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Simulation Studies for Structural Optimization of A 3D Printable Quadcopter

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Abstract

This work investigates the new structurally optimized 3D printable quadcopter drone frame. A model is designed and analyzed by finite element analysis to study its mechanical behavior for thrust at every propeller of magnitude 20 N. Topology optimization strengthens the structure by strengthening the highly stressed region, thereby minimizing the overall mass. Two materials, namely PLA and ABS, have been investigated in this work for their suitability. The optimized PLA design showed a 14.02% mass reduction with a maximum von Mises of 12.84 MPa. ABS designs with reinforced stress concentration regions demonstrated significant mass reductions while maintaining stress below its yield strength. This made ABS the better material in providing an optimized, lighter design with lower stress levels than PLA. Testing revealed that the ABS frame would support expected loads without failure, proving the best material to be used in this application of a UAV.

Keywords: Additive manufacturing (AM), Quadcopter optimization, Finite element analysis (FEA), 3D printing materials, Topology optimization.

1. Introduction

In recent years, with significant developments in embedded control systems, communication technologies, and sensor miniaturization, academic and research interest in UAVs has developed rapidly, especially quadcopters. Among multi-rotor designs, having four rotors, this is one of the most versatile, efficient, and maneuverable systems employed in many military and civilian applications [1]. VTOL capability enables it to take off and land vertically, hence relieving the constraint of the traditional runway. This allows its application in areas with confined spaces [2], [3]. Despite this, other multirotor UAVs exist, such as hexacopters and octocopters. Some advantages of a quadcopter include reduced power consumption, improvement in flying endurance, and reliable design with fewer critical components. Excellent agility in yaw control, realized by tilting the propellers, makes it very maneuverable in tasks requiring small displacements, such as surveillance and reconnaissance missions. Besides, the capability of mounting a camera with a wide field of view enhances its effectiveness in these missions. With developments in UAV technology, quadcopters are also becoming popular, from search and rescue to remote sensing and delivery applications, by taking advantage of enhancement in their automatic flight control algorithms, including PID controllers, for enhanced stability and performance [4]. Adopting 3D printing with materials like ABS and PLA is even more important for customization and efficiency, as ABS provides strength and heat resistance. At the same time, PLA is an eco-friendly and easy-to-handle material [5]. Continuous development in quadcopters guarantees new frontiers in UAV applications across industries and is said to be the future of flying robots [6].

In particular, AM is suited for manufacturing small batches of UAV parts to exact dimensions with good repeatability directly from CAD models, reducing labor costs and material waste [7]. Indeed, it enables complicated shapes to be fabricated at lower costs than traditional methods; thus, it is ideal when lightweight UAV structures are produced in limited-series batches, as demonstrated by Goh et al. [8]. Several works reported the fast fabrication of UAV components using AM techniques like stereo lithography, FDM, and foldable constructions [9], [10], [11]. However, 3DP has been explored by a few researchers to fabricate quadcopter components. Some researchers successfully fabricated quadcopter frames using ABS, PLA, and photopolymer plastics [12]. Satra and Shetty performed optimization of the frame weight by iterative procedures using AM techniques; similarly, Maldonado et al. have shown modular reconfigurable UAVs whose components were 3D printed. Takato and Shirayama also presented the development of mechanisms of rotor systems using FDM.

Leonardi's investigation of 3D printing mechanisms for micro-flapping wing vehicles was beneficial in illustrating one way to design unified quadrotor frames that could save time in the assembly and facilitate the installation of motors. However, the unified body has never been tried concerning functional and aerodynamic performance [13]. Ahmed et al. [14] proved that fabricating a UAV with 3D printing may result in cost-effectiveness, structural efficiency, and improved aerodynamic performance due to the less use of material. Ahn et al. [15] optimized DOE for tensile and compressive strengths of ABS components fabricated by FDM. They concluded that air gap and raster orientation are the two most significant factors in determining the tensile strength anisotropy of ABS. Chockalingam et al. [16] further improved those characteristics using CCD and a genetic algorithm. Injection molding was used in works [17], [18] by Yang et al. to design a 20-cm flapping-wing micro aerial vehicle and [19] to obtain flying micro cars weighing less than 10 grams by Hsiao et al. Even the injection molding method was time-consuming and expensive when Yang obtained the prototype design. While designing this quadcopter the use of topology optimization with taking in count the material choice between PLA and ABS and the factor of weight is also taken into account.

2. Optimized structure design of quadcopter

A unibody design for a 3D-printed drone was conceptualized using SOLIDWORKS. Detailed FEA simulations were performed in ANSYS Workbench to optimize the initial 30.159 g monocoque design. Parameters like thickness distributions, ribs, honeycomb structures, and panels were evaluated. Stress and deformation results identified high-stress areas. Further iterations included trusses and buttresses to reinforce these areas. After multiple analysis and design cycles, a lighter 25.93 g structure was achieved, a 14.02% or 4.229 g reduction compared to the initial design. The optimized design demonstrated comparable rigidity and strength with an improved strength-to-weight ratio. The designed structure is given below:

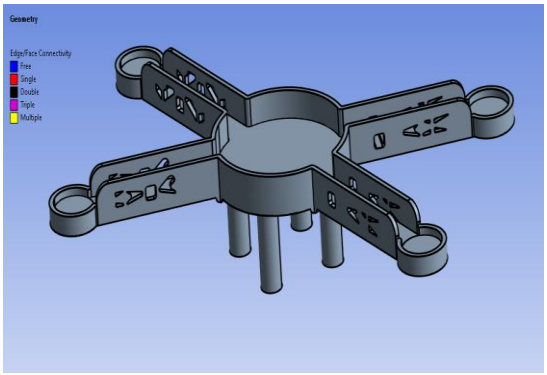


Fig.2.1. Optimized structure of Quadcopter

3. Finite element analysis

The mesh size is 0.8 mm. The total nodes and elements are 12743 & 70147, respectively. A good mesh with optimally sized elements and appropriately placed nodes is crucial for achieving accurate results from FEA simulations. The analysis of the quadcopter using ANSYS software considers the following loading conditions: The lowest surface of the basement construction receives fixed support, and a thrust of 20N is applied at each propeller. The figure of condition applied to the quadcopter is given below:

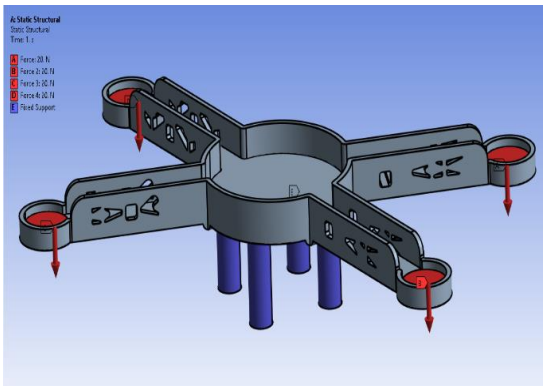


Fig.3.1. Boundary conditions

3.1. FEA analysis for PLA material

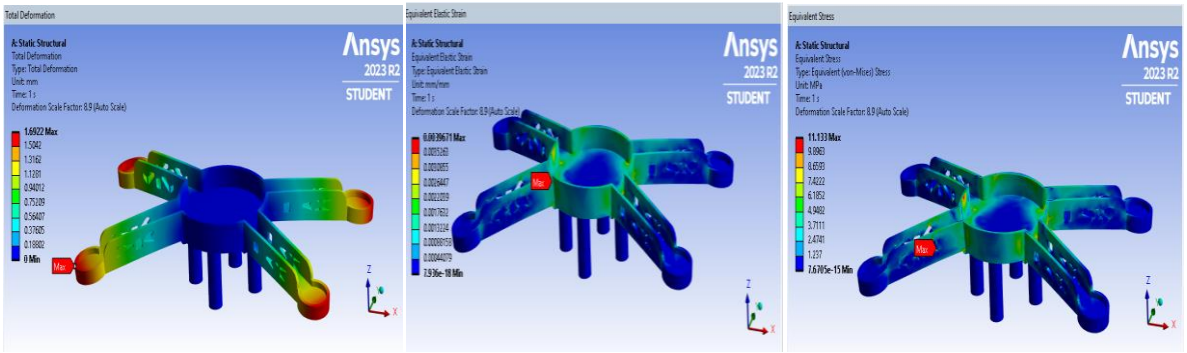


Fig.3.2. Contour Plots of deformation, strain, and von-mises stress for PLA

The above three pictures demonstrate that the optimized PLA (Polylactic acid) design has significantly improved the material's mechanical characteristics. Deformation capability saw the most significant gains, with maximum flexibility up to 2.07 mm and average deformation to 0.56 mm, providing enhanced elasticity under load. Strength also increased substantially - average stress was 1.5MPa, and maximum reached 16.6 MPa, strengthening load-bearing. Ductility grew dramatically with average strain at 5.06×10-4 mm/mm, allowing more deformation before yield. Overall, the custom design process transformed PLA into a higher-performance thermoplastic by proportionally enhancing its deformation, strength, and elasticity characteristics.

3.2. FEA analysis for ABS material

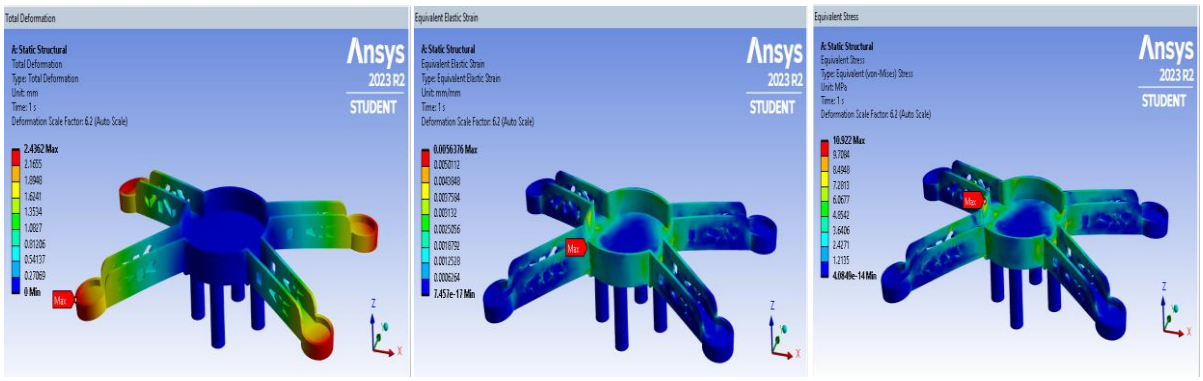


Fig.3.3. Contour Plots of deformation, strain, and von-mises stress for ABS

The above pictures demonstrate that ABS material design achieved more modest improvements than PLA, which still effectively preserved the material's mechanical strengths. Average deformation saw a negligible change at 0.93626 mm. However, maximum flexibility increased to 2.4362 mm, allowing for enhanced elastic bending. Strength properties, which abs already excelled at, remained foremost as average stress improved slightly to 1.601 MPa and maximum strength reached an exceptionally high 10.922 MPa, reinforcing its premier load-bearing functionality. Although the average strain declined minimally to 7.38×10^{-4} mm/mm, minimum and maximum bounds demonstrate retention of suitable tensile ductility.

4. Result and comparative discussion

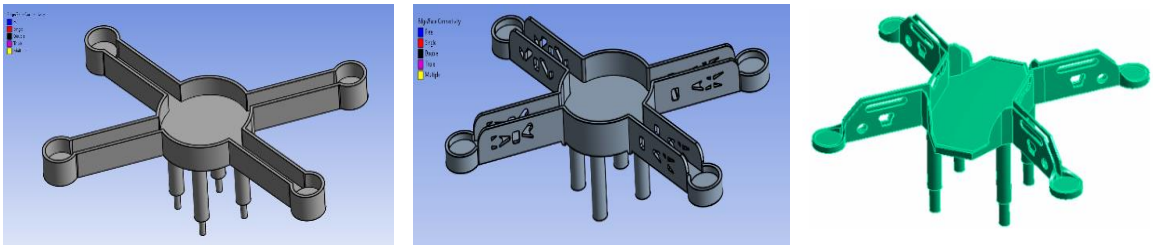


Fig.4.1. Primary structure, optimized structure, and previously proposed structure [20]

4.1. Comparative analysis for PLA material

Table 4.1. Comparable Data Set of PLA Plastic

	Deformation (mm)	Von-mises Stress (MPa)
Primary Data	0.93208	14.878
Optimized Data	0.93626	10.922
Previous Study	0.962	10.698
Error Percentage	2.68%	2.09%

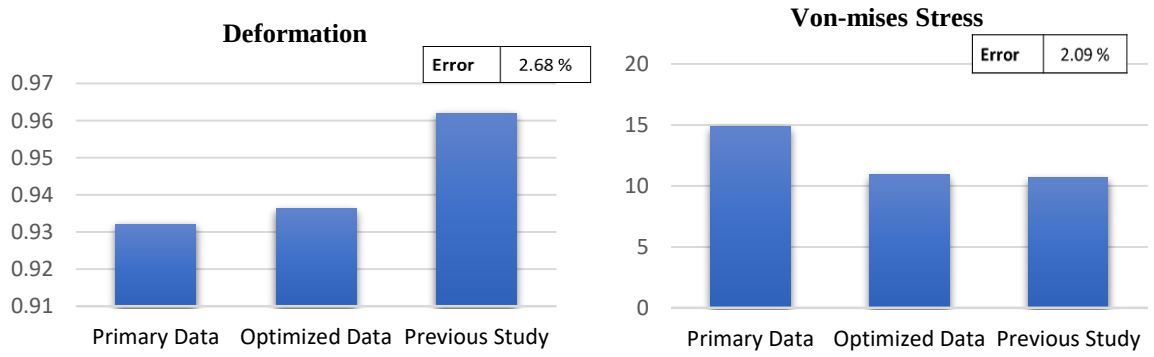


Fig.4.2. Comparison of deformation and von-mises stress for PLA material

This data appears to be from the same structural analysis study but with different initial results. The primary data shows deformation of 0.93208 mm and von Mises stress of 14.878 MPa. After optimization of the model and analysis, the values changed to 0.93626 mm deformation and 10.922 MPa von Mises stress. These optimized results were validated against a previous study, which found 0.962 mm deformation and 10.698 MPa von Mises stress. The percent error between the optimized data and the previous study was calculated. For deformation, the error was 2.68%, slightly higher than the 2% target but still relatively small. The mistake for von-mises stress was even lower at 2.09%. While the primary and optimized values in this case were different from the previous data set, the validation step again confirmed the optimization process successfully achieved results consistent with past work. Both errors were under 3%, demonstrating that the model optimization led to output that closely matched what had been found from similar prior analyses.

4.2. Comparative analysis for ABS material

Table 4.2. Comparable Data Set of ABS Plastic

	Deformation (mm)	Von-mises Stress (MPa)
Primary Data	0.6163	12.839
Optimized Data	0.56182	16.597
Previous Study	0.5517	17.02
Error Percentage	1.83 %	2.48 %

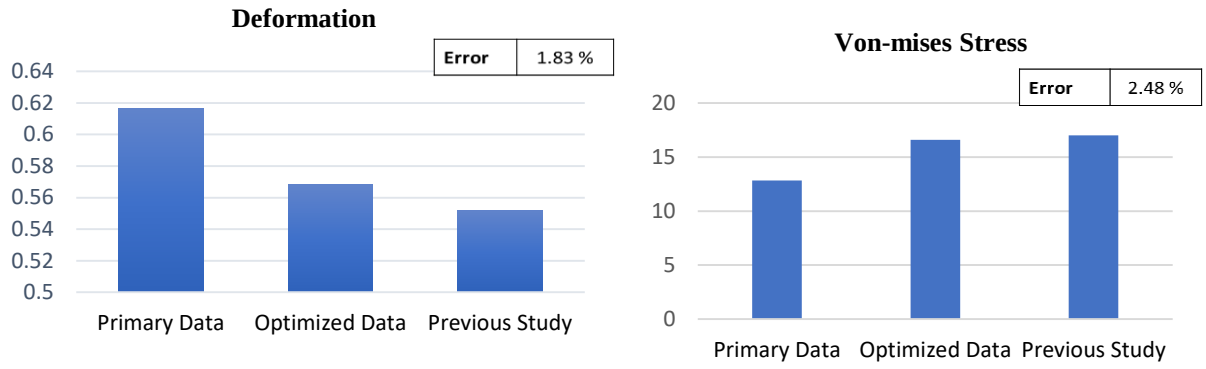


Fig.4.3. Comparison of deformation and von-mises stress for ABS material

The data shows results from a structural analysis study where deformation and von Mises stress values were calculated. Primary data was obtained directly from the analysis for a deformation of 0.6163 mm and von-mises stress of 12.839 MPa. This served as a baseline. The data was then optimized through adjustments to the model parameters and analysis settings, resulting in optimized data of 0.56182 mm deformation and 16.597 MPa von-mises stress. For validation, the results were compared to those from a previous study on a similar structure, which found 0.5517 mm deformation and 17.02 MPa von-mises stress. The error between the optimized data and the previous research was then computed. The error was 1.83% for the deformation, indicating the optimized value was within 2% of the earlier results. For the von-mises stress, the error was slightly higher at 2.48%. However, both errors were minor, suggesting that the optimized model and analysis provided results consistent with past work, validating the study and improving the original primary results through optimization

5. Suitable material selection

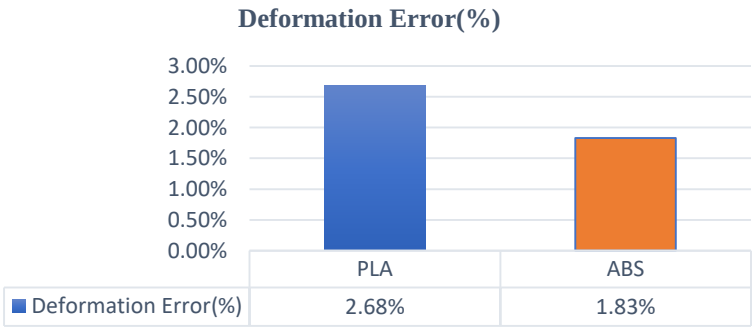


Fig.5.1. Comparative analysis of PLA and ABS material in terms of deformation

The data provided in Figure 5.1 gives valuable insight into comparing the mechanical properties of different 3D printing materials. ABS is the top-performing material based on assessing its deformation properties. It demonstrates the highest elasticity and strength values, can undergo sizeable tensile deformation before failure, and can withstand the most significant loads. ABS also exhibits average flex resistance to help maintain dimensional stability over repeated stress cycles. The critical factor is ABS's thermoplastic chain structure, allowing stress absorption that contributes to its balanced characteristics. According to the analyses, while PLA shows benefits for specific uses, ABS provides the best overall mechanical performance. Its versatility makes it well-suited for general applications undergoing every day and intermittent stresses.

6. Conclusion

The paper deals with optimizing the quadcopter structure through additive manufacturing and computational design techniques. It starts by analyzing, through finite elements, a quadcopter model to ascertain its mechanical behavior under operational loads. After that, topology optimization strengthens critical regions while reducing

overall weight. ABS and PLA were two of the most well-known 3D printing materials for this comparison. With higher mass reduction and lower maximum stresses, ABS outperformed PLA. Because of iterative design by simulations and testing, a lightweight quadcopter structurally sound frame could be obtained. This work integrates computational design, material selection, 3D printing, and structural validation to be in a position to generate an optimized structure for the proposed UAV. The lightweight design principle used herein enables a further step in combination with additive manufacturing for aerospace applications.

11. References

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