Study on the Influence of Lightweight Mechanical Structure on UAV Dynamic Response Characteristics and Control Strategy Optimization

Shihao Lu[1, a]

[1]Qingdao Jiaozhou Yingzi Private School, Qingdao, China
[a]Howardlu30@gmail.com

Abstract: In this paper, the influence of lightweight mechanical structure on the dynamic response characteristics and control strategy optimization of UAVS is deeply studied. With the wide application and rapid development of UAV technology, lightweight design has become one of the key technologies to improve the performance of UAV. Through the use of high-strength lightweight materials, structural optimization and advanced manufacturing processes, the weight of the UAV has been significantly reduced, thereby improving its load ratio, range and maneuverability. However, lightweight design also brings challenges such as reduced structural stiffness and increased vibration, and these changes have a profound impact on the dynamic response characteristics of UAVs. In order to comprehensively analyze the mechanism of the influence of lightweight mechanical structure on the dynamic response characteristics of UAVs, this paper firstly summarizes the key factors of lightweight design from three aspects: material selection, structure optimization and manufacturing process, and discusses how these factors affect the natural frequency, damping ratio, vibration mode and other key dynamic parameters of UAVs. Then, through theoretical analysis, the specific reasons for the change of UAV dynamic response characteristics caused by lightweight design are revealed, including vibration intensification and stability reduction. In order to deal with these challenges, on the one hand, an active vibration control system should be introduced to effectively suppress the vibration of UAVs during flight and improve flight stability through real-time monitoring and feedback control. On the other hand, adaptive control algorithm is needed to dynamically adjust control parameters according to the real-time flight status and environmental changes of the UAV, so as to improve the adaptability and robustness of the control system. The research results of this paper not only provide theoretical basis and practical guidance for the lightweight design of UAVs, but also provide new ideas and methods for the future development of UAVS technology.

Keywords: Drones; Lightweight echanical structure; Dynamic response characteristics; Control strategy; Optimize.

1. Introduction

Unmanned Aerial Vehicle can be controlled autonomously through its own program or radio remote control device [1]. With the rapid progress of science and technology and the continuous expansion of application fields, Unmanned Aerial Vehicle, as an advanced system integrating aviation, electronics, machinery, communication and other multidisciplinary technologies, is gradually penetrating from the military field to the civilian field. Military UAVs have developed rapidly in the fields of intelligence reconnaissance, command and control, weapon coordination and other combat applications, and have formed strong combat capabilities [2]. Civil UAVs have developed from small and medium-sized and commercial to various types and levels of UAVs in different industries, and are widely used in cruise detection, security prevention and control, logistics and other fields [3] [4].

A typical UAV system consists of three parts: UAV flight platform, data link and ground station [5]. The data link system carries the whole task of ground-air communication and air-air communication. With its advantages of low delay, excellent anti-interference ability and good reliability, the UAV data link focuses on the information transmission of the UAV mission sensor, and realizes the important functions of the ground command center for the UAV remote control and telemetry, tracking and positioning, flight path control and so on. At present, the link of UAVs is mainly based on ground and on-board point-to-point link, which usually needs to be configured with airborne terminal, ground console and control terminal. At present, the mainstream data links in the military side are tactical data links LINK-22 [6] and TTNT [7], and in the civil side, there are aviation data links. At present, the United States is leading the world in UAV data link research. Based on universal broadband data link, the US military has further developed the combat data link system of UAVs, and carried out relevant research and development for micro data link to be applied to medium and small UAVs. Its mainstream technologies include "one station and multiple aircraft" technology and networking technology [8] [9]. The level of domestic UAV data link is also constantly improving, and a series of technologies such as integrated channel, satellite relay, image digital compression, combined positioning and broadband signal tracking have been broken through in UAV information technology to realize remote control, telemetry, tracking and positioning and video information transmission of short, medium and long range UAVs [10].

As one of the key technologies to improve the performance of UAVs, lightweight design has received extensive attention and research in recent years. Through the use of high-strength lightweight materials, optimized structural design, and improved manufacturing processes, the weight of UAVs can be significantly reduced, thereby improving their load ratio, range, and maneuverability. However, lightweight design is not a simple "weight reduction" process, it needs to ensure the strength and stiffness of the structure, to achieve the minimum weight. At the same time, lightweight design will also have an important impact on the dynamic response characteristics of UAVs, such as vibration intensification, stability reduction, etc. These problems are directly related to the flight safety and control accuracy of UAVs. In view of the importance and complexity of lightweight design in UAV technology, this paper aims to deeply explore the mechanism of the influence of lightweight mechanical structure on the dynamic response characteristics of UAVs, and propose the corresponding control strategy optimization method.

2. Analysis of the Influence of Lightweight Mechanical Structure on the Dynamic Response Characteristics of UAVS

The dynamic response characteristics of UAV are directly related to its flight stability, maneuverability and control accuracy. Lightweight design is an important means to improve the performance of UAV, and the impact of its structural changes on the dynamic response characteristics cannot be ignored. The reduction of stiffness, the change of mass distribution and the change of aerodynamic performance will affect the dynamic response characteristics of the structure. Therefore, in the process of lightweight design, it is necessary to comprehensively consider the interaction and influence mechanism between these factors, and optimize the dynamic response characteristics of UAVs through reasonable structural design, material selection and manufacturing process.

2.1. Influence of Structural Stiffness on Dynamic Response Characteristics

The structural stiffness of UAV is one of the key factors affecting its dynamic response characteristics. Lightweight design is often accompanied by the replacement of structural materials and the optimization of structural forms, and these changes may lead to the reduction of structural stiffness. The reduction of structural stiffness will directly affect the dynamic parameters of UAV such as natural frequency and damping ratio, and then affect its vibration characteristics and stability during flight.

Specifically, when the UAV is subjected to external disturbances (such as wind shear, sudden obstacles, etc.), components with lower structural stiffness are more likely to produce larger vibration amplitude and longer decay time. This vibration will not only increase the energy consumption of the UAV, but also may affect the stability of its flight attitude and control accuracy. Therefore, in the process of lightweight design, it is necessary to fully consider the influence of structural stiffness on dynamic response characteristics, and maintain sufficient stiffness through reasonable structural design and material selection.

2.2. The Influence of Mass Distribution on Dynamic Response Characteristics

The mass distribution of UAV is also an important factor affecting its dynamic response characteristics. The lightweight design may change the mass distribution of the drone, resulting in a change in the position of the center of gravity. The change of the center of gravity position will directly affect the flight stability and maneuverability of the UAV.

If the center of gravity of the drone is too high or too low, it will increase its instability during flight. A high center of gravity will make the UAV more susceptible to external factors such as wind, resulting in flight attitude fluctuations; Too low a center of gravity may limit the maneuverability of the drone. Therefore, in the process of lightweight design, the mass distribution of the UAV needs to be reasonably adjusted to keep its center of gravity position within a suitable range to ensure flight stability and maneuverability.

2.3. Influence of Aerodynamic Performance on Dynamic Response Characteristics

The aerodynamic performance of UAV is also one of the important factors affecting its dynamic response characteristics. The lightweight design may change the aerodynamic shape and aerodynamic parameters of the UAV, which in turn affects its lift, drag and stability characteristics.

In general, lightweight designs can result in reduced wingspan, reduced wing area or changes in airfoil profile, which all have an impact on their aerodynamic performance. For example, a reduced wingspan may reduce the lift coefficient and stability derivative of a drone; The decrease of wing area may increase its drag coefficient and decrease its range. The variation of airfoil may change its lift-drag ratio and pitching moment. These changes will directly affect the dynamic response characteristics of UAVs during flight. Therefore, in the process of lightweight design, the influence of aerodynamic performance on dynamic response characteristics should be fully considered, and the flight performance and stability of UAV should be improved by optimizing aerodynamic shape and aerodynamic parameters. For example, advanced computational fluid dynamics (CFD) techniques can be used for numerical simulation and optimization of aerodynamic performance. Or verify and optimize aerodynamic performance parameters through experimental testing.

3. Effect of Lightweight Mechanical Structure on UAV Performance

In the rapid development of UAV technology, lightweight design has become an important trend to improve UAV performance. Through the use of high-strength lightweight materials, optimized structural design, and the application of advanced manufacturing processes, lightweight design not only reduces the overall mass of drones, but also has a profound and complex impact on their performance. It not only improves flight efficiency, enhances payload capacity, extends endurance, improves maneuverability, but also puts forward higher requirements for stability and safety. Therefore, the role and value of lightweight design should be fully emphasized in UAV design to achieve comprehensive improvement of UAV performance through scientific design and optimization. In the future, with the continuous development of material science, structural design and control technology, lightweight design will play a more important role in the field of unmanned aerial vehicles to promote the continuous progress and application of unmanned aerial vehicle technology.

3.1. Increased Flight Efficiency

The lightweight design directly reduces the energy consumption during flight by reducing the mass of the drone. With the powertrain remaining the same, the lighter drone needs to overcome less gravity, making its acceleration superior and able to reach cruising speed faster. In addition, due to the reduced mass, the energy required by the UAV during the climbing process is correspondingly reduced, thus improving the climbing efficiency. More significantly, lighter drones experience less air resistance when flying, which not only reduces energy loss, but also makes the drone more stable at high speeds. Therefore, lightweight design has a non-negligible role in improving the flight efficiency of UAVs.

3.2. Increased Load Capacity

Payload capacity is one of the important indexes to measure the practical value of UAV. By reducing the mass of the drone's own structure, the lightweight design allows the drone to carry more payload for the same takeoff weight limit. This enhanced load capacity provides a broader space for the application of UAVs in many fields such as aerial photography, surveying and mapping, agricultural plant protection, logistics and distribution. For example, in the field of agricultural plant protection, the increase in payload capacity means that drones can carry more pesticides and seeds, which improves operational efficiency and coverage; In the field of logistics distribution, stronger load capacity means that drones can transport more goods at one time, reducing logistics costs.

3.3. Improved Battery Life

Endurance is the length of time that the UAV can continue to fly during the execution of tasks, which is directly related to the operating range and efficiency of the UAV. The lightweight design reduces the energy consumption during flight by reducing the mass of the drone, thus extending the flight time of the drone with the same battery energy reserve. In addition, lighter drones require less energy to maintain altitude and speed during flight, which also helps improve endurance. Therefore, lightweight design is particularly important for drones that need to perform tasks for a long time, such as environmental monitoring, target tracking and other application scenarios.

3.4. Improved Mobility

Mobility is the ability of drones to respond quickly and operate flexibly in complex environments. The lightweight design reduces the inertial force of the UAV, thus improving its response speed to control commands. In maneuvers such as fast turns, climbs and descends, lighter UAVs can adjust flight attitude and speed more quickly to achieve more accurate flight control. This improvement of mobility is of great significance to the operation of UAVs in complex terrain and harsh climate. At the same time, the improvement of mobility also helps to improve the survival ability of the UAV, so that it can react quickly in the face of emergencies and take corresponding risk-off measures.

3.5. In-depth Analysis of Stability and Security

Although lightweight design brings many performance advantages, it also puts forward higher requirements for the stability and safety of UAVs. Lightweight may lead to the reduction of structural stiffness and the change of vibration characteristics, which will affect the flight stability of UAVs. In order to ensure the stability of the UAV, designers need to fully consider the stiffness and strength requirements of the structure in the lightweight design process, and adopt reasonable structural design and material selection schemes. At the same time, it is also necessary to strengthen the research and optimization of flight control algorithm to improve the anti-interference ability and fault tolerance of UAV. In addition, in view of the vibration problems that may be caused by lightweight design, advanced vibration suppression technology can be used to reduce the vibration amplitude and frequency, and improve the flight stability of the UAV. In terms of safety, in addition to considering the structural strength and stability, it is also necessary to pay attention to the design of flight safety protection mechanisms of UAVs, such as obstacle avoidance systems and emergency landing procedures, to ensure that UAVs can land safely or avoid collision accidents under abnormal circumstances.

4. Control Strategy Optimization Method

Control strategy optimization is a key method to improve system performance, stability and responsiveness. In modern industrial automation, aerospace, transportation and other fields, the optimal design of control strategy is of great significance to ensure the efficient, safe and reliable operation of the system.

Control strategy optimization usually involves the following basic methods: First, it is necessary to conduct in-depth analysis of the controlled system and establish its mathematical model. The mathematical model should accurately reflect the dynamic characteristics and control requirements of the system, and provide the basis for the subsequent optimization design. Secondly, according to the characteristics and control requirements of the controlled system, the appropriate control strategy is selected. Common control strategies include PID control, fuzzy control, neural network control, model predictive control and so on. Each control strategy has its advantages and disadvantages and scope of application, which should be selected according to the actual situation. Then, according to the control objectives (such as stability, response speed, tracking accuracy, etc.), the corresponding objective function is constructed. Objective function is the core of control strategy optimization, which is used to evaluate the control effect of different control strategies. At the same time, the optimization algorithm is used to optimize the control strategy. Common optimization algorithms include genetic algorithm, particle swarm optimization algorithm, simulated annealing algorithm and so on. These algorithms can find the optimal control strategy parameters of the objective function by iterative search under certain constraints. Finally, the optimized control strategy is verified in the simulation environment to ensure its feasibility and effectiveness in theory. Then, the experimental test is carried out in the actual system to further verify the actual control effect.

5. Conclusion

This paper focuses on the improvement of UAV performance, discusses the influence of lightweight mechanical structure on UAV performance, and expounds the importance and practical application of control strategy optimization method in detail. The lightweight design not only reduces the overall mass of the UAV, but also significantly improves its flight efficiency, payload capacity, endurance, and maneuverability. This comprehensive improvement in performance provides the possibility for the application of drones in more fields, such as aerial photography, agricultural plant protection, logistics distribution, environmental monitoring and so on. As the core component of UAV system, the optimal design of control strategy is very important to ensure the stable, efficient and safe operation of UAV. Through mathematical modeling, control strategy selection, objective function construction, optimization algorithm application, simulation verification and experimental testing and other steps, the UAV control strategy can be optimized to further improve its performance. In the process of improving UAV performance, it is often difficult to achieve the best results by relying solely on lightweight design or control strategy optimization. Therefore, it is necessary to combine lightweight design with control strategy optimization, adopt comprehensive optimization method, and comprehensively consider each performance index of UAV to achieve overall performance optimization.

The improvement of UAV performance is a continuous process, which requires continuous efforts and exploration in lightweight design, control strategy optimization and other aspects. It is believed that in the near future, with the continuous progress of science and technology and the continuous development of drone technology, drones will play an important role in more fields and make greater contributions to the progress and development of human society.

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