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Application of Tolerance Analysis in Wing Design

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Abstract:
With the increasing demand of modern aircraft for high lift ratio, low fuel consumption and high reliability, the geometric accuracy control of wings in the design and manufacturing stages has become particularly important. Based on this background, this study conducts a review and qualitative analysis and explores how geometric deviation can affect the performance of the wing through the aerodynamic mechanism. By analyzing the velocity field, pressure field, streamlined structure and regional average performance indicators, the study further reveals the typical pneumatic problems that may lead to geometric deviation. The research results indicate that the front edge shape error and surface smoothness are the most sensitive tolerance types, which are enough to cause significant changes in the lift coefficient C_L and drag coefficient C_D even within the range of conventional manufacturing standards. In general, simulation data demonstrate that accurate tolerance analysis and surface quality control can effectively solve the instability of pneumatic performance, improve the overall aerodynamic reliability of the wing, and provide direction for future manufacturing process optimization.

Keywords: Wing design; Tolerance analysis; Geographic deviation; precision

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1. Introduction

In modern aerospace engineering, the design and manufacture of wings plays a crucial role in the performance of aircraft. The wings should not only meet the requirements of flight stability and controllability but also maximize lift and reduce drag to optimize fuel efficiency. However, in the actual manufacturing process, the geometry of the wing is often affected by the manufacturing tolerance. These small geometric deviations are enough to have a significant impact on the aerodynamic performance of the wing, which in turn affects the overall performance of the aircraft. Therefore, how to reasonably control tolerance and ensure the aerodynamic performance of wing design under the premise of ensuring production efficiency and cost has become a key problem that engineers and researchers need to solve. Anderson pointed out that the subtle geometric changes in the shape of the wing will significantly affect the local pressure distribution, and further affect the lift and resistance performance [1].

Therefore, this paper focuses on the application of tolerance analysis in wing design, combines the principle of fluid mechanics, puts forward strategies to optimize tolerance allocation, and provides more accurate research for wing design. This research provides references and suggestions for the future mechanical design of the wing.

2. Tolerance Analysis and its Application in Wing Design

In the structural design and manufacture of modern aircraft, tolerance analysis has developed from a traditional geometric size control method to an important engineering tool that affects the overall performance. With increasing demands for aerodynamic efficiency, structural integrity, and fuel economy, geometric accuracy in wing design becomes extremely important. The wing shape and three-dimensional geometry, being the primary component of lift, directly affect airflow characteristics, such as lift distribution and drag levels. Abbott & Von Doenhoff emphasized that minor deviations in front edge curvature and wing thickness adversely impact the boundary layer adhesion, a vital aspect of wing performance [2]. Therefore, the introduction of systematic tolerance analysis in the wing manufacturing and assembly link can not only ensure the assembly accuracy of the structure, but also effectively reduce the uncertainty of aerodynamic performance caused by geometric deviation.

According to ASME Y14.5, geometric tolerance is vital for controlling key surfaces and contours to maintain functional and assembly quality [3]. The essence of tolerance analysis lies in identifying how geometric deviations affect functional attributes. These deviations can arise from errors in raw materials, limitations in processing methods, tooling positioning inaccuracies, or cumulative errors throughout the assembly process. Common geometric errors encompass variations in front edge radius, thickness fluctuations in wing structures, and surface ripple irregularities. Although these discrepancies may measure in millimeters or microns, their effects can substantially alter aerodynamic properties due to the wing's sensitivity.

Rae & Pope pointed out that the aerodynamic shape quality crucially influences wind tunnel test stability, where even slight shape inaccuracies can introduce dynamic bias [4]. The sensitivity of wing performance to geometric tolerances is notably evident in several areas. Primarily, the front edge area, where slight adjustments in curvature can alter flow adhesion and pressure gradients, potentially leading to premature flow separation. Studies indicate that a 1% change in front edge radius error results in a 0.5% to 1.2% shift in lift coefficient, directly affecting the lift curve's slope and stall margins at various angles of attack. Surface smoothness is another critical factor; surface roughness or processing artifacts disrupt laminar flow, consequently enhancing drag due to earlier boundary layer turbulence. For wings with high impedance ratios, maintaining an extended laminar flow region is essential, thus necessitating strict surface quality control during manufacture. Surface irregularities of just 30-80 microns can lead to a drag coefficient increase of 1%-3%, adversely affecting fuel efficiency. ISO 1101 establishes standardized geometric tolerance expression as foundational in maintaining aviation structural quality control [5].

Additionally, the tail edge region's thickness error can affect pressure recovery, with CFD studies revealing that deviations greater than 0.3–0.5 mm can expand eddy currents and weaken pressure recovery, heightening induced resistance. The processing difficulty associated with tail edge tolerance control underscores its significance for accurate resistance prediction. Moreover, assembly tolerances must also be carefully considered; as wings consist of multiple segments, positioning errors can lead to alignment and angular mismatches that compromise overall structural strength [6].

Moving forward, the role of tolerance analysis in wing design has expanded beyond conventional manufacturing quality control. It has become integral to early-stage aircraft design decisions. By pinpointing key factors influencing aerodynamic performance and crafting effective tolerance optimization strategies, tolerance analysis is poised to become an indispensable component of future wing design and manufacturing processes, ultimately enhancing aircraft performance.

3. The Combination of Fluid Mechanics and Tolerance Analysis: the Application of CFD in Wing Design

With the development of computing technology and optimization algorithms, tolerance optimization has become an indispensable part of wing design. In addition to CFD, modern optimization algorithms such as genetic algorithms, simulated annealing, particle swarm optimization, etc. are widely used to optimize tolerance settings to achieve more efficient design. Optimize tolerance and manufacturing cost. Through the combination of CFD and optimization algorithm, the design team can optimize the tolerance range in the manufacturing process while meeting performance requirements. This can not only improve the aerodynamic performance of the wing, but

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also reduce the manufacturing cost and production time. Munson explained that there is a highly sensitive coupling relationship between fluid velocity, pressure distribution and geometry, which is an important basis for evaluating errors in aerodynamics [7].

In addition, the combination of machine learning and artificial intelligence can further improve the accuracy of tolerance optimization. By analyzing historical data and simulation results, the intelligent optimization algorithm can automatically recommend the best tolerance design scheme.

First, reliance on costly physical testing is drastically reduced. CFD simulation can simulate multiple scenarios of tolerance changes in a virtual environment, thus reducing a large number of expensive physical tests. Second, multivariate analysis becomes straightforward. CFD can consider the influence of multiple factors at the same time, such as temperature, wind speed, flight angle, etc., and simulate how these environmental changes interact with different tolerance settings. Third, it can improve design efficiency. Through CFD analysis, designers can quickly identify the impact of tolerance on the aerodynamic performance of the wing and optimize it without redesigning each component. Bruce pointed out that it is more important to rationally allocate tolerances in the product design stage than to remedy in the manufacturing stage, which can significantly reduce the accumulation of errors [8].

This study conducts an in-depth analysis of three types of key data obtained based on CFD simulation results to explore their application in wing design, especially in tolerance analysis and optimization design. The data was collected from the simulation of a specific wing model, including simulation operation results, regional average data analysis and convergence chart. All data reveal the changes in fluid dynamics under different design conditions and their impact on wing performance. The CFD simulation results in this study come from the public project "compressible Flow Around a Wing" of the SimScale platform [9]. The official SimScale team provides the simulation results, which this study uses as reference data. This study discusses the application of tolerance analysis in wing design and manufacturing by analyzing these results and combining them with the classical formula of fluid mechanics.

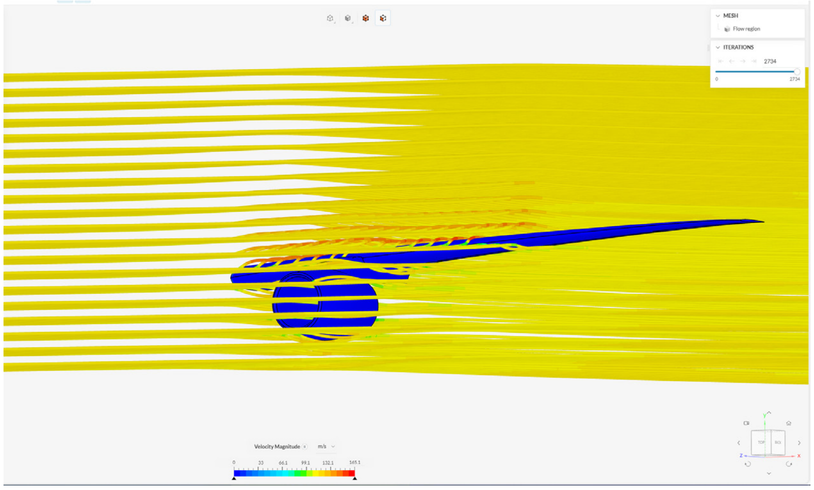

Fig. 1 Side map of airflow distribution

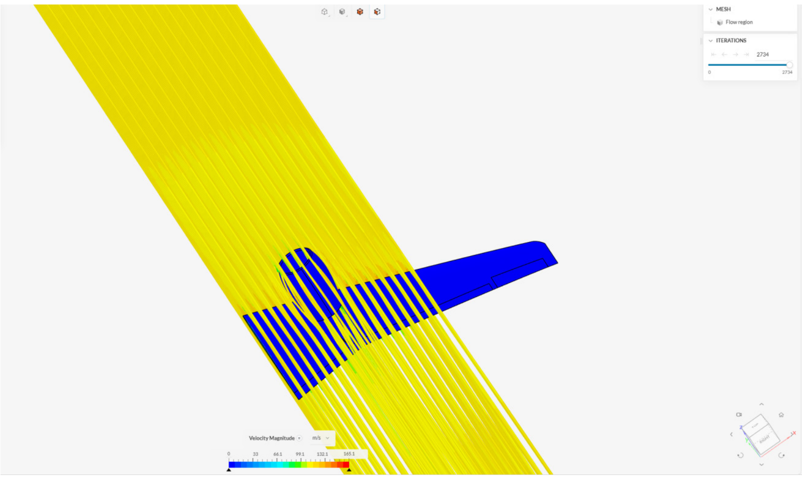

Fig. 2 A bird's-eye view of airflow distribution

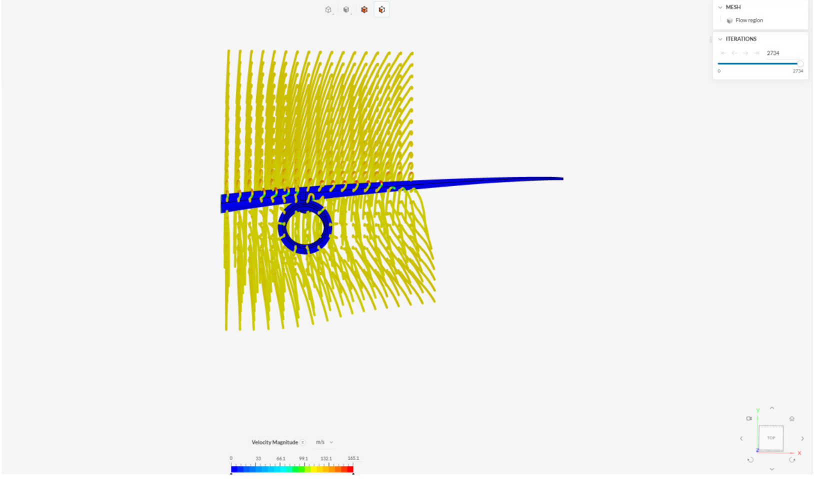

Fig. 3 Front view of airflow distribution

In this CFD simulation, this study makes a detailed analysis of the airflow around the aircraft wing, especially the airflow distribution near the wing surface.

First of all, Figure 1 shows the distribution of airflow velocity around the aircraft wings. Yellow indicates a higher flow rate, while blue indicates a lower flow rate. It can be seen from the figure that the airflow near the surface of the wing is relatively fast, especially in the front edge and tip areas of the wing, which may be due to the lift effect caused by the acceleration of the airflow. In the blue area below the wing, the low airflow velocity may be caused by the pressure zone formed by the airflow on the surface under the wing, which can also help speculate about the lift and resistance distribution of the aircraft. For tolerance analysis, it is crucial to understand the velocity distribution of the airflow, because a small tolerance deviation may affect the velocity and direction of the airflow, thus affecting the overall aerodynamic performance of the wing. Cooke emphasized that the aerodynamic shape accuracy of the wing structure is directly related to the performance of the whole machine, and the geometric deviation will affect the lift center and load distribution [10].

Figures 2 and 3 show the distribution of airflow lines. In these diagrams, you can see the flow patterns of the airflow above and below the wing. Especially at the front edge of the wing, the separation of airflow is more obvious, resulting in a significant change in the direction of airflow. The changes in the streamline reflect the aerodynamic performance of different parts and provide intuitive evidence of whether there is eddy current, separation and other unstable flow on the surface of the wing. The particle tracking animation in Figure 3 illustrates the dynamic process of airflow moving along the surface of the wing. These animations clearly show that at the front edge of the wing, the acceleration effect of the airflow is obvious. With the advancement of the streamlined line, the airflow gradually becomes stable, and finally forms a certain pressure difference at the tail of the wing. These changes in airflow not only affect the aerodynamic efficiency of the wing, but also are closely related to the manufacturing ac-

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curacy of the wing design.

4. Further Discussion

The simulation diagram shows the velocity distribution of the airflow around the wing. In aerodynamics, the geometry of the wing surface directly affects the distribution of airflow, which in turn affects the stability of lift, drag and airflow. When conducting tolerance analysis, it is necessary to pay attention to the subtle errors on the surface of the wing, which may cause the separation of the airflow or change the stream, affecting the aerodynamic performance of the wing. Bertin & Smith proposed that the lift coefficient and drag coefficient are significantly sensitive to geometric changes, especially under medium and high angle of attack flight conditions [11].

Tolerance analysis usually focuses on the geometric deviations generated in the manufacturing process. In CFD simulation, small geometric errors, such as small unevenness on the edge of the wing or local defects on the surface of the wing, will cause local disorder of the airflow. This flow field change can be described by Bernoulli's equation in aerodynamics:

$$\mathrm{P}+\frac{1}{2}\rho \mathrm{v}^2=\text{constant} \tag{1}$$

Where P is the air pressure, ρ is the gas density, and v is the fluid velocity. The small tolerance on the surface of the wing will cause changes in the airflow velocity, which will affect the pressure distribution. If the geometric error of the wing is large, it may cause drastic changes in fluid velocity, triggering airflow separation, which will significantly affect lift and resistance.

CFD simulation results can also show the resistance distribution around the wing, especially in the area of airflow separation or backflow. These phenomena usually occur when there are geometric defects on the surface of the wing. For example, the uneven surface or sharp edges of the wing will cause unstable air flow and increase the drag. Resistance D can be estimated by the following formula:

$$\mathrm{D}=\mathrm{C}_{\mathrm{D}}\cdot\frac{1}{2}\rho \mathrm{v}^2\cdot \mathrm{S} \tag{2}$$

Where C_{D} is the drag coefficient, ρ is the air density, v is the airflow velocity, and S is the surface area of the wing. The increase in the surface tolerance of the wing will lead to an increase in CD, thus increasing the resistance of the wing.

5. Conclusion

Based on CFD simulation results and theoretical analysis of fluid mechanics, tolerance analysis plays a crucial role in wing design. Through precise tolerance control, the phenomenon of airflow instability, lift decline and resistance increase caused by geometric errors can be effectively avoided. A reasonable tolerance optimization strategy can improve the aerodynamic performance of the wing, reduce the drag, improve the lift, and then improve the fuel efficiency and flight performance of the aircraft. Therefore, tolerance analysis and optimization in the process of wing design and manufacturing can ensure that the aerodynamic performance of the wing meets the design requirements and improve the performance of the overall aircraft.

This research mainly relies on public CFD data for analysis, and has not been systematically modeled and compared for different tolerance parameters. Due to the lack of experimental verification, some conclusions still need to be further confirmed through wind tunnel tests or physical measurements. In addition, in the future, a more comprehensive tolerance sensitivity analysis can be carried out by establishing a parametric geometric disturbance model to improve the rigor and applicability of the research.

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