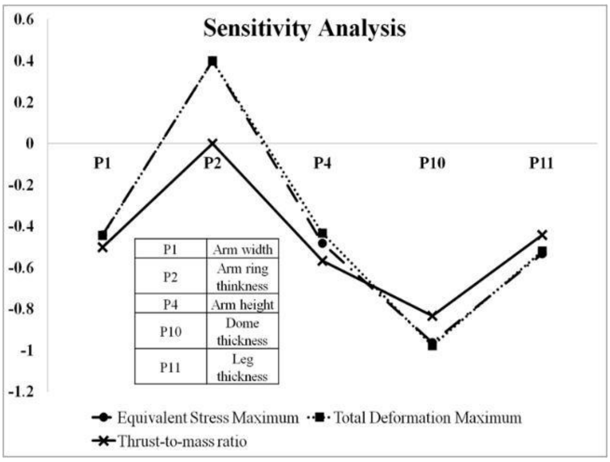
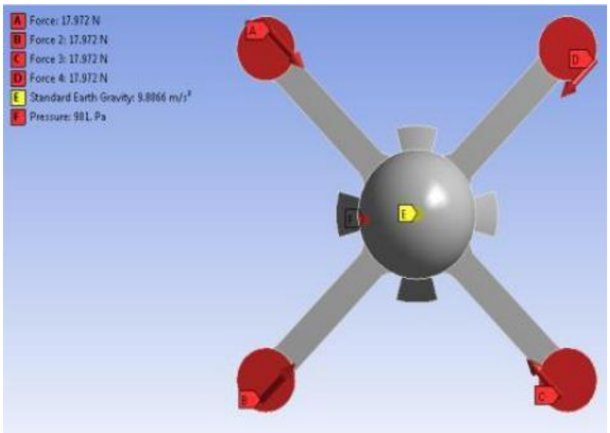


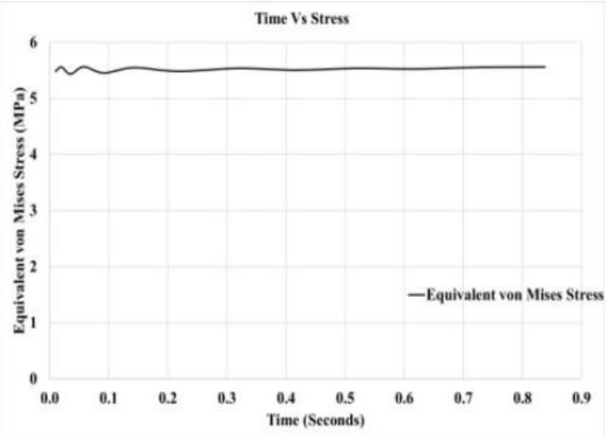
Fig. 8 Results of the sensitivity analysis

Validation of the model

Numerical validation: Since in real time scenario, the quadcopter is flying rather than having its legs fixed. Hence to simulate the real time response of a quadcopter, transient simulation has been carried out. Instead of "fixed" boundary condition, a payload is applied at the center of the frame. The optimized model is subjected to transient simulation with an overall thrust of 46.6 N and a payload of 1 kg at the center i.e., to the dome. The loading and boundary conditions are shown in Fig. 9(a) and the resulting variation of equivalent von Mises stress is shown in Fig. 9(b). The results clearly show that the stresses are within the range and the frame can take up the transient loads quite effectively. Also, it may be observed that the stress is fluctuating initially but has reached a steady state after few milliseconds.



(a) Loading condition



(b) Time Vs Stress graph

Fig. 9 Transient simulation

Physical prototyping: Next goal is to prove that the model can be manufactured without the need for any assembly. Hence the frame of the quadcopter is printed as a single piece using ABS as material and the image of the 3D printed frame is shown in Fig. 10. It took 18 hours to print the model with a layer thickness of 0.2 mm and 100% infill.

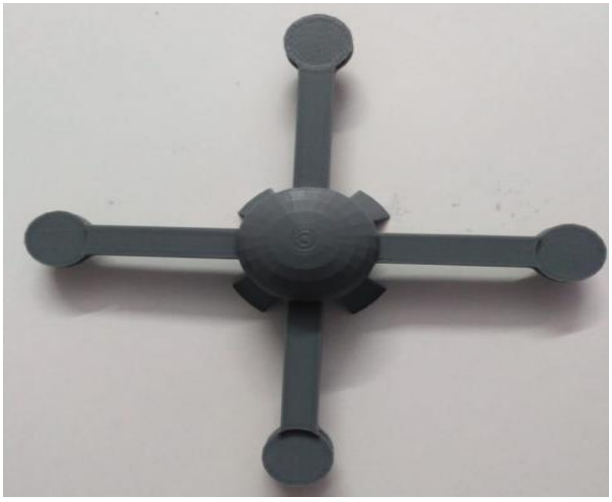


Fig. 10 3D printed optimized quadcopter frame

V. CONCLUSION

This paper presents the work carried out to optimize a single piece assembly quadcopter frame for both mass and thrust-to-weight ratio using design of experiments. The resulting mass of the optimized quadcopter frame is 108 grams which is less than the mass of a commercially available quadcopter frame. Also, the thrust-to-weight ratio of the optimized model is 4.287 which is higher than any commercially available non-racing quadcopter frames. Hence, it can be concluded that optimizing for thrust-to-weight ratio rather than mass yields a better optimized model. Sensitivity analysis shows that the dome thickness is a critical parameter in the design of the frame. In comparison to the commercially available quadcopter frame there is reduction of 30.77% in mass and an increase of 35.1% in thrust-to-weight ratio.

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