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Design of Monocoque Quadcopter Structure through Integration of Additive Manufacturing and Topology Optimization

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Abstract**:** ***The concept of topology optimization and additive manufacturing is inculcated for designing the structural frame of a quadcopter. Static structural analysis of the quadcopter design space is carried out using the principles of finite element analysis to understand the deformation and stress distribution. Topology optimization is carried out with mass minimization as an objective and allowable maximum stress as a constraint. Topologically optimized models have complex and uneven shapes which can be built only by additive manufacturing process. Fused deposition modelling (FDM) is suggested for manufacturing the frame as a unified body without the need for assembling structural components of Quadcopter frame. The manufacturing procedure using FDM are discussed based on the principles of design for additive manufacturing. Based on the validation of optimized model through static structural analysis, it is concluded that integration of design methodology with topology 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 innovative shape of minimum weight with complex geometry.***

Index Terms**:** ***Design for additive manufacturing, static structural analysis, Topology optimization, Quadcopter frame***.

I. INTRODUCTION

Quadcopter UAV's rapidly attaining their eminence in the fields of aerospace, and armed forces because of its ability to operate in hazardous conditions. The need to manoeuvre under suitable payload is perhaps tedious task pertaining to multifaceted applications. Since the endurance is influenced by the payload and all-up weight of the quadcopter, it is desirable to reduce the structural weight of Quadcopter [1]. It can be achieved either by designing light weight electronics (battery pack, ESCs, wiring etc.) or by designing a light weight frame. In this paper, emphasis is laid on the design of light weight frame. Thus, it is aimed to reduce the mass of the vehicle for improving the payload capacity. The frame is one of the main load-bearing parts and it constitutes up to 30% weight of the vehicle. Thus, it became a challenging task for researchers to design the lightweight frame which must be strong enough to withstand all the forces exerted. Consequently, through topology optimization, the shape of the Quadcopter structure is modified to minimize the mass of the frame. Topology optimization is a mathematical tool used for finding optimal distribution of material through maintaining its functional requirements [2]. It is used for designing new product and also to redesign the existing product [3]. It allows us to reduce the weight of the model by removing the material which is not necessary to meet the designed constraints. The material distribution is based on its design space with an aim to provide a solid body with minimal weight. It optimizes the layout by redistributing the material according to objective function subjected to prescribed constraints. The method of topology optimization is well suited for optimizing the shape of aerospace structures due to its high geometrical design freedom [4]. The first step in topology optimization involves partitioning the model in to design space and non-design space. Design space refers to the area that needs to be optimized, whereas non-design space refers to area which should not be altered [3]. Topology optimization often results with rough and uneven shape during the course of subtractive manufacturing. Hence additive manufacturing (AM) technique is recommended [5].

The present work focuses on employing fused deposition modeling in fabrication of monocoque Quadcopter structure for the topologically optimized structure.

II. FUSED DEPOSITION MODELLING AND UAV DEVELOPMENT

Fused deposition modelling is one of the additive manufacturing techniques that is widely used for fabrication of functional parts [6]. This method is based on solidification of molten material that extrudes from the nozzle head [7]. The process of manufacturing in FDM starts with modeling a geometry and converting it in to stereolithographic (STL) file format [8]. Then, the model needs to be checked for errors like gaps, dangling edges and flip triangles etc., and should be corrected. Finally, the model has to be sliced in to layers and G-codes will be generated. Then the G-codes are fed up into the machine. The machine will build the part layer by layer until the whole part is printed.

Owing to its advantages like reliability [9] low cost and wide variety of printing materials, FDM is emerging as the most popular option [10].

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Apart from universities, research centres and industries, FDM technology deployment by researchers has proved the relevance of FDM technology for the development of UAVs [11-12]. Complex shaped UAVs along with their embedded electronics are printed successfully and showed improvement in the aerodynamics performance and structural efficiency of UAVs. Due to its design freedom and capable of printing the parts irrespective of its geometrical complexity, it is widely accepted in fabrication of functional parts. Apart from that, the layer-by-layer technique used by FDM produces components that are anisotropic in nature. Many researchers have shown that part orientation, layer thickness, and feed rate influences the mechanical properties of the printed product to a great extent. Therefore, a good combination of process parameters is essential in overcoming or reducing the influence of these problems [13-14]. In FDM, it is always essential to reduce the time of printing and support material. In order to eradicate these issues concept of design for additive manufacturing (DFAM) is introduced. In the DFAM of fused deposition modelling allows the designer to take full of advantages of design freedom in topology optimization. DFAM provide rules and guidelines to the designer which enables to manufacture the part in lesser time with low material support. This manuscript discusses on integration of topology optimization with DFAM to produce light weight quadcopter frame.

III. COMPUTER AIDED MODELING AND FINITE ELEMENT ANALYSIS

In this work, monocoque quadcopter frame is designed with the help of topology optimization. Since the frame geometry is symmetric, a solid block with 450mm diagonal length is considered for initial design. A slot is provided for mounting electronics and also four slots are provided at the edges to fix motors as shown in Fig. 1. The basic geometry is defined to identify design and non-design spaces. Subsequently, the design space is meshed with a mesh element size of 1 mm. Propeller slots and base plate are identified as non-design space. Topology optimization based on finite element (FE) analysis is discussed in the following sections, which converts a solid space into design by iterating till the required constrained conditions are satisfied.

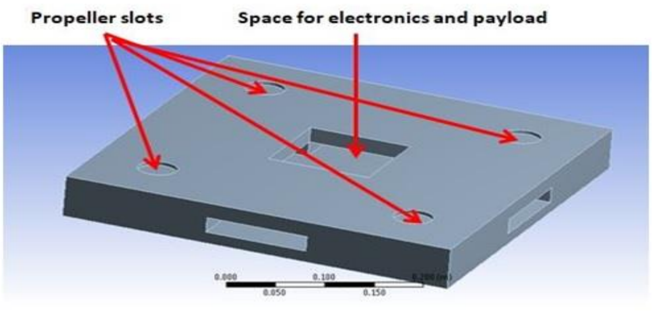
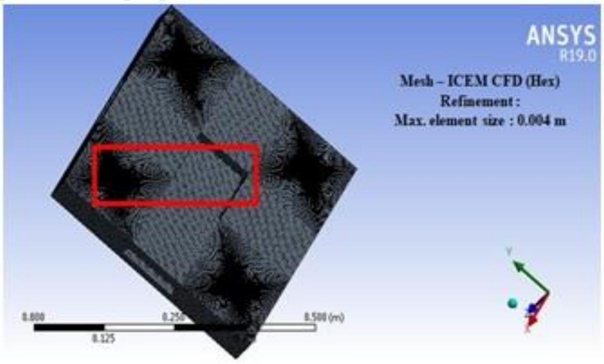
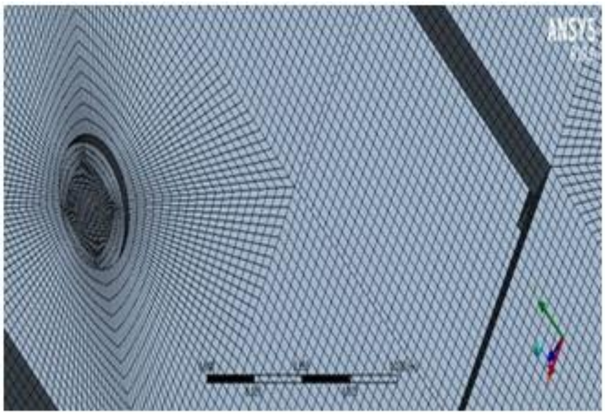


Fig. 1Design geometry

ANSYS design modeller is utilized for obtaining basic geometry of solid part. For having control over the shape, meshing is done manually using ANSYS ICEM CFD platform instead of automatic mesh generation tool. Fig. 2 shows the meshing of cad model. The geometry is divided into a total of 424430 hexahedral elements. Acrylonitrile butadiene styrene (ABS) is used as the material and its properties are given in the Table 1. Finite element analysis is implemented for enumerating the values of deformation and stress concentration. The model is analyzed by assigning a fixed constraint at the centre of the frame and thrust forces are applied at the propeller slots [15].



(a) Mesh in ICEM CFD (Hex)



(b) Magnified figure

Fig. 2 Meshing of the CAD model

Table 1. Mechanical properties of ABS [16, 17].

Property	Value
Density	1080 kg/m^3
Young's Modulus	2.5 GPa
Poissons Ratio	0.422
Tensile Strength	40 MPa
Compressive Strength	69MPa

For obtaining optimal shape, static structural analysis is carried out with the following boundary and loading conditions:

1. Centre of bottom plate is fixed and
2. Thrust at the propeller slots

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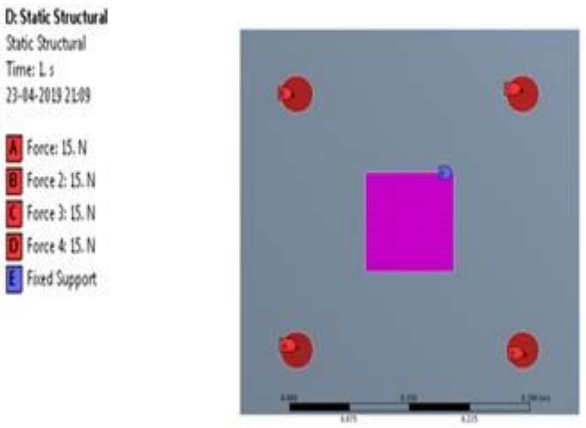
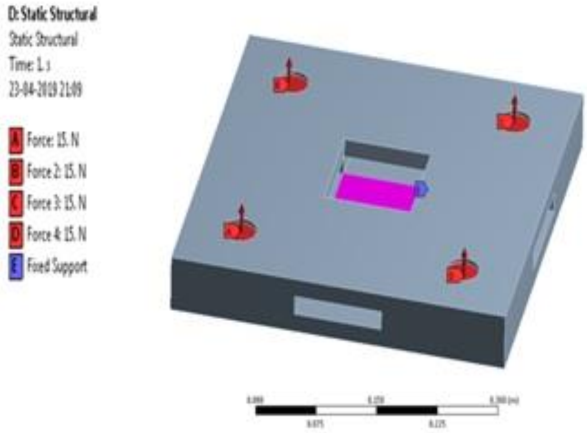
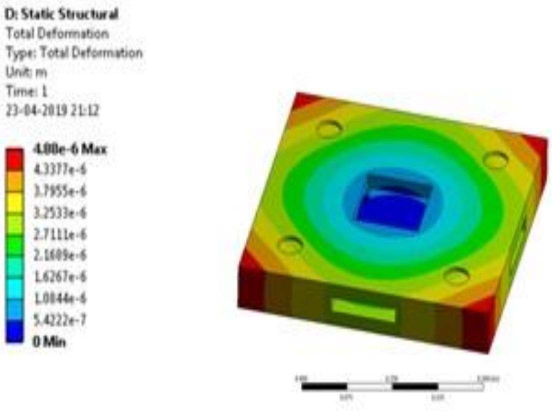


(a) Top view

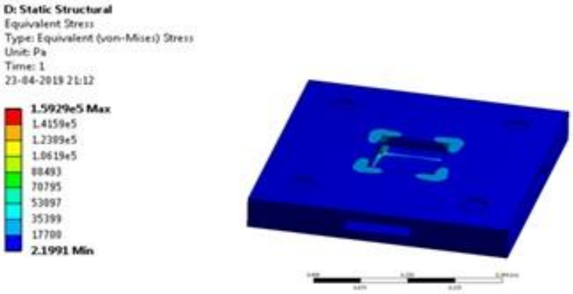


(b) Isometric view

Fig. 3 Description of load and supports



(a) Deformation



(b) Stress Concentration

Fig. 4 Von-Mises stress and maximum deformation

The FE analysis results suggested that minimal displacement of 0.004 mm and maximum stress of 0.15 MPa is encountered.

IV. TOPOLOGY OPTIMIZATION

The topology optimization (based on finite element solution) in the design of mechanical and aerospace structures is unparalleled. It is also called layout optimization in the sense that the shape optimization works around the known geometries whereas topology optimization distributes the material in such a way so as to reduce its weight [18-19] without any compromise in performance. Hence the shape from a topology optimization is always novel in nature. When there aren't any existing designs, it works by taking a solid block of material of appropriate shape and removes the material based on objective functions and responsive constraints. The process of redistribution of material is carried out iteratively and for each iteration FE analysis is performed to satisfy the loading and boundary conditions.

In this model, a frame is considered to be in equilibrium with static conditions. In a static topology optimization problem, the goal is to ascertain the material distribution, which optimizes a certain objective function (e.g. maximum displacement, minimum compliance and maximum stress) for a structure with a given loading and boundary conditions, subject to a prescribed volume. The distribution of the material is limited to the design domain, Ω, which forms part of a larger domain which can include areas prescribed to be solid or void. The general topology optimization problem is depicted in Fig. 5.

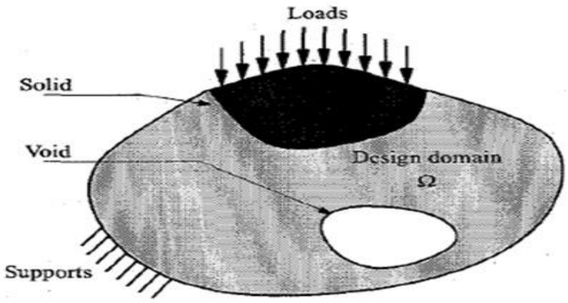


Fig. 5 General Topology optimization Problem

In this work, standard formulation also called “maximum static stiffness” design is employed for optimizing the topology of the quadcopter. In the course of design optimization, for a given loading conditions subjected to reduce the mass of the Quadcopter structure; minimization of structural static compliance (SSC) is achieved. It is equivalent in terms of maximizing the global structural static stiffness. In this case, the optimization problem is formulated which is given as,

“ SSC = a minimum w.r.t ρ_i” (1)

Subjected to: "$0 \le \rho_i \le 1$ where i=1,2,3…… N" (2)

"$M \le M_0 - M^*$" (3)

Where,
ρ_i are the densities and
ρ_i= 0represents material to be removed and
ρ_i= 1 represents material that should be kept.
M =Computed mass
M0=Original mass
M*=Amount of material to be removed

A. Objective functions and Design constraints

Topology optimization is carried out by considering Compliance as objective function and minimizing mass as constraint. The constraints are subjected to the mechanical properties of the material. The formulation of optimization problem is as follows:

Objective function: To minimize structural compliance
Constraint: Minimize mass
Subject to: Geometry Mass ≤ 0.35 kg
Von-Mises stress ≤ 20 MPa
Deformation ≤ 1 mm
Maximum principle stress ≤ 4.147MPa

The optimization is carried out with a convergence accuracy of 0.1% and a penalty factor of 3. The optimized model is achieved after 21 iterations as shown in Fig. 6.

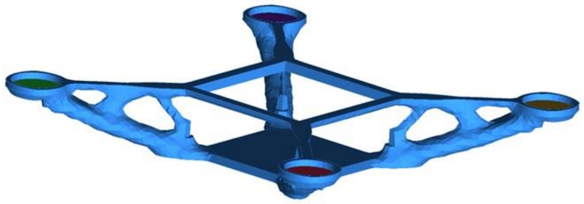


Fig. 6 Topology optimized model

B. Validation of results through static structural analysis

For validating the optimized model, Finite element analysis is performed to ensure that stresses and deformation are within acceptable limits. The analysis is carried out with same load and boundary conditions as used for optimization. Since the structure is much smaller in volume than the initial block, a mesh with 35930 tetrahedral elements as shown in Fig. 7 is used. The results show that the optimized model is in within the limits.

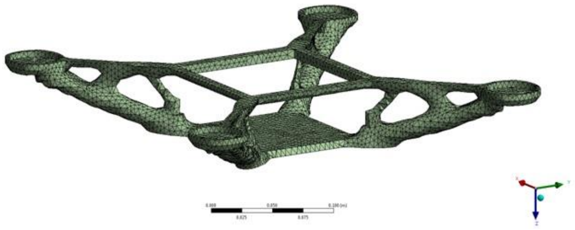


Fig. 7 Mesh for topology optimized model

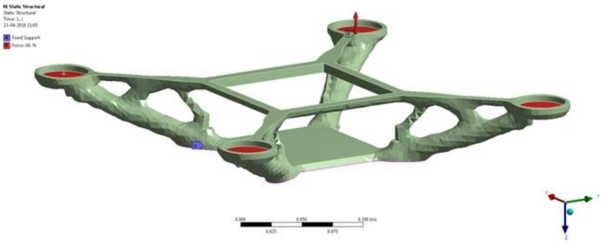


Fig. 8 Definition of load and supports

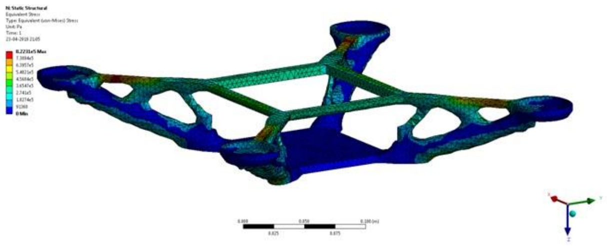


Fig. 9 Von-Mises stress

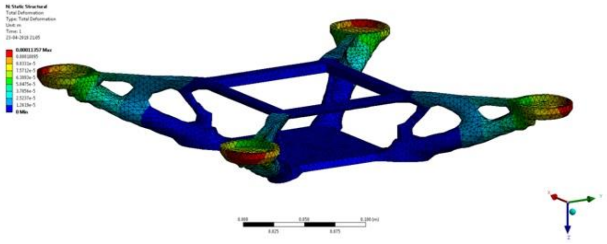


Fig. 10 Maximum deformation

The FE analysis results that displacement of 0.8 mm and maximum stress of 0.8 MPa is encountered.

V. DESIGN FOR ADDITIVE MANUFACTURING GUIDELINES

The application of design for additive manufacturing in manufacturing is increasing tremendously due to its manufacturing feasibility. The advantages of FDM process allows to manufacture UAV structure easily in comparison to conventional methods. It may be understood that the process challenges like overhang angle, orientation and the need for support structures are crucial for the successful manufacturing using FDM.As stated earlier, in order to reduce the amount of support material and printing time, it is suggested to print the model by following DFAM based suggestions [20].

In this specific model, DFAM rules like printing in the direction of loading and minimum wall thickness of more than 0.8 mm are maintained. As a result of this it took only 18.5 hours of printing time as shown in the Fig. 11. From the data, it is noted that 66% of material is consumed for printing of actual model and only remaining 34 % is consumed for supporting material.

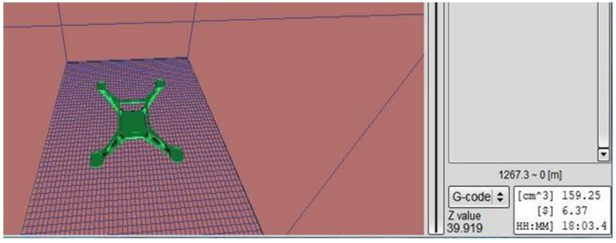


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Fig. 11 Model printing time

VI. CONCLUSION

In this work, integration of topology optimization with additive manufacturing of quadcopter frame is realized. Both compliance and mass are considered together for achieving optimum product design layout.

ANSYS topology optimizer resulted geometry with a lowest possible weight which is capable of withstanding all-up weight of 8kg and satisfying the constraints. Initially the design started with a solid block which weighs about 9.35 kg. With the help of topology optimization, the weight of the model is reduced to 0.317 kg. The total deformation is increased from 0.004 mm to 0.8 mm and stresses are increased from 0.15 MPa to 0.8 MPa. From the analysis, it is proved that stresses and deformations are within the acceptable limits throughout the part. Thus, it can be concluded that integration of topology with additive manufacturing shows promising results in reducing the weight of quadcopter structural frame. Optimized model is a monocoque body which can be manufactured using fused deposition modeling without the need for any assembly.

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Esakki Balasubramanian had completed his PhD in the field of Robotics and Control at Concordia University, Montreal, Canada. He has more than ten years of research experience and pursued various funded projects under the aegis of DST, DRDO and IEI. He has collaborated with Taiwan, Canada and Korean scientists in the development of flapping wing and rotary unmanned aerial vehicles for diverse applications, design of test rig to measure aerodynamic forces of ornithopters, integration of sensors and data acquisition systems. His research interests are UAVs, robotics, rapid prototyping, control and sensors with online data acquisition.

Chandrasekhar Udayagiri is presently working as a Visiting Professor at the Department of Mechanical Engineering, IIT Bombay. He is an Engineering Professional with more than three decades of experience in gas turbine engineering, additive manufacturing and mechanical analysis of aeronautical systems. He received a Gold Medal from the former President of India Dr. A.P.J Abdul Kalam for his academic achievements at IIT, Madras and also a commendation model from the scientific advisor to his contributions to design and development of aero engine components. He serves on the editorial board of International Journal of Rapid Prototyping and the Springer – Institution of Engineers (India) Journal on Mechanical Engineering. He setup the country’s first-ever additive manufacturing laboratory at GTRE – DRDO, Bangalore in 1997 and carried out several projects related to rapid prototyping, rapid tooling and also small series production of complex engineering parts including unmanned aerial vehicles, turbo charger assemblies, and turbojet turbines.