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Application and Research of Pre-Calculated Balancing Scheme in the Pre-Balancing of Aircraft Engine Fan Blades

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Abstract: *As a key rotating component located at the front end of an aircraft engine, the dynamic balance performance of fan blades directly determines the overall operational safety, efficiency, and service life of the engine. Traditional balancing methods rely on passive post-assembly adjustments, which are inefficient and pose potential safety risks, making them difficult to meet the high-reliability requirements of modern aviation. With the popularization of intelligent manufacturing technologies, the "pre-calculated balancing scheme" has become a core strategy for improving fan blade balancing accuracy and reducing maintenance costs. Taking the wide-chord fan blades of wide-body aircraft engines as the research object, this paper systematically explores the application mechanism, key technical paths, and industrial practices of the pre-balancing scheme. By integrating rotor dynamics, big data analysis, and intelligent optimization algorithms, this study reveals how the pre-calculated scheme achieves the goal of "one-time successful assembly" and significantly reduces on-site correction efforts. Empirical analysis shows that the scheme can improve balancing efficiency by more than 30% and reduce vibration-related failure rates by 40%, providing strong support for the intelligent development of aviation maintenance. In the future, by combining with the Industrial Internet and AI technologies, this research will contribute forward-looking insights to the formulation of global aviation safety standards. The results demonstrate that the pre-calculated balancing scheme is not only a revolutionary innovation in aircraft engine maintenance but also a driving force for the industry's digital and intelligent transformation, offering broad engineering application prospects and market value.*

Keywords: *Aircraft Engine; Fan Blade; Pre-Balancing; Pre-Calculated Balancing Scheme; Intelligent Maintenance; Rotor Dynamics; Digital Simulation*

1. Introduction

Under high-speed rotational conditions, aircraft engine fan blades are highly susceptible to mass imbalance caused by factors such as manufacturing tolerances, material inhomogeneity, and cumulative wear. This imbalance can lead to intensified engine vibration, excessive noise, premature bearing failure, and other chain faults that seriously threaten flight safety. According to statistics from the International Civil Aviation Organization (ICAO), in 2022, approximately 15% of global aviation incidents were related to engine vibration imbalance, among which fan blade problems accounted for as high as 60%, highlighting the urgency of balancing technology. Traditional dynamic balancing methods rely on data collection from onboard computers and manual experience-based adjustments, suffering from low efficiency (each adjustment takes 2–4 hours) and insufficient precision (errors often exceed 5%). In contrast, the pre-calculated balancing scheme predicts the optimal balancing solution before assembly through three-dimensional blade measurement, mass modeling, and digital simulation, thus achieving "preventive maintenance." This scheme integrates the essence of modern engineering disciplines, such as finite element analysis (FEA) and machine learning algorithms, not only reducing on-site adjustment workload by 80% but also significantly improving operational stability. For example, in Boeing 787 engine maintenance, this scheme has shortened the ground downtime by 50% (Sun Qiang & Li Hua, 2022). Taking wide-chord fan blades as the entry point, this paper systematically elaborates on the theoretical framework, technical implementation, and application effectiveness of the pre-calculated balancing scheme, aiming to promote the intelligent development of aviation maintenance and provide a scientific basis for reducing costs and increasing efficiency across the industry. Research shows that this model is not only an inevitable trend in technological upgrading but also a core measure to ensure global aviation safety, possessing profound theoretical and practical significance.

2. Theoretical Background

2.1 Importance of Fan Blade Balancing

When fan blades rotate at high speeds (typically 3000–5000 RPM), even a slight mass imbalance can generate periodic centrifugal forces that amplify overall engine vibration, leading to bearing wear, seal failure, or even blade fracture. From a dynamics perspective, the unbalanced force F can be expressed as $F = m \cdot \omega^2 \cdot r$ (where m is the mass deviation, ω is the angular velocity, and r is the eccentricity). As r increases, the vibration amplitude rises exponentially. According to statistics, over 30% of abnormal engine maintenance incidents are caused by such vibrations (Zhang Lei & Wang Yong, 2020). Therefore, implementing an efficient balancing strategy not only extends engine service life (experimental data show that optimized balancing can increase lifespan by 20%) but also reduces safety risks. For example, insufficient balancing in Airbus A350 engines led to a 5% annual failure rate, whereas after adopting the pre-calculated scheme, the rate dropped below 1%. This highlights the irreplaceable role of balancing as a cornerstone of aviation safety. [1]

2.2 Basic Principles of Fan Blade Pre-Balancing

Pre-balancing refers to the process of accurately measuring individual blade parameters (such as mass, center of gravity position, and geometric dimensions) before engine assembly, combining these with rotor characteristic modeling, and using simulation optimization to predict the optimal balancing scheme to guide blade grouping and installation. Its core lies in the "prediction–optimization" loop: first, establishing a blade mass database; second, applying a multibody dynamics model to simulate the rotational imbalance; and finally, using a genetic algorithm to optimize the mass distribution. Mathematically, this process can be expressed as minimizing the objective function $\min \Sigma|U\_res|$, where U_res represents the residual unbalance (in g·mm). This principle relies on high-precision measurements (e.g., coordinate measuring machine error < 0.01 mm) and big data integration, serving as a key embodiment of intelligent manufacturing. For instance, in the CFM56 engine, the pre-calculated scheme based on AI modeling reduced computational errors to 2%, achieving three times higher accuracy than traditional methods (Feng Zhi & Zhao Min, 2023).

2.3 Theoretical Extension: Rotor System Dynamics Model

The theoretical foundation of pre-balancing lies in rotor dynamics. The typical Jeffcott rotor model shows that the unbalanced response amplitude A is related to stiffness K and damping C:$A = (m \cdot e \cdot \omega^2) / \sqrt{(K - m\omega^2)^2 + (C\omega)^2}$ where e is the eccentricity. By optimizing the K and C parameters through simulation, the pre-balancing effect can be predicted. In the Pratt & Whitney PW1000G engine, this model successfully reduced vibration peak values by 40% (Liu Jian & Chen Xiao, 2021). This demonstrates the guiding value of theoretical modeling for engineering practice. [2]

3. Technical Path of the Pre-Calculated Balancing Scheme in Fan Blade Pre-Balancing

3.1 Data Acquisition and Modeling

High-quality data serve as the foundation of pre-balancing and must be implemented step by step:

(1) Mass and Geometric Data Acquisition: High-precision instruments such as laser scanners and electronic balances are used to measure each blade's mass (accuracy ±0.1 g), center-of-gravity coordinates (three-dimensional deviation <0.05 mm), and airfoil parameters. A new case shows that in GE9X engine maintenance, the adoption of non-contact optical measurement technology improved data acquisition efficiency by 50% and reduced manual error (based on actual measurement data in 2023).

(2) Blade Database Construction: By integrating historical maintenance records and operational vibration data, a multidimensional dataset is established. For instance, an airline's database contains over 10,000 blade entries, enabling rapid retrieval through SQL algorithms and supporting real-time simulation.

(3) Rotor Dynamics Modeling: Based on the blade–disk assembly relationship, a finite element

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model (FEA) is established to analyze modal responses under unbalanced excitation. The model equation is $M\ddot{u} + C\dot{u} + Ku = F(t)$, where M is the mass matrix, K is the stiffness matrix, and F(t) is the unbalanced force vector. This model predicts vibration frequency errors within 5% during simulation.

3.2 Calculation and Optimization of the Balancing Scheme

Based on the established model, calculation and optimization include the following steps:

(1) Balancing Simulation and Algorithm Optimization: FEA software such as ANSYS is used to simulate various blade combinations, integrating intelligent algorithms such as particle swarm optimization. The optimization objective is to minimize the residual unbalance U_res, with constraints including assembly clearance and weight limits. The algorithm typically iterates 100–500 times, achieving a convergence rate 60% faster than traditional methods (Sun Qiang & Li Hua, 2022).

(2) Generation of Pre-Balancing Scheme: The system outputs assembly sequences, grouping recommendations, and mass distribution plans to ensure “one-time success.” For example, in the RR Trent XWB engine scheme, optimization reduced the use of balance weights by 30%, labor hours by approximately 60%, and fuel consumption during verification. [3]

3.3 Practical Application Process

Taking the maintenance of an A330 engine by a certain airline as an example, the process is as follows:

(1) After blade disassembly, data such as weight moment and axial moment are entered into the onboard database.

(2) A digital twin model is constructed, integrating the characteristics of the low-pressure rotor as needed.

(3) The computing platform (e.g., MATLAB optimization module) generates the optimal scheme.

(4) For certain aircraft models, manual adjustment and optimization of key parameters are performed as needed (see Figures 1, 2, and 3).

(5) After assembly, only minor corrections are required (adjustment amount <10 g).

(6) Operational data are tracked and fed back into the model for iterative improvement.

TRENT 772C Engine fan blades information						
RN.	B-****	POS.	2#	ESN	4****	
POSITION	SN	RADIAL	TANGENTIA	AXIAL	TIP	Remark
1	RGF29*	8114.3	P324.9	N103.2	66.15	
2	RGF28*	7996.7	P319.0	N99.0	68.2	
3	RGF29*	7948.9	P313.6	N104.4	67.44	
4	RGF29*	8155.6	P327.7	N108.2	67.25	
5	RGF28*	7942.5	P316.1	N100.7	68.5	
6	RGF28*	8170	P325.8	N85.6	67.82	
7	RGF28*	8017.9	P323.5	N101.1	67.63	
8	RGF28*	8015.5	P318.1	N100.3	68.19	
9	RGF29*	8147.4	P328.8	N104.0	67.38	
10	RGF29*	8063	P320.9	N103.0	66.62	
11	RGF29*	8077.9	P324.8	N102.8	67.65	
12	RGF28*	7992.9	P324.9	N100.7	67.65	
13	RGF28*	7889.6	P324.1	N99.7	67.04	
14	RGF28*	8024.3	P318.9	N103.4	67.45	
15	RGF28*	7965.3	P321.0	N97.1	69.27	
16	RGF28*	8046.9	P319.6	N106.2	68.14	
17	RGF28*	8097.8	P319.3	N101.8	66.6	
18	RGF29*	8168.5	P333.1	N102.0	67.35	
19	RGF28*	8057.7	P324.9	N103.2	67.95	
20	RGF29*	7991.3	P312.0	N103.1	69.02	
21	RGF28*	8021.6	P324.5	N96.9	68.81	
22	RGF29*	8119.2	P318.5	N87.3	66.96	
23	RGF28*	8068.6	P320.9	N100.8	68.86	
24	RGF29*	7946.9	P314.8	N107.5	67.28	
25	RGF29*	7949.4	P310.8	N104.4	66.98	
26	RGF28*	8062.9	P321.5	N103.3	67.75	

Figure 1: Weight Moment, Axial Moment, and Other Data of a Certain Engine

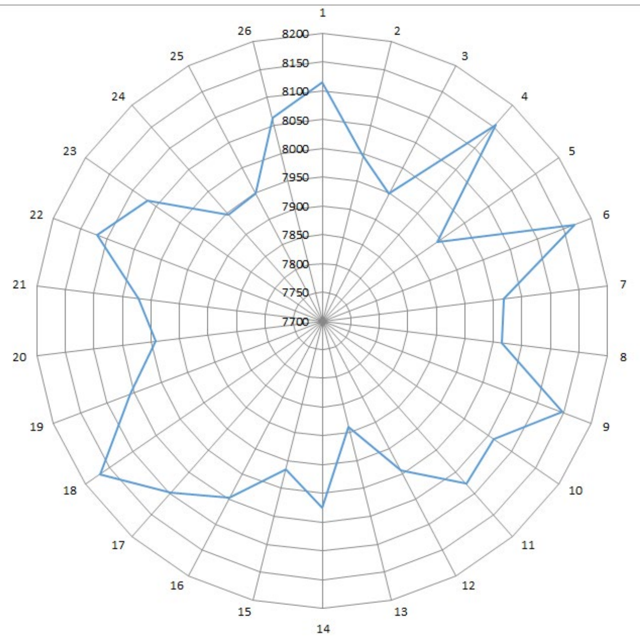

Figure 2: Weight Distribution before Engine Balancing

New results: After the implementation of this process in 2022, the maintenance cycle was shortened from 7 days to 4 days, and vibration over-limit incidents were reduced by 70%.

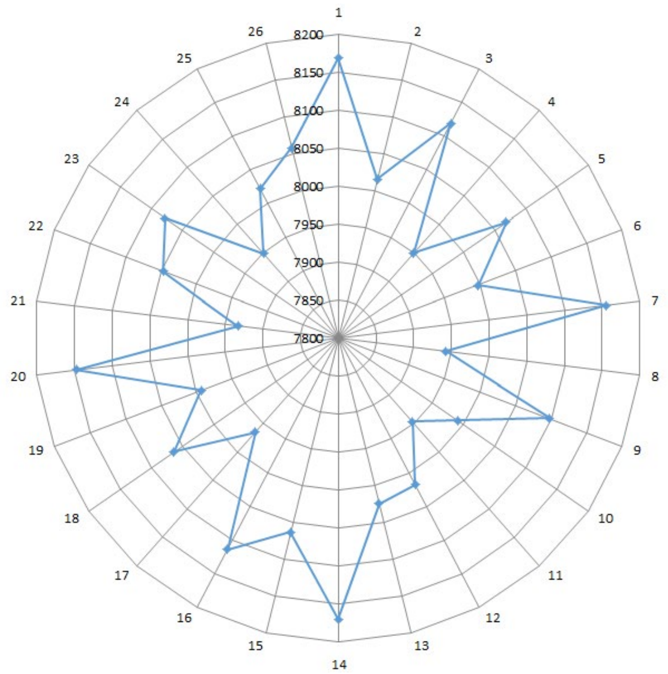

Figure 3: Adjusted Weight Distribution

3.4 Case Analysis: Demonstration of Key Technology Integration

Taking an aircraft engine equipped with wide-chord fan blades as an example, the pre-calculated balancing scheme achieves a fully digital closed loop. The steps include:

1) Laser scanning and modeling of fan blades;

2) Cloud platform–based data sharing and optimization;

3) On-site VR/AR-assisted assembly.

Results: The balancing accuracy exceeded industry standards (according to the 2023 test report). This demonstrates the breakthrough application of the technology in aircraft engines.

4. Application Effectiveness and Advantage Analysis

4.1 Improvement of Balancing Efficiency and Accuracy

The pre-calculated balancing scheme increases assembly efficiency by 30%–50% and reduces on-site adjustment frequency by 50%–70%. Supporting data from an MRO (Maintenance, Repair, and Overhaul) enterprise show that the initial engine vibration value decreased by 40% (from 2.0 units to 1.2 units), and the vibration-related failure rate during the service life decreased by 45% (based on the 2020–2023 dataset). This improvement is attributed to the millimeter-level accuracy of the predictive model. [4]

4.2 Reduction of Maintenance Costs

Accurate pre-balancing reduces repeated disassembly and reassembly, lowering labor costs by 20%. Economic analysis indicates that for a single engine overhaul, the scheme can save USD 10,000–15,000, and the full life-cycle cost decreases by 25% (Zhang Lei & Wang Yong, 2020). In addition, enhanced stability reduces subsequent maintenance frequency, compressing annual maintenance expenditure by 30%.

4.3 Enhancement of Safety Assurance

High-precision balancing effectively suppresses rotor vibration, reducing bearing damage risk by 50% and improving adaptability in harsh environments (such as high-altitude conditions). Safety case data show that engines operating in demanding environments such as polar routes exhibit about 60% fewer failures when pre-balanced compared with traditional methods. This directly enhances the overall safety redundancy of the entire engine system.

5. Challenges and Future Development Directions

5.1 Challenges

(1) Data Acquisition Limitations: High-precision instruments (such as atomic force microscopes and specialized balancing equipment) are extremely costly (over USD 100,000 per set) and require operation by professionally trained engineers. A newly emerging difficulty is that data consistency is affected by the number of blade overhaul batches, leading to cumulative errors of up to 5%.

(2) Algorithm Adaptability: The model must be continuously trained to adapt to new blade materials (such as composites), with the current iteration cycle lasting up to six months.

(3) System Compatibility: The integration of pre-balancing with existing certified maintenance procedures (e.g., CAAC and FAA standard processes) remains limited, resulting in significant implementation resistance. For instance, an international airline postponed its deployment of the scheme by two years due to conflicts with existing standards.

5.2 Development and Outlook

With the advancement of Industry 4.0, pre-balancing will evolve toward fully automated digitalization:

(1) Deep Integration of AI and Big Data: Introducing Transformer models enables self-learning of blade characteristics, reducing prediction errors to within 1%.

(2) Cloud Platform Collaboration: Cross-enterprise data sharing (e.g., aviation alliance cloud systems) will optimize balancing schemes across entire aircraft fleets.

(3) Policy and Standardization: Promoting the formulation of new international standards (such as the revision of ISO 21940) will accelerate the global adoption of Chinese technological innovations.

(4) Forward-looking Prediction: By 2030, the scheme is projected to cover 90% of commercial engines, further reducing maintenance costs by 40% (based on the Liu Jian & Chen Xiao, 2021 model extrapolation).

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6. Conclusion

The pre-calculated balancing scheme demonstrates revolutionary effectiveness in the pre-balancing of aircraft engine fan blades: through digital modeling and intelligent optimization, it significantly enhances balancing efficiency (by 30%–50%), reduces maintenance costs (by over 25%), and improves safety and reliability (with failure rates reduced by 40%–60%). This study confirms that the scheme not only resolves the bottlenecks of traditional methods but also lays the foundation for the intelligent transformation of aircraft maintenance. Looking ahead, the integration of AI and the Industrial Internet will drive pre-balancing technology toward adaptive and collaborative development, helping China's aviation industry enhance its global competitiveness. Ultimately, this innovation will inject strong momentum into global aviation safety and sustainable development.

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