Topology Optimization and CFD Analysis for DJI F450 Drone Mass Reduction and Aerodynamic Performance Enhancement

Zicheng Yang [1, a], Zhengkun Lu [2, b], Chenhaodong Cai [3, c]

[1] RCF Experimental School, Beijing, China

[2] Suzhou International Academy, Suzhou, Jiangsu, China

[3] Hefei No.8 Senior High School, Hefei, Anhui, China

[a] yangzicheng@rdfzcygj.cn, [b] 2063707772@qq.com, [c] 1160059119@qq.com

Abstract. With the widespread application of drones in logistics, agricultural surveying and mapping, environmental monitoring, and national defense, lightweighting and aerodynamic performance optimization have become key factors affecting flight efficiency and endurance. This research used the function topology optimization in SolidWorks and the CFD analysis in COMSOL Multiphysics®. This research primarily focused on reducing mass and improving aerodynamic performance. This study used topology optimization to decrease the mass of the drone's arm to 41 grams, with better performance in both static stress analysis and computational fluid dynamics analysis. This model decreased roughly 25% of the drag force and 2% of the mass compared to DJIF450. The maximum displacement of our drone is 300% lower than DJIF450. This article provides strong support for the research and development of efficient, safe and innovative drones in the low-altitude economic field.

Keywords: Topology Optimization; Computational Fluid Dynamics (CFD); Drone.

1. Introduction

The low-altitude economy is demonstrating robust expansion globally and within the People's Republic of China. Analysis by the Qianzhan Industry Research Institute indicates that the aggregate market valuation of the global low-altitude economy's core sectors reached approximately CNY 2.08 trillion in 2023. This sector is projected to sustain a compound annual growth rate (CAGR) of 11.51% over the forthcoming five-year period [1].

As the world's second-largest economy, China's low-altitude economy is currently experiencing an accelerated phase of development. In 2023, the domestic market size surpassed CNY 500 billion, representing a year-over-year increase of 33.8% [2]. UAVs are explicitly recognized as a 'leading industry' and 'one of the most significant growth sectors' within the low-altitude economy. Their rapid development approximately matches the overall growth of the low-altitude economy [3]. In 2023, China's civil UAV industry reached a scale of 117.43 billion RMB, marking a 32% year-on-year increase, closely aligning with the overall low-altitude economy's growth rate of 33.8% during the same period [4].

While the Main limitation of developing low altitude economy is the low energy density of its battery [5]. It is hard to improve the energy directly so our research focus on decreases its mass and drag force to eliminate the energy consumption [6].

Topology Optimization is used to reduce the weight of the UAV, which means to optimize the distribution of materials within a given area to achieve structural lightweighting and find the optimal load transmission path.

Moreover, COMSOL are used to determine significant parameters, such parameters, like drag force and lift force. We choose Computational Fluid Dynamics (CFD) analysis to evaluate and enhance the aerodynamic performance of the modified drone design.

However, it is a tough task to both decrease the mass of the drone, maintain acceptable stress, and improve Aerodynamic shape, so we model several different components of drone, upload it into COMSOL, and compare the result given by CFD analysis to figure out the best structure.

This report is structured as follows. Section 2 below provides an overview of the principle of CFD analysis and topology optimization; Section 3 introduces the research methodology, including the setup process for topology optimization and CFD simulation; Section 4 presents the main results of the optimization and analysis; Section 5 provides an in-depth discussion of the research results; Finally, Section 6 presents the research conclusions and proposes future research directions.

2. Literature Review

2.1 Topology

Topology optimization has emerged as a revolutionary computational design tool, enabling engineers to discover optimal material distributions within a given design space. Unlike traditional design methods that focus on optimizing predefined shapes or dimensions, topology optimization provides the freedom to generate novel and highly efficient structural layouts. Among the various approaches, the Solid Isotropic Material with Penalization (SIMP) method stands out as one of the most widely adopted and mathematically robust techniques.

At its heart, the SIMP method aims to predict the most efficient material distribution within a specified initial design domain, considering defined load cases, boundary conditions, and performance requirements [7]. The primary objective is typically to maximize the overall stiffness of a structure, which is equivalent to minimizing its compliance (a measure of flexibility or softness) for a given volume of material [6]. This is achieved by iteratively determining whether material should be present or absent at every point within the discretized design space. The mathematical expression is shown.

$$\left.\begin{aligned} &\min_{\rho} \quad F = F(\mathbf{u}(\rho),\rho) = \int_{\Omega} f\,(\mathbf{u}(\rho),\rho)\,dV \\ &\text{s.t. } G_0(\rho) = \int_{\Omega} \rho\,(\mathbf{x})\,dV - V_0 \le 0 \\ &\quad G_j(\mathbf{u}(\rho),\rho) \le 0, \qquad j = 1,\dots,M \\ &\quad \rho(\mathbf{x}) = 0 \text{ or } 1, \qquad \forall\,\mathbf{x} \in \Omega \end{aligned}\right\} \tag{1}$$

The foundational concept of SIMP involves discretizing the design domain into a grid of finite elements. Each element is then assigned a continuous "pseudo-density" design variable, ρe, which can range from 0 to 1 [7]. A value of ρe=1 signifies the presence of solid material, while ρe =0 indicates a void (absence of material). In an ideal scenario, the final optimized design would consist purely of elements with binary densities (either 0 or 1), representing a clear "black-and-white" structure [7].

However, directly solving a binary (0-1) optimization problem is computationally challenging due to its discrete nature and the vast number of possible solutions [7]. To circumvent this, SIMP introduces a continuous density variable and, crucially, a penalization scheme. This is where the "Penalization" in SIMP becomes vital. The material properties, specifically the Young's modulus (E) of an element, are made dependent on its pseudo-density using a power law relationship[6][7]:

$$E(\mathrm{\rho e}) = \mathrm{\rho}_e{}^p E_0 \tag{2}$$

Here, $E_0$is the Young's modulus of the solid material, ρe is the element's density, and p is the penalization factor, typically chosen as p=3 based on empirical and theoretical findings [7][8]. The purpose of this penalization is to diminish the contribution of elements with intermediate densities (often referred to as "gray" elements) to the overall stiffness [8]. For instance, if an element has a density of 0.5 and a penalization factor of 3, its effective stiffness will be 0.53=0.125 times the stiffness of the full material. This strong penalization makes it energetically unfavorable for intermediate densities to exist, thereby driving the design towards a clear solid-or-void configuration that is physically manufacturable [8].

The optimization process in SIMP is iterative and gradient-based. In each iteration, a finite element analysis (FEA) is performed on the current material distribution to assess the structural response. Subsequently, a sensitivity analysis is conducted to determine how changes in each element's density would impact the objective function [8]. This sensitivity information guides the update of element densities using mathematical programming techniques, such as the Method of Moving Asymptotes (MMA) [7][8]. Elements that contribute significantly to the structural performance tend to retain or increase their density, while those that are less critical see their densities reduced.

To address common numerical artifacts like "checkerboard patterns" (alternating solid and void elements) and mesh dependence, filtering schemes are often integrated into the SIMP algorithm [7][8]. These filters average the sensitivities or densities over a defined neighborhood, promoting smoother material transitions and ensuring that the optimized design is less sensitive to the initial mesh resolution [9].

In previous years, Topology optimization has used in aerodynamic industry. For instance, in 2004, Allaire G used this method in designing the layout of materials in airframe [10]. Other engineers invest the new stiffener ribs for aircraft panels and for aerospace multi-component structural systems [10].

While primarily used for static stiffness maximization, the SIMP method has also been extended to dynamic problems, such as the topology optimization of resonating structures and micro-actuators [8]. In these applications, the objective might be to maximize steady-state vibrations at a given excitation frequency. However, dynamic problems introduce additional complexities, including the presence of localized eigenmodes in regions of low density and the challenge of handling non-proportional damping [8]. Furthermore, practical designs obtained through SIMP can sometimes feature "grey" elements or "hinges" (flexible pivots) that are difficult to fabricate directly, necessitating post-processing steps to convert them into pure black-and-white images [8]. Despite these challenges, the SIMP method remains a cornerstone of topology optimization, offering a powerful framework for generating innovative and high-performance designs across various engineering disciplines.

Computational Fluid Dynamics (CFD), as comprehensively detailed in Jiri Blazek's "Computational Fluid Dynamics: Principles and Applications," fundamentally involves the numerical solution of the governing equations that describe fluid motion, heat transfer, and related phenomena. At its core, CFD is built upon the foundational physical laws of conservation of mass (continuity equation), conservation of momentum (Navier-Stokes equations), and conservation of energy (energy equation), which are expressed as a set of coupled, non-linear partial differential equations. Since analytical solutions to these complex equations are rarely feasible for real-world engineering problems involving intricate geometries or turbulent flows, CFD employs a systematic numerical approach to approximate their solutions. This process begins with spatial discretization, where the continuous physical domain is transformed into a discrete computational mesh or grid, comprising numerous small control volumes or elements. Blazek elaborates on widely used techniques like the Finite Volume Method, which applies the integral form of the conservation laws to each discrete volume, converting the partial differential equations into a solvable system of algebraic equations. This spatial transformation can utilize structured grids, characterized by their regular, organized arrangement, or unstructured grids, offering greater flexibility to conform to complex geometries. For time-dependent problems, temporal discretization is equally crucial, involving the application of explicit or implicit time-stepping schemes to advance the solution through time, each with distinct stability and computational efficiency characteristics. Blazek critically addresses the vital concepts of consistency, accuracy, and stability—three pillars that underpin the reliability of any CFD simulation. Consistency ensures that the numerical scheme correctly approximates the original differential equations as the mesh and time step are refined; accuracy quantifies how closely the numerical solution matches the true physical solution, often influenced by the order of the discretization scheme; and stability guarantees that numerical errors do not grow unboundedly, preventing solution divergence, with tools like Von Neumann stability analysis used for assessment. Finally, the practical yet fundamental aspect of grid generation is thoroughly covered, as the quality and type of the computational mesh significantly dictate the overall accuracy, efficiency, and robustness of the CFD simulation.

3. Methodology

3.1 Topology Optimization

Topology optimization of SolidWorks is chosen to improve out structure. Comparing this with topology optimization in COMSOL, SolidWorks one consumes less time and require less computing rate.

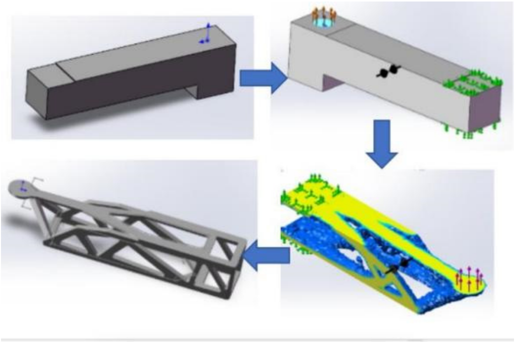

Figure 1. The process of topology optimization

DJI F450 is filling in to a simple structure with no optimization because it is hard to do further optimization on DJIF450. We want to discover a new structure rather than cutting some details on its structure. So, we revert it in to original shape.

In the following paragraph, we goanna introduce the setting of topology optimization. The material of our arm is ABS, a kind of plastic. Two parts of the model are set to fixed geometry. A 50N lift force is exerted in a colored area. The goal of topology is finding the best stiffness mass ratio while decreasing 90% of mass and the maximum thickness of the new structure is 6mm.

After getting the result of topology optimization, a new model is designed based on the result. Some irregular details need to be removed otherwise the CFD analysis may take long time because the function is too complicated. We reform the model based on result of static stress analysis. The setting is similar with the optimization one.

The static stress analysis gives out the stress and strain of this condition as showing in the following figures.

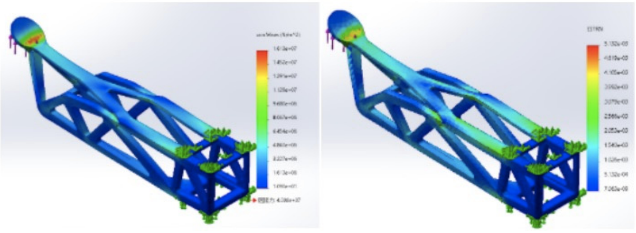

Figure 2. the stress and strain of our model.

The part with low stress or low strain are removed. The holes one left- and right-hand side are likely to be triangle because we find out that triangle is the most stable structure. It decreases strength of the arm less than other and can improve aerodynamic performance. To ensure the safety of the structure, we take safety factor into consider. The model has a minimum safety factor of 3 to insure the strength of this structure.

After balanced all these factors, our model is upload into COMSOL to gather its aerodynamic performance.

3.2 CFD Analysis

The following part of this essay will introduce the setting of CFD analysis.

This research chooses k-w turbulent stationary field for its precise prediction for the area near drone. The reason of using k-w turbulent field is that it can solve both low Reynolds number turbulence which is condition of the area near our drone and the laminar flow which is condition of area near the wall of cubic precisely.

After setting the k-w field, the model of our optimized drones and DJIF450 are uploaded into COMSOL. Then, we create a cubic to pack the drone inside. The drone is rotated by 45 degrees around y axis and then rotated by the attack angle around z axis to stimulate the real working condition.

The cubic is filled with air given a 3 m/s speed. The middle drone becomes the inner wall of air by the set difference. After that, the solution is generated by computer.

4. Result of Topology Optimization

4.1 Topology Optimization

The original filled arm is about 80g. Our new arm is about 41g. We decreased about 48.8% mass relative to original filled one.

The main idea of this result is that first, topology optimization divides the arm into 2 parts, the top plane and the under plane. On the right side and left side, two plane are connected by several girders, forming several triangle holes. Triangular shape can minimize the decrease in strength. The most unique part of this design is the two slanted pillars. It provides extra strength to ensure that the cylinder will not have great displacement.

To compare performance of our model and DJIF450 one, the following table is made.

Table 1. Conditions With 50n Lift Force

	Mass/g	**Stress/Nm^-2**	**Displacement/mm**	**Safety factor**
Our model	41	2.07e+07	3.08	1.9
DJIF450	42	2.43e+07	1.23e+01	1.6

Table 2. Conditions With 30n Lift Force

	Mass/g	**Stress/Nm^-2**	**Displacement/mm**	**Safety factor**
Our model	41	1.242E+07	1.85	3.2
DJIF450	42	1.51e+08	62.22	0.26

Take 50 N condition as an example, our structure perform better than DJIF450. The structure is lighter than DJIF450. The most significant difference is about the displacement. The displacement of DJIF450 is roughly 4 time of optimized one.

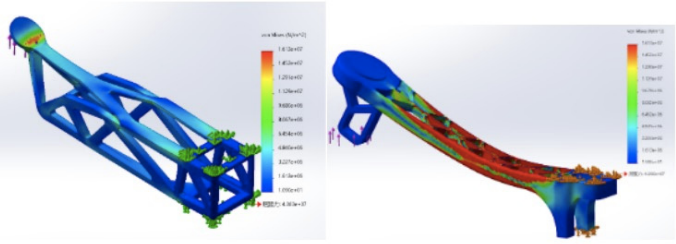

Figure 3. the graph of our arm and DJIF450.

The safety factor of our structure is 19% larger than DJIF450. To be more visualized, the figure of two arms in 50N condition are shown.

It is more obvious that in graph of our arm, blue occupies most of the area but in graph of DJIF450's arm, red occupies the most area, so if we use same material as DJIF450, the force exerted on unit area in our arm is less than DJIF450's one, so our arm has lower displacement and higher safety factor.

Overall, our structure performs better than DJIF450 one in all aspect in static stress analysis.

4.2 CFD Analysis

The two models are uploaded into COMSOL to compare the drag force and lifting force by using CFD.

Table 3. Measured Value Of Cfd Analysis

Model	Attack angle/°	Wind speed/ms^{-2}	Drag force/N	Lift force/N
Our model	0	3	0. 0315	3.98E-4
	3	3	0. 0335	-0.011
	6	3	0. 0353	-0.018
DJIF450	0	3	0. 0494	-0.036
	3	3	0. 0433	-0.020
	6	3	0. 0447	-0.033

Overall, this model has better performance as in three different attack angles (0°, 3°, 6°), and it has lower drag force and lower lifting force downwards.

When the attack angle is 0°, the drag force of our model is about 36.2% lower than the drag force of DJIF450 and the lifting force of our model is upwards but the lifting force of DJIF450 is downwards.

When the attack angle is 3°, the drag force of our model is about 22.6% lower than the drag force of DJIF450 and the downward lifting force of our model is almost the half of the lifting force of DJIF450.

When the attack angle is 6°, the drag force of our model is about 21.0% lower than the drag force of DJIF450 and the downward lifting force of our model is lower than the half of the lifting force of DJIF450.

To explain the difference of drag force, the speed graph of DJIF450 and new drone are shown in Figure 4.

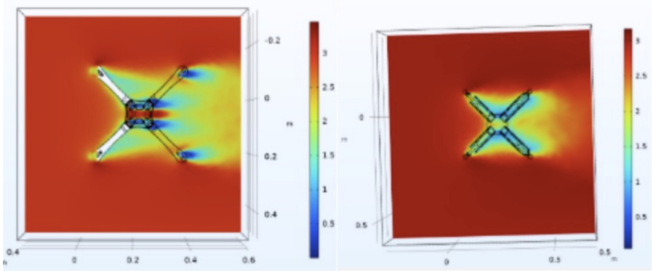

Figure 4. The graph of our drones and DJIF450 in 3m/s wind with 3 degrees attack angle

Comparing two speed graphs, it is obvious that our graph contains more red, yellow, and no dark blue. In the graph of DJIF450, dark blue appears near each supportive cylinder. Thus, it means the DJIF450 creates more turbulence than ours. DJIF450 creates a larger separation area, a low-pressure area, because more energy is turned into heat energy. So DJIF450 creates a larger pressure difference and experiences a larger drag force. This model has more holes in the difference plane, so air can flow fluently through our drone and create less drag force.

5. Discussion

By applying topology optimization within SolidWorks, this study managed to decrease the mass of the DJI F450 drone arm. And it did so while still keeping the structural integrity intact. The optimized design brought about a notable mass reduction, which was around 48.8% when compared to the original filled arm. The static stress analysis showed that the optimized arm, even though it was considerably lighter, actually displayed better structural performance. The new design had a lessened stress concentration, a higher safety factor (1.9 as opposed to 1.6), and a substantially lower displacement (3.08 mm instead of 12.3 mm) under a 50 N load when contrasted with the stock DJI F450 arm. These findings verify the efficacy of topology optimization in crafting a lightweight yet sturdy structure by purposefully distributing material to match up with the main load paths.

The Computational Fluid Dynamics (CFD) analysis carried out in COMSOL Multiphysics® disclosed notable aerodynamic enhancements within the optimized drone design. The study indicated that the optimized arm constantly generated lower drag forces over a range of attack angles, namely 0°, 3°, and 6°. In particular, when compared to the DJIF450 arm, the drag force was decreased by up to 36.2% at a 0○ attack angle. Moreover, the flow characteristics around the optimized arm were better too, as air was flowing vigorously through the triangular openings that were created by the topology optimization. This passive airflow helped in reducing the drag and it showed that the structural and aerodynamic aims of the design could be dealt with in a way that they work together well.

6. Conclusion

The research managed to fulfill its main goals, specifically reducing the mass of the drone and boosting its aerodynamic performance. The combined method of employing topology optimization to cut down on mass and using CFD analysis to enhance aerodynamic aspects turned out to be really effective. The ultimate design is lighter and has a more solid structure compared to the original one. Additionally, it is more efficient aerodynamically. This directly tackles the crucial challenge of low energy density within the low-altitude economy as it lessens the overall power consumption.

An important presumption within this study was to utilize a simplified load situation, specifically a static vertical lift force amounting to 50N. This does offer a solid foundation for making comparisons. However, in actual drone flights out in the real world, there are complex dynamic loads, vibrations, as well as forces coming from multiple directions. And this model doesn't manage to capture all of these aspects completely. The aerodynamic examination further presupposed a consistent wind speed and a restricted range of attack angles. These kinds of simplifications might have an impact on the universality of the outcomes and on how the drone performs when it's flying under conditions that are more diverse and turbulent.

The existing methodology has the potential to be enhanced by integrating more intricate and practical load cases within the topology optimization. For instance, one can consider dynamic loads that stem from motor vibrations as well as impacts. Moreover, it would be worthwhile to explore a multi-objective optimization method to optimize for both mass and aerodynamic drag all at once, instead of carrying out these analyses one after another. In doing so, a more comprehensive and unified design solution can be attained.

The next logical step in this research is to carry out experimental validation. This would entail physically creating a prototype of the optimized drone arm with a material such as ABS and then doing flight testing. The real-world data that comes from flight tests, which encompasses power consumption metrics, flight time, and measurements of structural stress, would be of great importance to verify the simulation results and to affirm the practical advantages of the design.

Future work might look into advanced optimization techniques. Multi-objective topology optimization could be utilized to identify a Pareto front of solutions that balance between mass and aerodynamic drag. This would enable the selection of a design that presents the best compromise between the two competing performance metrics for diverse applications.

The optimized design, which has an intricate and non-uniform geometry, is quite fitting for additive manufacturing, that is, 3D printing. Future research needs to look into the employment of specific 3D printing techniques as well as materials for fabricating the optimized arm. This will entail analyzing the printing process, the orientation of layers, and the properties of materials so as to guarantee that the manufactured part complies with the performance and safety standards.

The present study made use of ABS plastic. In the future, work might explore the utilization of new and advanced materials or composites, like carbon fiber-reinforced polymers that present a higher strength-to-weight ratio. When the same topology optimization approach is applied to these materials, it could bring about an even more significant mass reduction as well as enhanced structural performance.

This research shows the notable potential of incorporating advanced simulation techniques such as topology optimization and CFD analysis within the drone design process. The capacity to iteratively improve a design in a digital manner, attaining considerable enhancements in both structural and aerodynamic performance, offers a potent framework for speeding up innovation in the low-altitude economy. Through continuous exploration and refinement of these methodologies, it becomes possible to develop more efficient, safer, and higher-performing unmanned aerial vehicles, thus making a contribution to the strong growth of this crucial industry.

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