Research on topological optimization in design of Drone components fabricated by 3D printing technologies

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Received 1 Mar. 2024; Revised 19 Apr. 2024; Accepted 14 May 2024; Published 25 Aug. 2024.

DOI: https://doi.org/10.54939/1859-1043.j.mst.97.2024.148-156

ABSTRACT

Recently, drones have been widely used to perform tasks in different fields, such as military and agriculture. To improve exploitation performance, being compact and lightweight, drones are constantly designed and optimized. One of the current research directions in drone design is to optimize the structure and geometry of their main components, such as the arms and the body frame, and manufacture them using 3D printing. In this paper, the topology optimization and the geometrical optimization using lattice structures were investigated and applied to optimize the structure of the arms of a quadcopter Drone (DJI-f450) with the aid of Hyperworks software. The optimization design methods were performed according to the criteria of minimizing weight, increasing the rigidity and reliability of components. The results obtained show that all the methods considered enable the increase of stiffness and reliability while reducing the weight by at least 21.88% compared to the original structure. Among the studied optimization methods, the combination of topology and lattice optimization is more effective in increasing the rigidity and safety factor. The findings in this study confirm the necessity and performance of geometry optimization methods and 3D printing technologies to improve the product design and manufacturing process compared to traditional methods.

Keywords: Topological optimization; Drone; Lattice structures; 3D printing technology; Hyperworks.

1. INTRODUCTION

Topology optimization (TOP) is known as a technique based on several computational mathematical methods to determine the effective allocation of materials in a component from the perspective of maximizing or minimizing the physical and technical parameters of the product under certain constrained conditions. The first research in TOP appeared in the publications of Bendsøe Martin Philip et al. [1, 2]. The theory, methods and applications of TOP have been widely presented in the literature [3, 4].

Nowadays, in addition to durability and stability, products also need to meet other requirements such as aesthetics, compactness, space-saving, user-friendliness, and environmental friendliness. The design problem becomes a multi-objective optimization problem, and it is often carried out with structural analysis and optimization software. Some popular software commonly used to solve structural analysis and optimization problems include Abaqus, Ansys, Hyperworks, Nastran [5].

The main objective of TOP methods is to determine the effective distribution of materials in components according to defined constraints; for example, the weight of components should be minimized while still satisfying a required strength. Normally, the optimized geometry is very complex, and it is difficult to fabricate with conventional manufacturing processes (e.g., casting and machining). In this case, 3D printing technologies become an excellent solution [6-9]. This technique can produce complex structures by adding material layer by layer. Hence, the combination of TOP and 3D printing in the design and production enables unlimiting the ability to create complex shapes from different materials. Both 3D printing and TOP have been increasingly applied in various sectors such as aviation, rocket engineering, automobiles, mechanical engineering, civil engineering, architecture, and design.

A drone is a flying device of various sizes that is remotely controlled or highly automated to perform certain purposes. Initially, it was developed for the aviation and military industries, thanks to its ability to be controlled remotely, fly at different distances and altitudes, and have high reliability and safety. There are many types of drones, but they can be divided into 4 types based on flight ability: single propeller, multi-blade propeller, fixed wing, and hybrid fixed wing.

Today, the load-carrying capacity of drones is increasingly required because many modern devices need to be mounted on them. Therefore, the problem of optimization design of drones' components is extremely necessary, especially the optimization design of their frame and arms. The drone's frame and arms need to have minimum weight and high rigidity to carry a lot of loads and save battery energy. Therefore, the structural optimization problem of the drone frame is a multi-objective problem.

Analyzing the research results of some recent publications on this research direction, it was found that developing an advanced drone framework is still one of the major challenges. In particular, accurate mechanical structural design analysis will provide optimal design solutions. Berke Bay and Meltem Eryildiz [10] used SolidWorks software to build design options for drone frames with different structures. These designs were analyzed using the finite element method, optimizing the topology in SolidWorks with the goal of lightening the frame structure, improving the overall performance and structural integrity of the design. The design is then subjected to drop testing, stress and displacement analysis and flow simulation to evaluate its resistance to deformation and aerodynamic performance. The results have shown that topology optimization techniques enable a reduction in weight by 30% compared to the initial design without compromising structural integrity. The findings of this study provide valuable insights for the development of efficient and reliable drones.

Sagar Nvss et al. [11] also conducted research on optimizing the drone frame by redesigning the frame into a monolithic structure. The objective was to reduce weight and assembly time. The redesigned framework was then evaluated both theoretically and experimentally in terms of structural, vibration and fatigue characteristics. Based on the obtained results, the authors confirmed an improvement in performance and durability compared to commercial drone designs. In another study by Sagar Nvss et al. [12], the 4-rotor drone frame was also optimized in three phases. Accordingly, the drone frame is optimized for shape using the design of experiments (phase 1), and it was optimized for volume using topology optimization (phase 2). In phase 3, the authors used the static structural finite element analysis method to redesign the structure to better suit the production process. The results showed that applying optimization technology in design has reduced the frame weight by 39.2% and topology optimization has reduced by 5.64% compared to the original design, while retaining the frame strength.

Martinez Leon et al. [13] also carried out a structural-mechanical optimization study of the drone airframe using a generative design algorithm through the topology optimization method in SolidWorks. Additionally, the carrying capacity estimation of the drone frame was performed using an analytical method. Jerrin Bright et al. [14] focused on optimizing the design of an F450-style drone frame using the Autodesk generative design tool embedded in Fusion 360. The new design model has improved fracture resistance and minimal displacement when compared to the original design. The results of the above studies [13, 14] have shown that the optimized drone frame was suitable for manufacturing with FDM 3D printing, while the prototype frames of most commercial drones today are produced by injection molding.

Although certain results have been achieved, the problem of developing and optimizing the drones' framework has not been completely resolved. More in-depth research needs to be conducted to come up with new and superior design models. In addition, the combination of structural optimization technology and 3D printing provides the ability to apply lattice structure optimization and topology optimization technology to the design and production of quadcopter frames.

Therefore, this study was carried out to evaluate the effectiveness of applying the above-mentioned structural optimization methods combined with 3D printing to minimize weight and improve the mechanical properties of drone frames. The optimization procedure is performed using Hyperworks software. The methods and results obtained in this study can be used for the design and fabrication of various types of drones and other products.

2. METHODOLOGY

2.1. Structure optimization procedure

The general procedure to optimize the geometry of components is presented in figure 1 [3], including the main following steps: (i) Setting initial values, (ii) Structure analysis, and (iii) optimal calculation. The optimization procedure is terminated when the optimization calculation is converged.

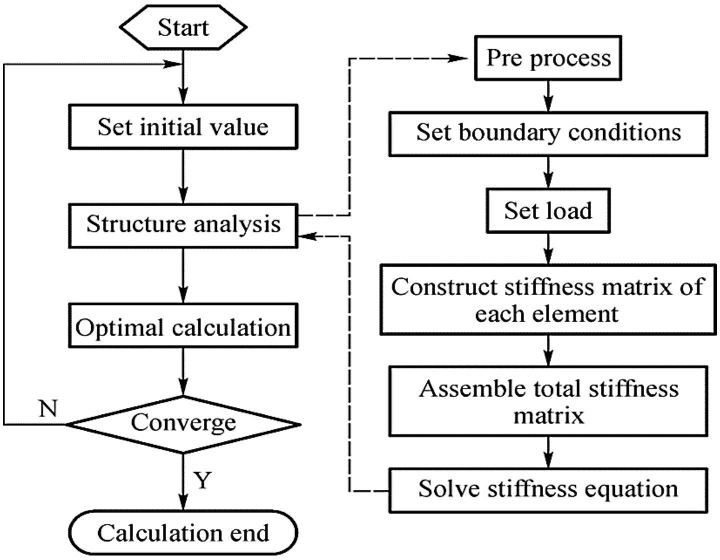


Figure 1. *The flowchart of the optimization process [3].*

Among the steps of the optimization process, optimal calculation is the most important step, determining the efficiency and quality of the whole process. This step is carried out by constructing mathematical equations that represent the relationship between variables and determining methods to solve them. Today, one of the powerful and popular tools used to perform topology optimization is Altair Hyperworks software.

2.2. Structure optimization with Hyperworks software

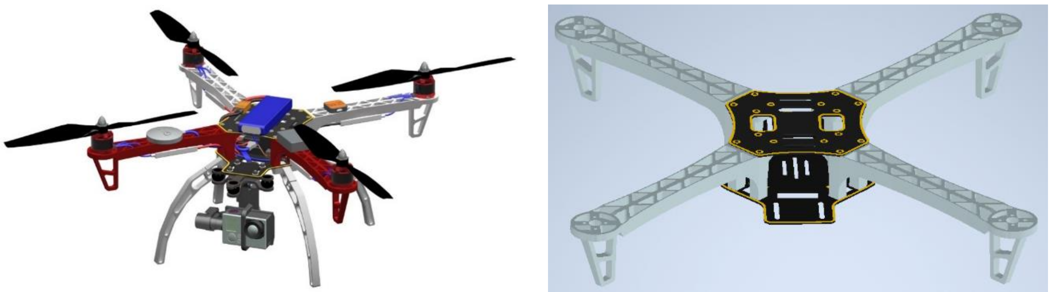
The topology optimization steps performed on Altair Hyperworks follow the general process steps for structural optimization shown in figure 1. In the Altair Inspire module of Hyperworks, the structure optimization procedure be performed according to the following steps: (i) selecting the optimization method (e.g., topology optimization, optimization with lattice structures, and topology-lattice optimization combination), (ii) defining the optimization objectives (such as increasing stiffness and minimizing mass), and (iii) setting other relevant conditions.

In the topology optimization problem, it is necessary to set the minimum and maximum thickness constraints of the model. For the optimization process using the lattice structure, it is necessary to set the parameters of the lattice cell, the length dimension, the smallest diameter of the frame, and the proportion of parts replaced by lattice cells in the model.

Finally, the resulting optimized models are simulated in terms of residual stress, displacement, and safety factors to compare with each other and with the original structure.

2.3. Description of the case study

In this study, the structure optimization was conducted on one aim of the X-frame of a drone model (DJI-f450) (figure 2). The original drone arm is designed to be suitable for manufacturing using conventional machining methods such as injection molding or molding. Generally, drones operate in adverse conditions, are affected by many random factors, and have limited loading capacity. Optimizing the drone frame structure is essential to minimize weight, increase rigidity for increasing loading capacity, and save consumed energy. In this case, the structure optimization of the body frame and the drone arm is a multi-objective optimization problem.



(a) *(b)*

***Figure 2.** (a) DJI-f450 drone model and (b) X-frame to be optimized.*

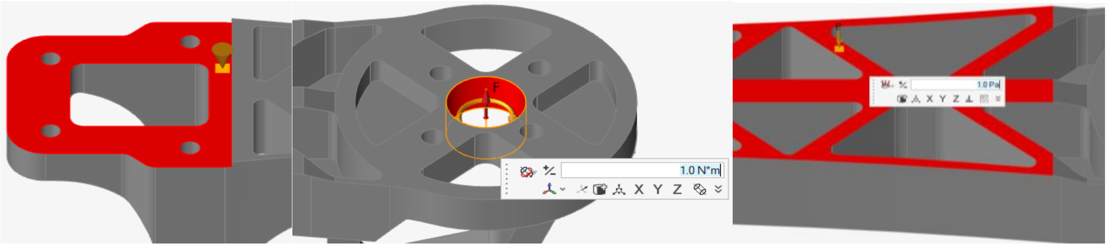
Stresses and displacements in the drone frame are determined using simulation methods. The set limit conditions are calculated according to reality, considering the safety factor of the device. The lift force of the propeller (L) is determined according to the Bernoulli equation:

$$L = \frac{1}{2} \times \rho \times V^2 \times A \times C_L \qquad (1)$$

where ρ is air density (about 1.2 kg/m^3), V is velocity in m/s, A is the surface area of the impeller in m^2, and C_L is the lift coefficient.

The total mass of the carrying parts on the drone DJI-f450 is 542.3 g. The mass of the drone frame is about 250 g, and the mass of other drone components is about 20% of the total mass. Thus, the total mass of the drone with carrying devices is about 1000 g. The gravitational acceleration G is approximately 10 m/s^2. Therefore, for 4 engines to create a lift force equal to the drone's load, each engine will have to create a lift force of 2.5 N.

In stable conditions of flying, the gravity acting on the drone will balance with the lifting force of the propellers, we consider the following model: the drone's arm will be fixed (actually, it is attached to the drone body), the lifting force for each propeller is $F = 2.5$ N, and the moment from the engine acting on the drone's arm has a value of $M = 1$ Nm.



(a) *(b)* *(c)*

***Figure 3.** (a) Setting the support, (b) the lift force F = 2.5 N and moment M = 1.0 Nm at the propeller motor mounting location, and (c)the pressure for the model p = 1.0 Pa.*

To compare and evaluate the effectiveness of optimization methods, the study conducted simulations of the displacement and stress of the original drone arm and those of the optimized structures. The initial setup for the simulations is shown in figure 3, in which the red surface is the surface on which the constraint conditions are set.

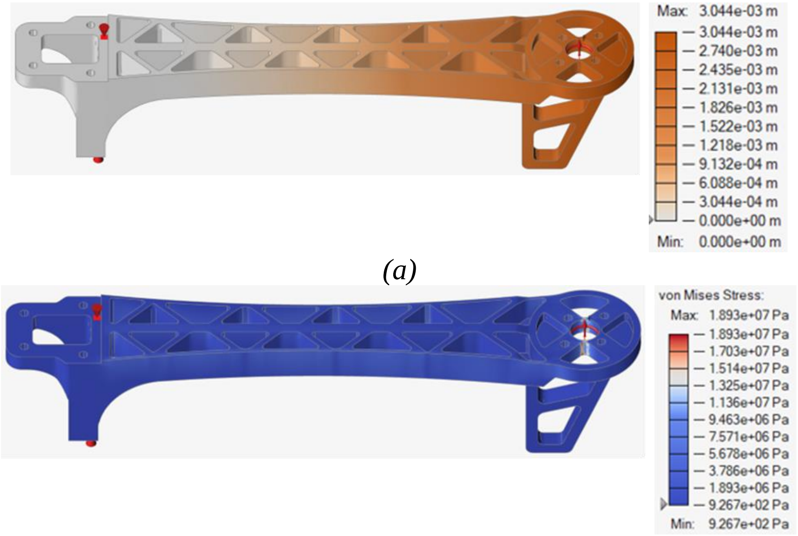
From the initial drone arm structure (figure 4a), the area requiring design optimization is defined as the block-shaped area and indicated in white in figure 4b. The optimization process is conducted using three different methods: (i) topology optimization, (ii) optimization with lattice structures, and (iii) topology + lattice structure combination optimization. The results of these methods are compared with each other and with the original structure in terms of mass, load-bearing conditions and safety factors to make recommendations for choosing the appropriate structure. The material of the drone arm is ABS plastic.

(a) *(b)*

Figure 4. *(a) DJI-f450 drone arm model and (b) the space of optimization.*

3. RESULTS AND DISCUSSION

The results of the displacement and stress simulations of the original drone arm model are shown in figure 5. It can be seen that the largest displacement value occurs at the tip of the drone's arm and reaches 3.04 mm. The maximum stress appearing in the original drone arm is 18.93 MPa.



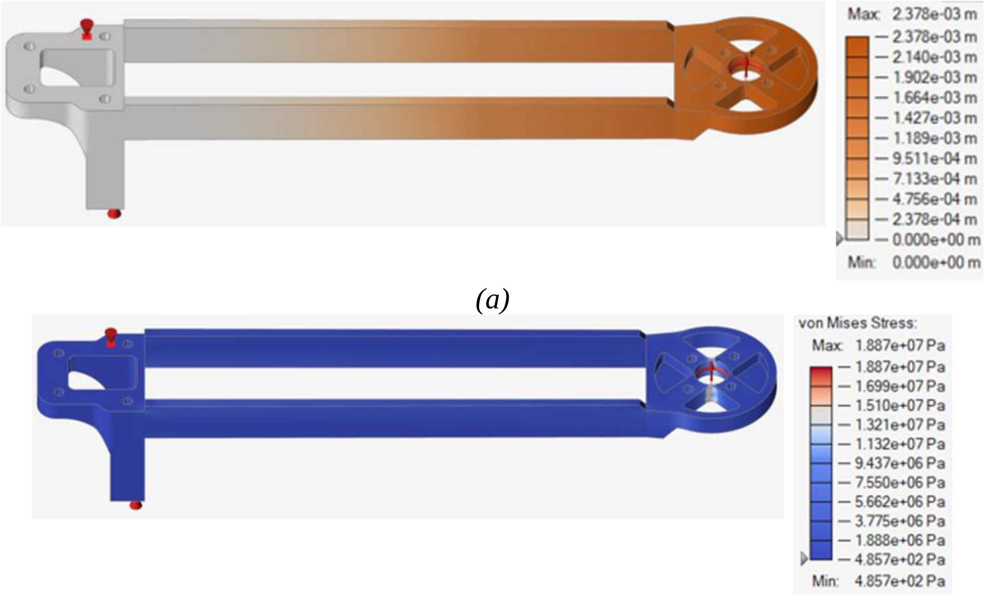
(a)

(b)

Figure 5. *Simulation results of the original drone arm: (a) Displacement and (b) stress.*

As mentioned in section 3, the optimization process is performed with three methods: topology optimization, optimization with lattice structures, and topology + lattice structure combination optimization. The topology optimization results are shown in figure 6. With this structure, the arm mass was reduced to 28 g compared to the original 39 g (39.28% reduction). The simulation results of displacement and stress also show that the maximum displacement is 2.38 mm, and the maximum stress is 18.87 MPa.

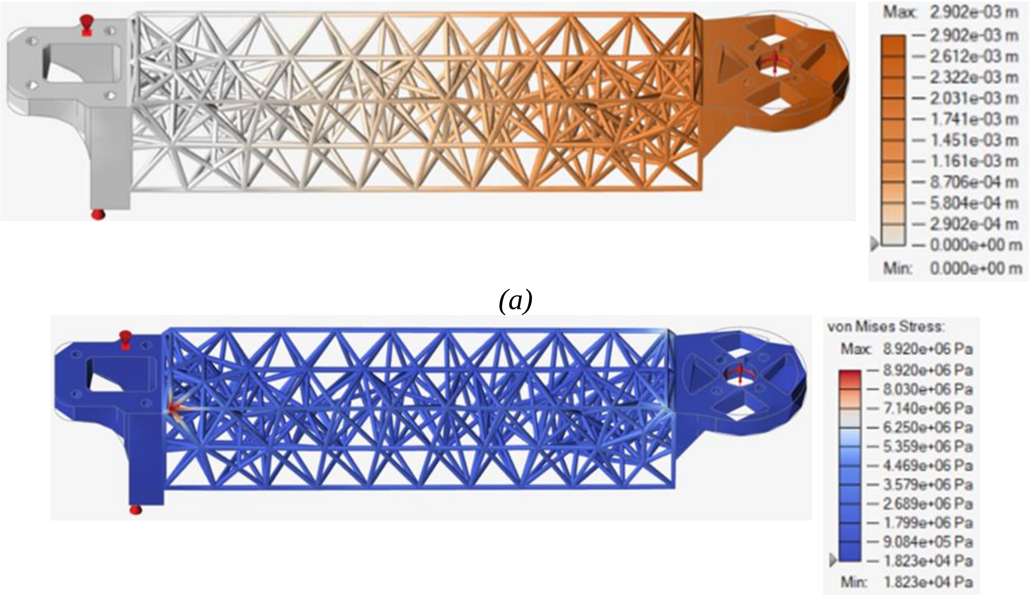
The optimized drone arm obtained by the lattice structure optimization method is shown in figure 7. In this case, the traditional structural drone arm is replaced by the lattice structure**,** where solid elements are replaced with lattice beams. As a result, the part mass is 31 g (with 25.8% reduction compared to the original structure), and the maximum displacement of the drone arm is 2.9 mm with the maximum stress of 8.92 MPa.



(a)

(b)

Figure 6. *Simulation results of the topologically optimized arm: (a) Displacement and (b) Stress.*



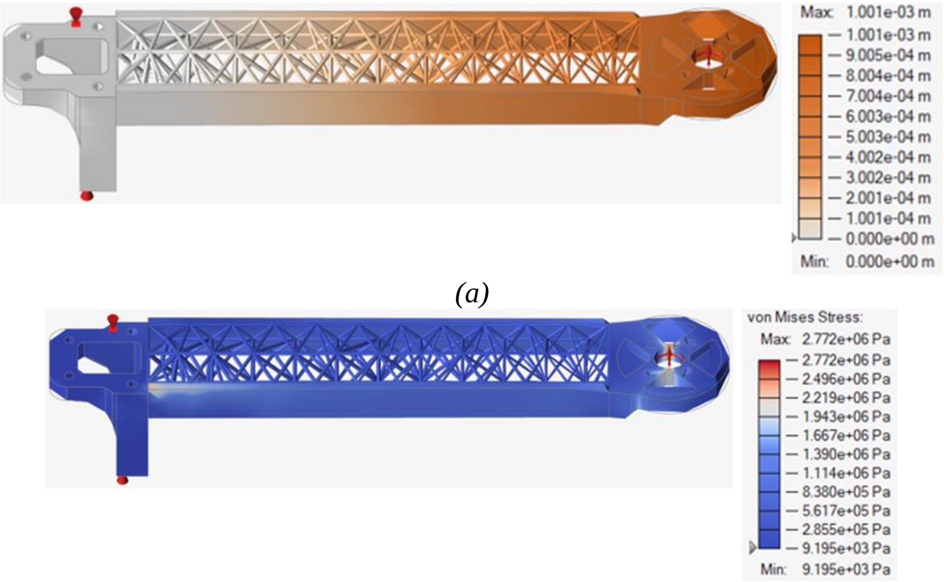
(a)

(b)

Figure 7. *Simulation results of lattice structure optimized arm: (a) Displacement and (b) stress.*

The result of combining topology and lattice structure optimization method**s** for the drone arm is shown in figure 8. The results show that the volume of the optimized part is 32 g (reduced by 21.88% compared to the original), the largest displacement at the tip of the drone arm is 1.0 mm and the maximum stress is 2.77 MPa.

The simulation results of displacement and stress of the drone arm structure optimized by the above three methods are shown in table 1. In addition to the maximum displacement and stress, the obtained structures are also simulated to determine the smallest factor of safety. From table 1, we see that all three optimization methods bring positive results when reducing the weight of the drone arm from 21.88% to 39.28% compared to the original while still ensuring achieve structural rigidity. The maximum displacement (1.00 - 2.38) mm and the maximum stress (2.77 - 18.87) MPa of the optimized structures do not exceed the value of the original design (3.04 mm and 18.93 MPa).



(a)

(b)

Figure 8. *Simulation results of topology + lattice structure optimized arm: (a) Displacement and (b) stress.*

According to the mass, the topology optimization method brings the highest efficiency when the mass is only 28 g compared to 39 g of the original design**,** while other criteria are guaranteed within limits. According to robustness, combined topology and lattice structure optimization brings the highest efficiency. This may be due to the heterogeneously combined structure creating an effect that increases the rigidity of the part and the weight changes are not significant.

When evaluating the overall optimization results according to all criteria, it was found that although the combined optimization method does not reduce the mass as much as the other two methods, it creates a strong structure and a higher safety factor. This is shown in the maximum displacement value of only 1 mm compared to 2.38 mm and 2.90 mm of the other two methods, and the maximum stress of 2.77 MPa is many times smaller than those in the topology optimization and the optimization with lattice structures. The safety factor is also an important criterion for evaluating optimization results. The higher the minimum safety factor, the more reliable the product's structure is. From table 1, it can be seen that the optimized combination of topology and lattice structures provides a much higher safety factor than other methods and the original structure.

Lastly, the geometries of the drone arm obtained by different methods are significantly different. The topology optimization method generated a simple geometry, and it can be manufactured by conventional manufacturing methods. However, the geometries obtained by the lattice structure and combining topology and lattice structure methods have a complex shape, which is impossible to fabricate with traditional methods. Therefore, structural optimization research needs to be combined with 3D printing technologies to achieve perfection in product design and manufacturing.

Table 1. *Comparison of optimization results and original design.*

Specification	**Structures**			
	Topology optimization	**Optimization with lattice structures**	**Topology+lattice structure optimization**	**Original**
Mass (g)	28	31	32	39
Mass reduction vs. original (%)	39.28	25.80	21.88	0
Displacement max (mm)	2.38	2.90	1.00	3.04
Von Mises stress max (MPa)	18.87	8.92	2.77	18.93
Safety factor min	2.4	5.0	16.2	2.4

4. CONCLUSIONS

In this study, the structural optimization process of the drone arm is carried out by three methods: topology optimization, optimization using lattice structures, and optimization combining topology and lattice structures. The main conclusions of the study are *the* following:

- The topology optimization and optimization with lattice structures methods enable enhancing the stiffness and reducing the mass of the pass with at least a 21.88% reduction.
- Compared to the other two methods, the combined topology-lattice optimization method is highly effective in increasing the rigidity and safety factor of the part.
- Topology optimization combined with 3D printing technology allows the design and manufacture of aircraft parts with the smallest possible volume while still ensuring the durability, rigidity, and reliability of components. This technology is recommended for further research to be applied in drone manufacturing to reduce energy consumption and extend the drone's operating time.

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TÓM TẮT

Nghiên cứu thiết kế tối ưu hình học chi tiết máy bay không người lái chế tạo bởi công nghệ in 3D

Gần đây, drone đã được sử dụng rộng rãi để thực hiện các nhiệm vụ trong các lĩnh vực khác nhau như quân sự và nông nghiệp. Để nâng cao hiệu suất khai thác, có kích thước nhỏ gọn và nhẹ, drone không ngừng được thiết kế và tối ưu hóa. Vì vậy, một trong những hướng nghiên cứu hiện nay là tối ưu hóa cấu trúc hình học các bộ phận chính của drone như khung thân và chế tạo chúng bằng công nghệ in 3D. Trong bài báo này, tối ưu hóa topology và tối ưu hóa sử dụng cấu trúc lattice đã được nghiên cứu và áp dụng để tối ưu hóa cấu trúc cánh tay của drone (DJI-f450) với sự hỗ trợ của phần mềm Hyperworks. Các phương pháp thiết kế tối ưu được thực hiện theo tiêu chí giảm thiểu trọng lượng, tăng độ cứng và độ tin cậy của chi tiết. Kết quả thu được cho thấy các phương pháp được sử dụng đều cho phép tăng độ cứng và độ tin cậy, đồng thời giảm trọng lượng ít nhất 21,88% so với kết cấu ban đầu. Trong đó, phương pháp kết hợp giữa tối ưu hóa topology và sử dụng cấu trúc lattice có hiệu quả hơn trong việc tăng độ cứng và hệ số an toàn. Những phát hiện trong nghiên cứu này khẳng định sự cần thiết và hiệu quả của các phương pháp tối ưu hóa hình học và công nghệ in 3D để cải thiện quy trình thiết kế và chế tạo sản phẩm so với các phương pháp truyền thống.

Từ khoá: Tối ưu hóa cấu trúc liên kết; Máy bay không người lái; Cấu trúc lattice; Công nghệ in 3D.