

Research on Propeller Blade Load Calibration Methods and Post-print of Experimental Verification

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Abstract

Abstract: Turboprop engines generate the majority of their thrust through the rotation of the propeller, thereby propelling the aircraft forward. During operation, propeller blades are subjected to the composite effects of various loads, including flapping bending moments, lead-lag bending moments, and torsion. Propeller blade load measurement is an essential means of acquiring structural data for the propeller and conducting a reasonable assessment of its fatigue life. However, the accuracy of in-flight blade load measurements is significantly influenced by the calibration curves obtained from ground calibration tests. Addressing the common issue of coupling between flapping and lead-lag loads in ground calibration tests, this study investigates a physical decoupling method. The strain gauge measurement positions were continuously adjusted using a step-by-step approximation method, and experimental verification was conducted on actual propeller blades. The experimental results demonstrate that this method effectively achieves the decoupling of flapping and lead-lag loads. Before decoupling, the relative coupling coefficient between the two was as high as 178%; after decoupling, the relative coupling coefficients of all tested sections were reduced to below 3%. This indicates that the decoupling method is reasonable and feasible, providing significant reference experience for subsequent load calibration tests of other propeller blades.

Full Text

Preamble

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Research on Calibration Methods and Experimental Verification of Propeller Blade Loads Zhai Yahao¹, Lu Kaixing², Wang Ye¹, Zhang Shuai¹ (¹Chinese Flight Test Establishment, Xi'an 710089; ²Aviation Industry Huiyang Propeller Co., Ltd., Baoding 071052)

Abstract: Turboprop engines generate the majority of their propulsive force through the rotation of the propeller, which subsequently drives the aircraft forward. During operation, propeller blades are subjected to complex combined loads, including flapping moments, lead-lag moments, and torsion.

Propeller blade load measurement is a critical means of obtaining structural data and performing reasonable fatigue life assessments. However, the accuracy of in-flight blade load measurements depends heavily on the calibration curves obtained from ground calibration tests. Addressing the common issue of coupling between flapping and lead-lag loads in ground calibration tests, this study investigates a physical decoupling method. By employing a step-by-step approximation approach, the measurement positions of the strain gauges were continuously adjusted, and experimental verification was conducted on actual propeller blades. The experimental results demonstrate that this method effectively achieves decoupling between flapping and lead-lag loads. Before decoupling, the relative coupling coefficient between the two reached as high as 178%; after decoupling, the relative coupling coefficients at each test section were reduced to below 3%. These results indicate that the proposed decoupling method is reasonable and feasible, providing significant reference experience for future load calibration tests on other propeller blades.

关键词

Propeller blade; Flapping load; Lead-lag load; Calibration test; Stepwise approximation; Physical decoupling

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Research and experimental verification of propeller blade load calibration method ZHAI Yahao¹, LU Kaixing², WANG Ye¹, ZHANG Shuai¹

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Abstract

The thrust of the turboprop engine is mostly generated by the rotation of the propeller, which propels the aircraft forward. The propeller blade is subjected to the combined action of various loads such as flapping bending moment, shimmy bending moment and torsion when it is working. And blade load measurement is an important means to obtain propeller structural data and evaluate its fatigue life reason-

ably. However, the accuracy of blade load measurement in the air is greatly affected by the calibration curve obtained from the ground calibration test. In this paper, the physical decoupling method is studied for the common coupling problem of flapping and shimmy loads in ground calibration test. This method continu-

ously adjusts the measurement position of the strain gauge by the step-by-step approach method, and the

experimental verification is carried out on the propeller blade for the first time. The test results show that

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Abstract

The accurate measurement of propeller blade loads is essential for assessing structural integrity and optimizing aerodynamic performance. This paper investigates load calibration methods for propeller blades, focusing on the relationship between strain responses and applied loads. Through theoretical analysis and experimental verification, a calibration procedure is established to determine the influence coefficients for multi-point loading scenarios. The results

demonstrate that the proposed calibration method effectively decouples complex load distributions, providing a reliable basis for real-time load monitoring during flight tests.

1 Introduction

Propellers serve as the primary propulsion components for many aircraft, and their structural reliability is directly related to flight safety. During operation, propeller blades are subjected to complex aerodynamic forces, centrifugal loads, and vibratory stresses. To ensure the structural integrity of the blades, it is necessary to accurately measure the actual loads acting on them during operation.

Traditional load measurement techniques often rely on strain gauge bridges. However, due to the complex geometry and material anisotropy of modern composite propeller blades, the relationship between strain and load is highly nonlinear and coupled. Therefore, establishing a precise load calibration method is a critical prerequisite for accurate load identification. This study aims to develop a robust calibration framework that can account for the spatial distribution of loads and the inherent coupling effects in propeller structures.

2 Theoretical Basis of Load Calibration

The fundamental principle of load calibration is based on the linear elastic behavior of the structure. For a propeller blade, the relationship between the applied load vector \mathbf{P} and the measured strain response vector $\boldsymbol{\varepsilon}$ can be expressed as:

$$\boldsymbol{\varepsilon} = \mathbf{C}\mathbf{P}$$

where \mathbf{C} is the compliance matrix. In practice, we seek the inverse relationship to identify the loads from measured strains:

$$\mathbf{P} = \mathbf{K}\boldsymbol{\varepsilon}$$

where \mathbf{K} is the load influence coefficient matrix. For a propeller blade, the loads are typically decomposed into bending moments in two perpendicular planes (flapwise and chordwise) and centrifugal tension.

2.1 Selection of Strain Gauge Positions

The selection of strain gauge locations

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the method can better realize the decoupling of flapping and shimmy loads. Before decoupling, the relative coupling coefficient of the two is as high as 178%. However, after decoupling, the relative coupling coefficient of each test section reaches below 3%, indicating that the decoupling method is reasonable and feasible, which provides important reference experience for the subsequent load calibration tests of other propeller blades.

Key words: propeller blade; flapping load; shimmy load; calibration test; gradually approaching; physical decoupling

effective decoupling of the two [12]. To overcome the extreme complexity of helicopter rotors, researchers have increasingly turned to advanced computational methods.

[Figure 1: see original paper]

The aerodynamic environment of a helicopter rotor is characterized by high nonlinearity and unsteady flow conditions. Specifically, the rotor must operate across a wide range of Mach numbers, from subsonic flow on the retreating blade to transonic flow on the advancing blade. This disparity creates significant challenges for traditional analytical models, necessitating the use of high-fidelity numerical simulations and machine learning techniques to achieve precise control and performance optimization.

Recent developments in deep learning have provided new avenues for modeling these complex physical phenomena. By leveraging large-scale datasets derived from wind tunnel tests and Computational Fluid Dynamics (CFD) simulations, researchers can now develop surrogate models that significantly reduce the computational cost of rotor design. These models are particularly effective at capturing the intricate interactions between the blade vortex and the subsequent wake, which are critical for noise reduction and structural integrity.

The propeller is a critical component of the propulsion system in propeller-driven aircraft. Its primary function is to convert the torque generated by the engine into aerodynamic thrust, thereby providing the necessary power for flight. As a rotating aerodynamic surface, the design and performance of the propeller directly influence the aircraft's efficiency, fuel consumption, and overall flight characteristics. In modern aviation, advancements in materials science and computational fluid dynamics have led to the development of highly optimized propeller blades capable of maintaining high efficiency across a wide range of operating conditions.

During the flight of an aircraft, the propeller blades are mounted onto the propeller hub. These components are subjected to complex aerodynamic loads and centrifugal forces, which necessitate high structural integrity and precise installation. The interaction between the blades and the hub is critical for ensuring efficient thrust generation and maintaining the overall stability of the propulsion system. Any misalignment or structural failure in this assembly can lead to

significant vibrations, reduced performance, or catastrophic mechanical failure. Therefore, the analysis of stress distribution and the mechanical behavior of the blade-hub interface remains a vital aspect of aeronautical engineering and design.

complex load environments, utilizing sophisticated structures such as flapping hinges and lead-lag hinges to provide

While rotating at high speeds along the propeller shaft to generate aerodynamic thrust, the propeller also rotates around...

Its controllable flexibility, combined with a structure that typically features a high aspect ratio, often employs a relatively symmetrical design.

adjusts the blade pitch angle by rotating around its own axis. During the operation of the blades,

airfoils; whereas modern propellers (especially those utilizing advanced composite blades)

The wind turbine blade is subjected to the combined action of various loads, including flapping moments, edgewise moments, and torsional moments.

To maintain high propulsive efficiency at high speeds, structural designs predominantly feature low aspect ratios.

These loads are the primary source of fatigue damage in rotor blades; therefore,

Compared to conventional designs, these components typically feature highly complex three-dimensional aerodynamic profiles, including large-curvature geometries.

Accurately obtaining the aforementioned loads is of critical importance.

[1- 2]

degree, high twist, and complex tip geometry, while employing a high-stiffness

Measurement techniques for propeller blade loads are relatively mature. Currently,

precise shape-retention design to ensure aerodynamic performance. Consequently, compared to relatively straight

both domestic and international researchers primarily measure loads by attaching strain

helicopter rotors, the blade structures of fixed-wing aircraft propellers are more complex,

gauges at appropriate positions on the blade surface and forming bridges. Subsequently, load calibration tests are conducted in the laboratory to obtain the

possess higher stiffness, and present greater difficulty in load decoupling.

linear relationship between the applied load and the output voltage of the strain bridge. Finally, the actual

Existing studies have utilized numerical decoupling methods to decouple flapping and lead-lag bending

measured bridge voltage data obtained during flight is converted

moment loads. However, numerical decoupling methods involve a heavy computational workload and often yield

to obtain the actual operational loads of the blades. For example, Tao Ye et al. results with significant errors. Drawing on experience from helicopter rotor load calibration, this study investigates physical decoupling methods for load calibration tests

attached strain gauges to the blade root and conducted ground-based load calibration tests

specifically for fixed-wing aircraft propellers. Experimental verification was subsequently

using a half-bridge configuration to measure bending moments, thereby establishing calibration equations. Niu Hongwei

performed.

conducted blade stress measurement tests on aviation propellers; Guo Haidong et al.

carried out flight tests and analysis of the vibration stress characteristics of pusher-type

propellers by installing strain gauges on the blades.

Load Calibration Measurement System

Strain Gauge Attachment

The load calibration test is a critical step in obtaining accurate blade loads. If coupling effects exist between flapping and lead-lag bending moment loads during the calibration test, the accuracy of the blade load measurements will inevitably be compromised. Currently, there is limited literature discussing the coupling problem of flapping and

To obtain more accurate propeller blade loads, this experiment

lead-lag bending moments in propeller blade load calibration tests. However, some scholars have

utilizes a full-bridge configuration for the strain gauges. The full-bridge not only achieves signal

conducted research on helicopter rotor load calibration techniques. For instance, Yu Xun

amplification but also maximizes the elimination of effects caused by temperature variations.

addressed the coupling problem between helicopter rotor flapping and lead-lag loads

by proposing numerical and physical decoupling methods, providing an analysis and comparison of the two. Liu Zhengjiang et al. [?] conducted

calibration research on model blade loads,

laying the foundation for actual blade load calibration. Yu Xun [?] proposed

an efficient method for determining the flapping and lead-lag planes of a blade. Han [?]

proposed a new method for determining the actual pre-twist

angle of helicopter rotor blades to eliminate the coupling of flapping on lead-lag motion. Li Yongshou [?]

proposed an experimental method to determine the loading direction of helicopter

blades based on the output response of the strain bridge. Jiao Shuaike et al. [?] researched rotor load calibration testing techniques under the influence of blade gravity. The key to measuring blade flapping and lead-lag bending moments lies in achieving

The strain bridge configuration is shown in [Figure 1: see original paper]. The four arms of the bridge, R_1 , R_2 , R_3 , and R_4 , are all active strain gauges. Based on the deformation of the blade under a specific load, the strain gauges where resistance increases under that deformation are defined as R_1 and R_3 , while those where resistance decreases are defined as R_2 and R_4 . In this way, the deformation of the blade is converted into resistance changes in the strain gauges, which are then characterized by the output voltage of the strain bridge. The relationship is expressed as:

$$u = \frac{U \cdot K}{4}(\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4)$$

In the equation: u represents the bridge output voltage; U represents the bridge excitation voltage; and K represents the sensitivity coefficient of the strain gauge.

The sensitivity coefficient of the strain gauge is denoted as K . Let ϵ_1 , ϵ_2 , ϵ_3 , and ϵ_4 represent the strains measured by the strain gauges R_1 , R_2 , R_3 , and R_4 , respectively. The total strain measured by the bridge circuit is denoted as ϵ .

Abstract

This paper investigates the dynamic response and vibration characteristics of complex mechanical systems using advanced numerical simulations and experimental validation. By employing machine learning algorithms and deep learning architectures, we propose a novel framework for structural health monitoring and predictive maintenance. The results demonstrate that the integrated approach significantly improves the accuracy of damage detection and the reliability of life cycle assessments for critical engineering components.

Introduction

The field of applied mechanics has undergone a significant transformation with the advent of high-performance computing and data-driven methodologies. Traditional analytical models, while foundational, often struggle to capture the non-linearities and stochastic behaviors inherent in modern composite materials and multi-scale structures. Consequently, there is an increasing demand for hybrid models that combine physical principles with the flexibility of machine learning.

Structural health monitoring (SHM) serves as a vital tool for ensuring the safety and longevity of infrastructure. Recent advancements in sensor technology have enabled the collection of vast amounts of vibrational data. However, extracting meaningful features from this high-dimensional data remains a challenge. Deep learning, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs), has shown great promise in identifying patterns that signify structural degradation.

Methodology

3.1 Mathematical Modeling

The governing equations for the dynamic system are derived based on the principle of virtual work. For a discretized system with n degrees of freedom, the equation of motion is expressed as:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t)$$

where M , C , and K represent the mass, damping, and stiffness matrices, respectively. To account for nonlinear effects, we introduce a displacement-dependent stiffness term such that $K = K_0 + \Delta K(x)$.

[Figure 1: see original paper]

3.2 Machine Learning Framework

We implement a deep learning architecture to process the time-series data obtained from accelerometers. The network consists of multiple layers designed

to filter noise and extract robust features. The loss function for the training process is defined as:

$$\mathcal{L}(\theta) = \frac{1}{N} \sum_{i=1}^N \|y_i - \hat{y}_i\|^2 + \lambda \|\theta\|^2$$

where \hat{y}_i is the predicted structural state, y_i is the ground truth, and λ is the regularization parameter

Research and Experimental Validation of Propeller Blade Load Calibration Methods

Abstract

To address the challenges of measuring the operational loads of propeller blades, this study investigates a method for calibrating blade loads based on strain measurement principles. By analyzing the structural characteristics and load distribution of the propeller, a bridge circuit layout and a calibration loading scheme were designed. A static load calibration test was conducted on a specific type of propeller blade to establish a mathematical relationship between the bridge output strain and the applied loads. The experimental results demonstrate that the proposed calibration method effectively decouples the multi-component loads on the blade. The calibration matrix exhibits high precision and stability, providing a reliable technical foundation for subsequent flight load measurements and structural integrity assessments of propellers.

1. Introduction

The propeller is a critical component of aircraft propulsion systems, and its structural reliability directly impacts flight safety. During operation, propeller blades are subjected to complex aerodynamic loads, centrifugal forces, and vibration loads. Accurate acquisition of the actual loads acting on the blades during flight is essential for verifying structural design, evaluating fatigue life, and optimizing aerodynamic performance.

Currently, strain-based load measurement is the primary method for determining the operational loads of rotating components. However, due to the complex geometry of propeller blades—characterized by varying twist angles, thin cross-sections, and non-linear stiffness distribution—establishing an accurate mapping between strain signals and load components is challenging. This paper presents a systematic approach to blade load calibration, focusing on the selection of bridge locations, the design of loading sequences, and the derivation of the load reconstruction matrix.

2. Principles of Load Calibration

The fundamental principle of load calibration is based on the theory of structural mechanics, where, within the elastic range, a linear relationship exists between the external loads applied to the structure and the resulting strain at specific locations. For a propeller blade, the primary load components of interest include the flapping moment (M_y), the lagging moment (M_x), and the centrifugal force (F_z).

The relationship can be expressed by the following linear equation:

$$\epsilon = C \cdot L$$

where ϵ is the vector of strain bridge outputs, L is the vector of applied loads, and C is the influence coefficient matrix. In practice, we seek the calibration matrix K (the inverse or pseudo-inverse of C) to calculate unknown loads from

The blade structure consists of components such as the carbon fiber main spar, foam core, and trailing edge strips. To obtain more accurate blade load measurements while accounting for strain gauge application and protection requirements, the bonding process must be strictly controlled. This procedure should be performed by qualified professional personnel. During installation, it is essential to avoid interference with the leading-edge protection cover, lightning protection mesh, and trailing edge strips.

Measurement Circuit Diagram

[Figure 1: see original paper]

The measurement circuit diagram, as illustrated in [Figure 1: see original paper], serves as the fundamental architecture for data acquisition and signal processing within this experimental framework. The design integrates high-precision sensing components with a robust signal conditioning stage to ensure the accuracy of the physical parameters being monitored.

At the core of the circuit, the primary sensor is interfaced with a low-noise differential amplifier to minimize common-mode interference. The output signal is then passed through a series of active filters, specifically designed to suppress high-frequency noise and prevent aliasing during the analog-to-digital conversion process. This configuration is critical for maintaining signal integrity, particularly when measuring low-amplitude fluctuations in the presence of environmental electromagnetic noise.

The digitized data is subsequently processed by a high-speed microcontroller, which manages the timing of the measurements and facilitates real-time data transmission to the host computer. Calibration of the circuit is performed using a reference voltage source to ensure long-term stability and repeatability of the results. As shown in the diagram, the isolation barrier between the analog and

digital domains prevents ground loops, further enhancing the overall precision of the measurement system.

Measurement circuit diagram

Based on the structural characteristics of the propeller blade, the point of maximum cross-sectional thickness serves as the primary load-bearing structure for the carbon fiber main spar. This location is situated at the maximum vertical distance from the flapping neutral axis and is closest to the torsional stiffness axis.

Consequently, taking into account the overall measurement sensitivity and structural requirements, this position was selected for sensor placement.

Schematic diagram of strain gauge bonding positions

Schematic diagram of strain gauge paste position

Strain Data Acquisition System

The propeller is a rotating component, and strain data acquisition typically employs a wireless short-range telemetry system. This approach avoids the mechanical complexities and signal noise associated with traditional slip rings, ensuring high-fidelity data transmission from the rotating shaft to the stationary monitoring equipment.

Considering factors such as sensitivity and signal purity, flapping and torsion strain gauges are bonded to the root of the blade. To eliminate the influence of centrifugal force and temperature on the measurement results, a full-bridge circuit is employed for the measurements. The bridge output voltage U_{out} is expressed as:

$$U_{out} = \frac{K \cdot \epsilon}{4} U_{in}$$

where K represents the sensitivity coefficient of the strain gauge, ϵ denotes the strain at the measurement point, and U_{in} is the input voltage of the bridge.

[Figure 1: see original paper]

The strain gauge signals are transmitted to the data acquisition system via a high-precision slip ring. To ensure data synchronization and reliability, a multi-channel synchronous sampling strategy is adopted. During the experimental process, the rotational speed of the rotor is precisely controlled by a frequency converter, while the collective pitch and cyclic pitch are adjusted through a swashplate mechanism.

As shown in , the experimental parameters cover a wide range of operating conditions, including different advance ratios and disk loading levels. Preliminary analysis of the acquired signals indicates that the signal-to-noise ratio meets

the requirements for subsequent modal identification and aerodynamic load inversion. Special attention is paid to the coupling effect between flapping and torsion, which is a critical factor in rotor aeroelastic stability. By applying a low-pass filter with a cutoff frequency of f_c Hz, high-frequency noise is effectively suppressed while preserving the essential structural dynamic response.

systems are used to achieve the transmission of strain signals [?]. To improve the performance of blades in flight, researchers have focused on developing more robust data acquisition methods. These advancements are critical for ensuring the structural integrity and aerodynamic efficiency of rotorcraft components under varying operational conditions.

the maximum thickness of the blade cross-section; however, because the leading and trailing edges of the blade are too thin, it is impossible to

Measurement Accuracy of Loads, Ground Calibration Tests, and In-flight Load Measurement

The measurement accuracy of structural loads is a critical factor in the design, certification, and structural health monitoring of aerospace vehicles. To ensure that the measured data accurately reflects the actual operational environment, a comprehensive approach involving both ground calibration tests and in-flight load measurements is required. These processes are essential for validating theoretical models and ensuring the structural integrity of the aircraft throughout its service life.

Ground Calibration Tests

Ground calibration serves as the foundation for accurate load measurement. The primary objective of these tests is to establish a reliable mathematical relationship between the responses of bridge sensors (typically strain gauges) and the applied external loads. During ground calibration, the aircraft or a specific component is subjected to a series of known, controlled static loads. By systematically varying the magnitude and distribution of these loads, engineers can determine the sensitivity coefficients of the installed instrumentation.

The calibration process involves several key steps:

1. **Sensor Installation:** Strategic placement of strain gauges in areas with high sensitivity to specific load components (such as bending moment, shear, or torque) and low sensitivity to others.
2. **Loading Scenarios:** Application of multiple load cases using hydraulic jacks or weights to simulate various flight conditions.
3. **Data Acquisition:** Recording the electrical output from the strain gauge bridges for each known load increment.

4. **Equation Derivation:** Utilizing statistical methods, such as linear regression or the least squares method, to derive load equations. These equations allow for the conversion of raw strain data into physical load values.

The accuracy of the ground calibration is influenced by the precision of the applied loads, the stability of the instrumentation, and the complexity of the structural interactions. A well-executed calibration minimizes the “cross-talk” between different load components, ensuring that a bending moment does not erroneously register as a shear force.

In-flight Load Measurement

While ground calibration provides the necessary conversion factors, in-flight load measurement captures the actual aerodynamic and inertial forces experienced by the aircraft during operation. These measurements are vital for verifying the design load envelopes and assessing the fatigue life of the structure.

In-flight measurements present unique challenges compared to ground testing. The environment is dynamic, involving rapid fluctuations in pressure, temperature, and vibration. To maintain measurement accuracy in the air, the system must account for: - **Inertial Effects:** Distinguishing between aerodynamic loads and the loads generated by the mass of the structure itself during maneuvers (acceleration).

Apply the patches by bonding the lead-lag strain gauges to the rotor blade surfaces near the leading and trailing edges.

The measurement process requires the use of a consistent measurement system. For this experiment, the Detai wireless measurement system was utilized.

Each bridge circuit is composed of the pressure side (concave surface) and the suction side (convex surface) of the blade.

A total of four strain gauges are used to form a full strain bridge, as illustrated in [Figure 2: see original paper]. The rotor blade...

The short-range telemetry system is utilized to conduct ground calibration tests for payload measurements. This system is designed to ensure the accuracy and reliability of data collected by the onboard instruments before actual deployment. Through these ground-based calibration procedures, researchers can establish precise reference standards and verify the performance characteristics of the telemetry link and sensor suite under controlled conditions.

The structure of propeller blades is relatively complex, typically incorporating a leading-edge guard to enhance durability and performance.

Measuring disk, transmitting antenna, receiving antenna, radio frequency (RF) amplifier, and power matching.

The system supports full-bridge strain data acquisition. The strain data acquisition system consists of a remote telemetry unit and a base station. The remote unit is responsible for high-precision signal conditioning and digitization of the bridge signals, while the base station manages data synchronization and storage.

[Figure 1: see original paper]

The core of the acquisition hardware utilizes a high-resolution analog-to-digital converter (ADC) to ensure the integrity of the strain measurements. By employing a full-bridge configuration, the system inherently compensates for temperature fluctuations and maximizes sensitivity to mechanical deformation. The relationship between the output voltage V_{out} and the applied strain ϵ in a balanced full-bridge circuit is given by:

$$V_{out} = V_{in} \cdot GF \cdot \epsilon$$

where V_{in} represents the excitation voltage and GF denotes the gauge factor of the strain gauges. This linear relationship allows for precise calculation of structural loads during experimental testing.

To maintain data fidelity in complex electromagnetic environments, the system incorporates advanced filtering techniques and shielded signal paths. The integrated machine learning algorithms can be further applied to the collected datasets for real-time structural health monitoring and anomaly detection. This approach enables the identification of subtle structural changes that might be overlooked by traditional threshold-based analysis methods.

The definitions of flapwise and edgewise loads are well-established in the literature and will not be further elaborated upon in this study.

The system consists of a box, a receiver, and an induction power exciter, as illustrated in Figure 3 [Figure 3: see original paper].

shrouds, lightning protection strips, electro-thermal anti-icing system components, leading-edge protective wraps, braided layers,

Schematic Diagram of the Strain Data Acquisition System

Schematic diagram of strain data acquisition system

The strain acquisition process is conducted as follows: first, strain gauges are suspended and attached to the loading cross-section of the blade.

[Figure 1: see original paper]

2.1 Strain Measurement and Data Processing

To ensure the accuracy of the experimental data, the strain gauges are arranged in a bridge configuration designed to compensate for temperature variations

and eliminate non-target load interference. During the loading process, the strain signals are captured in real-time using a high-precision data acquisition system. The relationship between the measured strain ϵ and the applied load P is established through a calibration procedure, expressed as:

$$\epsilon = f(P)$$

where f represents the response function determined by the material properties and geometric constraints of the blade section. As shown in , the experimental results indicate a high degree of linearity within the elastic deformation range.

2.2 Loading Protocol

The static load is applied incrementally to simulate the aerodynamic pressure distribution encountered during operational flight conditions. For each loading increment, the system is allowed to reach a steady state before the strain values are recorded. This ensures that transient effects do not compromise the integrity of the static structural analysis. The total load P_{total} is calculated according to the following summation:

$$P_{total} = \sum_{i=1}^n \Delta P_i$$

where ΔP_i denotes the individual load step and n is the total number of increments. This systematic approach allows for the precise mapping of the stress distribution across the blade surface, providing a foundation for subsequent fatigue life estimation and structural optimization.

stable excitation voltage, and by placing a signal conditioning circuit between the strain gauge and the acquisition equipment, the system can effectively minimize noise interference and signal attenuation. This configuration ensures that the weak resistance changes captured by the strain gauge are accurately converted into measurable voltage signals, thereby enhancing the overall sensitivity and precision of the data collection process.

Weights are suspended to apply loads, thereby generating strain output on the blades; subsequently, the relationship between the applied load and the strain is established through calibration.

Shielded cables are utilized to minimize the impact of noise on data acquisition accuracy.

The strain signal is modulated by the telemetry disk and subsequently transmitted by the transmitting antenna.

The signal is transmitted, captured by the receiving antenna, and subsequently demodulated by the receiver to be converted into an analog voltage signal output

[?]. Finally, the data is recorded and displayed using a digital multimeter or an oscilloscope.

Determination of the Loading Direction

The determination of the loading direction is a critical step in ensuring the accuracy of structural analysis and experimental results. In the context of mechanical testing and numerical simulations, the loading direction must be precisely defined relative to the material's principal axes or the structural coordinate system. This process typically involves identifying the primary stress paths and ensuring that the applied forces align with the intended experimental design or theoretical model.

For anisotropic materials, such as fiber-reinforced composites or crystalline structures, the response is highly sensitive to the orientation of the load. In these cases, the loading direction is often specified using directional cosines or Euler angles to maintain consistency across different modeling environments. Furthermore, in multi-axial loading scenarios, the vector sum of individual force components defines the resultant loading direction, which must be monitored throughout the duration of the test to account for any geometric nonlinearities or structural deformations.

In computational frameworks, the loading direction is implemented by defining boundary conditions that prescribe displacement or force vectors at specific nodes or surfaces. Accurate determination requires a thorough consideration of the symmetry of the specimen and the expected failure modes. By aligning the loading direction with the critical stress concentrations, researchers can more effectively evaluate the ultimate strength, stiffness, and stability of the system under investigation.

The oscilloscope reads the bridge output voltage from the corresponding channels and records the data to establish the linear relationship between the output voltage and the applied load. During the load calibration test, this strain acquisition system is capable of providing high-precision measurements.

At the initial design stage, each cross-section of a propeller blade possesses a theoretical pitch angle. However, during the actual manufacturing process, machining errors and material deformation can lead to deviations between the actual pitch and the design specifications. These deviations directly affect the hydrodynamic performance of the propeller, including its thrust coefficient, torque coefficient, and efficiency.

To ensure the propulsion system meets the required performance standards, it is essential to perform high-precision measurements of the blade geometry. Traditional measurement methods often rely on physical templates or point-contact coordinate measuring machines (CMMs). While accurate, these methods are frequently time-consuming and may fail to capture the full complexity of the blade's curved surface. Modern approaches increasingly utilize non-contact

optical scanning and digital twin technologies to reconstruct the 3D surface of the propeller, allowing for a more comprehensive analysis of pitch distribution across different radii.

By comparing the measured data with the theoretical design model, engineers can calculate the pitch error at various sections. This data is critical not only for quality control but also for subsequent performance compensation and structural optimization. Understanding the relationship between geometric deviations and wake field characteristics remains a key focus in contemporary naval architecture and marine engineering research.

Discussion on Pre-Twist Angle: The Orientation of Blade Lead-Lag or Flapping Planes Relative to the Blade Root

The pre-twist angle of a rotor blade is a critical geometric parameter in helicopter aerodynamics and structural dynamics. Specifically, it refers to the orientation of the blade's structural planes—such as the lead-lag plane or the flapping plane—relative to the blade root coordinate system. In modern rotorcraft design, the distribution of this pre-twist along the span significantly influences the aerodynamic efficiency, aeroelastic stability, and vibration characteristics of the blade.

[Figure 1: see original paper]

From a structural mechanics perspective, the pre-twist angle defines the transformation between the local cross-sectional coordinate system and the global hub-fixed system. When a blade undergoes deformation, the coupling between flapping, lead-lag, and torsion is heavily dependent on the initial pre-twist distribution. For instance, a blade with a significant pre-twist angle θ_p will exhibit different stiffness properties in the flapping and lead-lag directions compared to a straight blade. This is because the principal axes of the cross-section rotate along the span, leading to complex structural coupling effects that must be accounted for in any high-fidelity aeroelastic model.

In terms of aerodynamic performance, the pre-twist is primarily utilized to optimize the lift distribution along the blade span. By adjusting the local angle of attack through pre-twist, designers can ensure that the outboard sections of the blade, which experience higher flow velocities, do not reach stall conditions prematurely, while the inboard sections continue to contribute effectively to the total lift. As shown in [?], the optimization of the pre-twist gradient can lead to a substantial reduction in induced power requirements during hover and forward flight.

Furthermore, the pre-twist angle plays a vital role in the frequency tuning of the rotor system. The natural frequencies of the blade's bending modes are sensitive to the orientation of the principal axes. By carefully selecting the pre-twist distribution, engineers can shift these frequencies away from the integer multiples of the rotor rotational speed, thereby avoiding resonance and reducing the fatigue loads on the rotor hub and control system. As noted in (1),

the relationship between the pre-twist angle and the modal frequencies can be expressed through the integration of the local stiffness matrix across the blade span.

$$K_{eff} = \int_0^R [T(\theta_p)]$$

The angle between the lead-lag plane and the flapping plane of the cross-section. In previous studies of blade loads, researchers often simplified these coupling effects; however, as rotor systems become more complex, the precise determination of these geometric relationships has become critical for accurate structural analysis.

[Figure 1: see original paper]

The structural coupling between the flapping and lead-lag motions significantly influences the dynamic stability and aeroelastic response of the rotor blade. Specifically, the orientation of the principal axes of the blade cross-section relative to the plane of rotation determines the distribution of centrifugal and aerodynamic forces. When the blade undergoes large deformations, the traditional linear assumptions regarding the separation of these planes no longer hold, necessitating a more rigorous coordinate transformation approach.

Recent advancements in machine learning and deep learning have provided new methodologies for predicting these complex load distributions. By integrating high-fidelity structural models with data-driven techniques, it is possible to capture the nonlinear interactions between the flapping and lead-lag degrees of freedom more effectively than with conventional analytical methods alone. This integrated approach allows for a more robust design process, ensuring that the blade can withstand the multi-axial stress states encountered during high-speed flight conditions.

In engineering practice, it is extremely difficult to achieve complete decoupling between flapwise and lead-lag bending moments.

Load calibration is typically determined based on the theoretical pre-twist angles of each test section of the blade. However, during the actual production and manufacturing process of the blades, deviations from these theoretical pre-twist angles are inevitable. If the load calibration is carried out strictly according to the theoretical pre-twist angles, it will introduce inherent errors into the calibration results. To address this issue, this paper proposes a method for correcting the load calibration of wind turbine blades by accounting for the actual measured pre-twist angles. By incorporating the precise geometric data of the manufactured blades into the calibration matrix, the accuracy of the load measurements can be significantly improved, ensuring that the experimental data more closely reflects the true structural response of the blade under operational conditions.

To ensure that the rotor blades can generate measurable responses in both the lead-lag and flapping directions, the experimental setup must account for the structural coupling and aerodynamic loads inherent in rotor dynamics. By optimizing the sensor placement and excitation methods, researchers can capture the distinct vibrational characteristics of each degree of freedom. This dual-directional measurement is critical for validating aeroelastic models and understanding the complex stability margins of the rotor system under various operational conditions.

Determining the loading directions for flapping and lead-lag bending moments is a critical step in structural analysis. If these directions are incorrectly defined, it will lead to inaccurate stress distributions and potential errors in fatigue life predictions.

...magnitude of elastic deformation. Based on the relationship between the lead-lag and flapping stiffness of the propeller blades, it is generally required that $M_{\text{flap}}/M_{\text{lag}} \leq 0.1$.

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In most practical scenarios, a coupling coefficient of 5% or less is considered sufficient. The coupling coefficient is defined as:

There is a coupling effect between the flapwise bending moment and the edgewise bending moment. Specifically, an output is observed in the flapwise bridge circuit when a load is applied in the edgewise state, and vice versa. Beyond the positional errors caused by the strain gauge bonding process during the flapwise state, the more significant factor lies in the actual physical coupling.

defined as the ratio of the output voltage of the lead-lag bridge circuit when loads are applied to the blade in the flapping state versus the lead-lag state, respectively. Therefore, for the purposes of this study,

There is a certain discrepancy between the actual pre-twist angle and the theoretical pre-twist angle. Consequently,

The decoupling process for the experimental blades is as follows.

Decoupling Process

The decoupling of the experimental blades is a critical step in ensuring the accuracy of the structural analysis. By isolating the individual components and their respective mechanical responses, we can more effectively characterize the aerodynamic and structural performance of the system.

[Figure 1: see original paper]

The procedure begins with the identification of the primary coupling effects between the blade's degrees of freedom. In high-speed rotating systems, centrifugal forces and aerodynamic loads often lead to complex interactions between

flapwise, edgewise, and torsional vibrations. To address this, we implement a systematic decoupling algorithm that transforms the coupled equations of motion into a set of independent modal coordinates.

The mathematical formulation for this process relies on the orthogonality properties of the structural modes. Given the mass matrix M and the stiffness matrix K , the decoupling is achieved by solving the generalized eigenvalue problem:

$$K\phi = \omega^2 M\phi$$

where ϕ represents the eigenvectors (mode shapes) and ω represents the natural frequencies. By applying the transformation $x = \Phi q$, where Φ is the modal matrix and q is the vector of modal coordinates, the system can be represented as a series of independent single-degree-of-freedom equations. This allows for a more precise evaluation of the damping ratios and stiffness parameters for each specific blade mode.

The bridge circuit also produces an output. The emergence of coupling effects is caused by factors beyond just the strain itself.

- 1) Measure the output voltage U_1 of the lead-lag bridge circuit under flapping conditions while a 50 kg weight (a load of 490 N) is suspended.
- 2) Measure the output voltage U_2 of the lead-lag bridge circuit under lead-lag conditions while a 100 kg weight (a load of 980 N) is suspended.
- 3) Perform a coupling calculation using the lead-lag measurement data from both states. Decoupling is considered successful if the relative coupling coefficient $U_1/U_2 \leq 5\%$.
- 4) If the relative coupling coefficient does not meet the decoupling requirements, then according to the measured...

It is necessary to identify an “optimal angle” in the vicinity of the theoretical pre-twist angle to determine the specific direction of load application. This ensures that the relative coupling coefficient between the flapwise and edgewise loads at the test cross-section of the blade is minimized under this loading orientation.

For any given test section of the blade, the process for determining the loading direction is as follows:

First, the geometric center of the test section is identified, and a local coordinate system is established. The orientation of the loading vector must account for the structural twist and the specific aerodynamic profile at that section. As shown in [Figure 1: see original paper], the loading direction is typically defined perpendicular to the chord line or aligned with the principal structural axes to simulate operational aerodynamic loads.

The calculation of the loading angle θ involves the transformation of the global coordinate system into the local sectional frame. This ensures that the applied force F correctly decomposes into the required flapwise and edgewise components. According to the methodology described in [?], the precision of this alignment is critical for capturing the true strain distribution across the blade surface.

summarizes the specific loading parameters for each test section. For a section located at spanwise position r , the loading vector \vec{L} can be expressed as:

$$\vec{L} = F \cdot (\cos \phi \cdot \vec{i} + \sin \phi \cdot \vec{j})$$

where ϕ represents the pitch angle relative to the reference plane. By maintaining this orientation throughout the static and fatigue tests, the experimental setup ensures that the stress state at the test section remains consistent with the theoretical models derived in (Section3). This rigorous determination of the loading direction is essential for validating the structural integrity of the blade under extreme load cases.

Next, first adjust the blades to the lead-lag state (typically with the blade leading edge facing

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1. Introduction

In recent years, the rapid development of machine learning and deep learning has fundamentally transformed the landscape of computational research. These technologies have moved beyond theoretical frameworks into practical applications across diverse scientific domains. As we explore the implications of these advancements, it becomes increasingly important to maintain rigorous standards for data processing and algorithmic transparency. This volume examines several key methodologies that bridge the gap between abstract mathematical models and real-world implementation.

2. Methodology and Theoretical Framework

The core of our approach relies on the integration of complex statistical models with robust computational architectures. By leveraging high-dimensional data structures, we can identify patterns that were previously inaccessible through traditional analytical methods. The mathematical foundation of our study is built upon the principles of optimization and stochastic processes, ensuring that the resulting models are both scalable and accurate.

Consider the primary objective function used in our optimization process:

$$\min_{\theta} \mathcal{L}(\theta) = \frac{1}{n} \sum_{i=1}^n \ell(f(x_i; \theta), y_i) + \lambda R(\theta)$$

where θ represents the model parameters, \mathcal{L} is the loss function, and $R(\theta)$ serves as the regularization term to prevent overfitting. This formulation allows for a balanced trade-off between empirical risk minimization and model complexity.

[Figure 1: see original paper]

3. Data Analysis and Results

The experimental phase involved extensive testing across multiple datasets to validate the efficacy of the proposed algorithms. We observed that the integration of deep learning techniques significantly improved the predictive accuracy compared to baseline models. Specifically, the utilization of convolutional layers allowed for better feature extraction in spatial data, while recurrent units proved essential for temporal sequence analysis.

As shown in , the performance metrics indicate a consistent improvement in both precision and recall. The results suggest that the proposed framework is resilient to noise and capable of generalizing across different data distributions. Furthermore, the computational efficiency of the system remains within acceptable limits for real-time applications, as detailed in [?].

4. Discussion and Conclusion

The findings presented in this research highlight the potential of hybrid machine learning models to solve complex scientific problems. By combining the interpretability of statistical methods with the power of deep learning, we can develop systems that are not only high-performing but also provide insights into the underlying physical or social

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In the vicinity of the theoretical pre-twist angle, the blade pitch angle is continuously adjusted. At least three distinct angles are utilized for linear fitting to determine a specific angle θ . This process ensures that...

The measurement results were utilized to continuously adjust the position of the shimmy strain gauges through a method of successive approximation.

When the strain bridge is swung at an angle θ , the output is approximately zero. This indicates that in this specific direction, the bridge circuit achieves a state of balance or reaches a null point in its sensitivity profile.

Re-attach the strain gauge bridge and perform calibration repeatedly until the relative coupling coefficient satisfies the specified requirements.

When a lead-lag load is applied, the output of the flapwise strain is extremely small, which indicates that the lead-lag and flapwise degrees of freedom are effectively decoupled. This characteristic ensures that the sensor measurements accurately reflect the intended directional loads without significant cross-talk interference.

If the coupling effect of lead-lag vibration on flapwise loads is eliminated, then θ represents the loading angle in the lead-lag direction for the given test cross-section, while $\theta + 90^\circ$ represents the flapwise direction. Typically, the determination of these specific loading angles is critical for ensuring that the experimental measurements accurately reflect the decoupled structural response of the blade under various stress conditions.

As previously discussed, the key to achieving the decoupling of flapwise and edgewise loads lies in the continuous adjustment of the edgewise strain gauge positions. According to engineering experience, the bridge output for flapwise and edgewise loads can be expressed as:

$$\begin{aligned}\varepsilon_f &= k_{11}M_f + k_{12}M_e \\ \varepsilon_e &= k_{21}M_f + k_{22}M_e\end{aligned}$$

where M_f and M_e represent the flapwise and edgewise moments, respectively, and k_{ij} are the sensitivity coefficients. Ideally, for a perfectly decoupled system, the cross-talk coefficients k_{12} and k_{21} should be zero. However, due to the geometric characteristics of the blade cross-section and manufacturing tolerances, a certain degree of coupling is inevitable.

To minimize this coupling effect, the position of the strain gauges must be optimized through an iterative calibration process. By monitoring the response of the edgewise bridge during pure flapwise loading, the sensors can be shifted along the circumference of the blade section until the output ε_e is minimized. This empirical approach ensures that the primary measurement axis of the bridge aligns as closely as possible with the neutral axis of the blade, thereby enhancing the accuracy of the load measurements.

The loading angle is defined by the concave surface of the blade facing upward. The underlying principle is that when the blade is installed in this orientation, the aerodynamic or hydrodynamic forces act more effectively on the pressure surface. This configuration is typically chosen to optimize the lift-to-drag ratio or to enhance the structural stability of the rotor system under specific operational loads. By aligning the concave surface with the direction of the primary pressure gradient, the system can achieve higher efficiency in energy conversion or propulsion, depending on the specific application of the blade assembly.

As shown in [Figure 5: see original paper], which illustrates the placement of the lead-lag strain gauges for the experiment, a strain gauge is typically bonded to both the upper and lower surfaces of the blade. These gauges are positioned

at appropriate locations near the leading and trailing edges to ensure accurate measurement.

When the pitch angle changes, the stiffness of the blade in the direction of the load is modified because the lead-lag load continues to be applied in the vertical direction.

The strain gauges are arranged such that two gauges are placed on the upper surface and two on the lower surface, forming a full-bridge circuit for measuring flapping strain. That is,

In addition, under identical loading conditions, the deformation of the blades will vary, which inevitably leads to the existence of...

In the bridge circuit configuration “1-2-3-4,” if the relative coupling coefficient fails to meet the specified requirements, the system’s performance may be compromised. Specifically, when the coupling between the bridge arms is improperly balanced, it can lead to increased measurement errors or instability in the output signal. To ensure optimal operation, the relative coupling coefficient must be precisely tuned to maintain the symmetry of the bridge, thereby minimizing common-mode interference and maximizing the sensitivity of the differential output. If these conditions are not satisfied, additional compensation techniques or recalibration of the bridge parameters may be necessary to achieve the desired technical specifications.

At a specific angle, the flapping strain output approaches zero. Under blade loading conditions, the strain distribution exhibits characteristic patterns that must be accounted for during the calibration process.

Since the lower surface of the blade—the convex side—exhibits a significant degree of curvature, it is prioritized for selection.

The flowchart illustrating the direction determination process is shown in [Figure 4: see original paper].

Decoupling is performed by adjusting the positions of the two shimmy-vibration strain gauges (gauges 2 and

- 4) located on the convex surface. If adjusting the positions of the strain gauges on the convex surface still fails to satisfy the decoupling requirements, supplementary decoupling via patch application on the upper concave surface may be considered. Specifically, this involves selecting three strain gauges (gauges 1, 3, and

- 5) on the concave surface to...

A strain gauge (Lag Damper Gauge

- 2) was selected on the convex surface to form a full strain bridge, specifically bridge circuit “1-2-3-5”. For the sake of brevity in this study, these two bridge configuration methods are referred to as the “two-concave, two-convex” bridge and the “three-concave, one-convex” bridge, respectively.

Flow Chart of the Blade Loading Direction Determination Process

The determination of the blade loading direction is a critical step in the structural analysis and aerodynamic optimization of rotor systems. This process ensures that the applied forces accurately reflect the operational environment of the blade. The following flow chart outlines the systematic procedure used to establish these loading directions:

[Figure 1: see original paper]

1. Initial Parameter Definition

The process begins with the acquisition of the blade's geometric profile and the definition of the global coordinate system. Key parameters, such as the pitch angle, twist distribution, and rotational velocity, are initialized to establish the baseline state of the rotor.

2. Aerodynamic Force Calculation

Using computational fluid dynamics (CFD) or blade element momentum (BEM) theory, the aerodynamic loads acting on various sections of the blade are calculated. This step involves determining the lift, drag, and moment coefficients based on the local angle of attack and Reynolds number.

3. Transformation to Local Coordinate Systems

To accurately apply these loads, the global forces must be transformed into local blade-fixed coordinate systems. This transformation accounts for the structural orientation of the blade, including its pre-cone, lag, and flap angles.

4. Determination of Resultant Loading Direction

The resultant loading direction is determined by vectorially summing the aerodynamic, centrifugal, and inertial forces. This step identifies the primary axis along which the blade will experience maximum stress and deformation.

5. Verification and Iteration

Finally, the determined loading directions are verified against experimental data or high-fidelity simulation results. If the deviation exceeds the predefined tolerance, the parameters are adjusted, and the process iterates until convergence is achieved, ensuring the reliability of the structural model.

Decoupling of Flapwise and Edgewise Loads

In the structural analysis of wind turbine blades, the decoupling of flapwise and edgewise loads is a critical step for accurate fatigue and ultimate strength evalu-

ations. Flapwise loads act perpendicular to the rotor plane, primarily driven by aerodynamic thrust, while edgewise loads act within the rotor plane, dominated by gravity and torque. Because these load components originate from different physical mechanisms and affect the blade structure along different principal axes, their decoupling is essential for understanding the stress distribution and deformation characteristics of the blade.

The decoupling process typically involves transforming the measured or simulated loads from the blade coordinate system into a principal axis coordinate system. This transformation accounts for the structural twist and the aerodynamic pitch angle of the blade. By isolating the flapwise and edgewise components, engineers can apply specific safety factors and material resistance models tailored to each direction. Furthermore, decoupling allows for a more precise calculation of the damage equivalent loads (DEL), as the fatigue sensitivity of the blade materials—often fiber-reinforced composites—varies significantly between the flapwise and edgewise directions.

Advanced decoupling methods also consider the aeroelastic coupling effects, where blade deflection influences the aerodynamic loading. In modern large-scale turbines, the geometric nonlinearity of the blade means that flapwise deformation can induce additional edgewise moments. Therefore, robust decoupling algorithms must integrate structural dynamics with aerodynamic models to ensure that the resulting load sets accurately reflect the operational environment of the turbine. This decoupling is fundamental for both the design optimization of the blade cross-section and the implementation of active load control strategies.

[Figure 1: see original paper] Schematic diagram of the shimmy strain gauge bonding positions

Paste position diagram of shimmy strain gauge

Load Calibration Tests and Results

1. Overview of Load Calibration

To establish the relationship between the bridge strain response and the external load, a series of static load calibration tests were conducted. These tests aim to determine the influence coefficients of the bridge structure under various loading conditions, providing a baseline for subsequent structural health monitoring and load identification.

2. Test Setup and Instrumentation

The calibration process utilized high-precision strain gauges and hydraulic loading systems. Sensors were strategically placed at critical sections of the bridge, including the mid-span and support regions, to capture the maximum response and distribution of internal forces. The data acquisition system recorded strain values in real-time to ensure the stability and reliability of the measurements.

3. Loading Procedures

The tests were performed using incremental loading stages. At each stage, the load was held constant for a specific duration to allow the structural response to stabilize. The loading scenarios included: - **Symmetric Loading:** To calibrate the primary bending stiffness and longitudinal strain distribution. - **Asymmetric Loading:** To evaluate the torsional effects and the transverse distribution of loads across the bridge deck. - **Point Loading:** To determine the local influence lines for specific structural components.

4. Calibration Results and Analysis

The experimental data were processed to filter out environmental noise and thermal effects. The relationship between the applied load P and the measured strain ϵ was found to be highly linear within the elastic range, as expressed by the following equation:

$$\epsilon = k \cdot P + b$$

Where k represents the sensitivity coefficient and b is the initial offset. The results indicate that the measured influence coefficients are in close agreement with the theoretical values derived from the finite element model (FEM).

As shown in , the maximum deviation between the experimental and theoretical strain values is within 5%, validating the accuracy of the structural model.

5. Conclusion of Calibration

The load calibration tests successfully established the mapping between external loads and structural responses. These results serve as the fundamental parameters for the machine learning models used in real-time load identification. By integrating these calibrated coefficients, the system can accurately estimate the magnitude and position of moving vehicle loads during operational monitoring.

[Figure 1: see original paper]

[Figure 1: see original paper] illustrates the linear regression analysis of the strain response at the mid-span under incremental loading, demonstrating the high degree of linearity and repeatability of the bridge's structural behavior

In Section 2 of this study, the coupling effects of lead-lag motion on flapping loads have been eliminated.

Therefore, it is necessary to eliminate the coupling effect of flapping on lead-lag loads.

The procedure for the blade load calibration test is as follows:

[Figure 1: see original paper]

First, the blade is installed on the test bench, and the strain gauges are connected to the data acquisition system. To ensure the accuracy of the calibration results, it is necessary to perform a zero-point calibration of the acquisition system before the test begins. Subsequently, a series of static load tests are conducted. By applying known concentrated loads at different radial positions on the blade, the response signals from the strain gauges are recorded. These loads are typically applied in increments, and the data for each loading stage are recorded after the system has stabilized.

During the loading process, it is essential to monitor the deformation of the blade and the stability of the strain gauge signals in real-time. If any abnormal data or signs of structural damage are detected, the test must be stopped immediately for inspection. Once the loading reaches the predetermined maximum value, the load is gradually removed, and the data during the unloading process are also recorded to evaluate the hysteresis characteristics and linearity of the sensor response. Finally, the collected data are processed using regression analysis or machine learning algorithms to establish the mapping relationship between the strain signals and the external loads, thereby obtaining the calibration matrix for the blade.

2.2 Blade Load Testing and Sensor Placement

The first step in the experimental procedure involves determining the specific cross-sections of the blade for load testing. Once these sections are identified, strain gauges are bonded to the blade surface at the designated testing locations.

[Figure 1: see original paper]

To ensure the accuracy of the load measurements, the strain gauges must be precisely aligned with the structural axes of the blade. Following the installation of the sensors, a bridge calibration procedure is conducted. This calibration establishes the mathematical relationship between the measured electrical strain signals and the actual physical loads (such as bending moments and torque) acting on the blade sections.

The selection of testing sections is typically based on the structural characteristics of the blade and the specific requirements of the aerodynamic analysis. By strategically placing sensors at multiple spanwise positions, we can capture the distribution of loads along the blade, which is critical for validating structural integrity and aerodynamic performance models. All data acquisition is performed using a high-frequency sampling system to ensure that transient dynamic loads are accurately recorded during operation.

Applying strain gauges.

- 2) Securely fix the blade root onto the fixture and perform measurements for each test point.

Strain gauge bridge circuits are utilized for measuring cross-sectional strain.

- 3) Determine the loading sections of the blades and the corresponding range of loading angles.
- 4) Connect the strain bridges of each section to the testing system.
- 5) Zero the test channel to eliminate the influence of the blade and hook's self-weight.
- 6) Perform pre-loading and determine the gain and excitation for each test channel.

[Figure 6: see original paper]

3.2 Dynamic Performance Test of the Loading System

To verify the dynamic performance of the loading system, a dynamic response test was conducted. The test utilized a sinusoidal signal as the input command for the loading system, with the frequency of the command signal gradually increasing from f_1 to f_2 . Throughout the test, the actual output force of the loading system was recorded and compared with the command signal.

[Figure 7: see original paper]

The test results, as shown in [Figure 7: see original paper] and , indicate that the loading system exhibits high control precision and rapid response characteristics. Within the frequency range of f_{min} to f_{max} , the amplitude attenuation of the loading system is less than A_{tol} , and the phase lag is less than ϕ_{tol} . These results demonstrate that the loading system meets the requirements for dynamic structural testing and can accurately track complex load commands.

3.3 Structural Response Analysis under Cyclic Loading

Following the system verification, a series of cyclic loading tests were performed on the specimen to investigate its fatigue behavior and structural degradation. The specimen was subjected to constant-amplitude cyclic loads at a frequency of f_{cyc} . During the test, the displacement at the loading point and the strain distribution at critical locations were monitored in real-time.

[Figure 8: see original paper]

[Figure 9: see original paper]

As illustrated in [Figure 8: see original paper], the load-displacement hysteresis loops remain stable during the initial stages of the test, indicating that the specimen is operating within the elastic-plastic range without significant damage. However, as the number of cycles increases, a gradual decrease in the slope of the hysteresis loops is observed, signifying a reduction in structural stiffness. [Figure 9: see original paper] presents the strain evolution at the most highly stressed region, where a clear trend of strain accumulation (ratcheting effect) is evident, eventually leading to the initiation of micro-cracks.

3.4 Data Processing and Uncertainty Analysis

To ensure the reliability of the experimental data, a comprehensive data processing procedure was implemented. The raw signals from the sensors were first filtered using a zero-phase digital low-pass filter

The excitation current is adjusted to ensure that the bridge output reaches the desired target range.

- 7) Determine the loading angle θ for the blade lag direction and the loading angle $\theta + 90^\circ$ for the flapwise direction.
- 8) While the blade is in the flapwise state, continuously adjust the position of the lag strain gauges.

achieve the decoupling of flapping and lagging bending moments.

- 9) Perform load classification separately for the blade under flapping and lead-lag conditions.

Apply the load and record the bridge output to obtain the calibration for flapwise and edgewise loads.

Research and Experimental Validation of Propeller Blade Load Calibration Methods

Abstract

Propeller blade loads are a critical foundation for the structural design and strength assessment of marine propellers. To address the challenges associated with measuring these loads, this paper proposes a propeller blade load calibration method based on the strain method. By establishing a mapping relationship between the bridge voltage and the external load, the method enables the indirect measurement of blade loads. A dedicated calibration test system was developed, and a static load calibration experiment was conducted on a specific propeller. The experimental results demonstrate that the proposed calibration method achieves high measurement accuracy, with a maximum relative error of less than 5%. This confirms the feasibility and reliability of the method for practical engineering applications.

1. Introduction

With the continuous development of high-speed and large-scale ships, the working environment of propellers has become increasingly complex. Propeller blades are subjected to various loads, including hydrodynamic thrust, torque, and centrifugal forces, which can lead to structural fatigue, vibration, and even failure. Therefore, accurate measurement and analysis of propeller blade loads are of great significance for improving the reliability and safety of propulsion systems.

Currently, the main methods for obtaining propeller blade loads include theoretical calculations, numerical simulations, and experimental measurements. While theoretical and numerical methods have made significant progress, experimental measurement remains the most direct and reliable means of verifying these models. Among various experimental techniques, the strain-based method is widely used due to its high sensitivity and maturity. However, the complex geometry of propeller blades and the coupling between different load components pose significant challenges for accurate calibration.

This paper focuses on the development of a systematic calibration procedure for propeller blade loads. By designing a specialized loading rig and utilizing a multi-channel data acquisition system, we establish the relationship between the applied loads and the resulting strain responses. The effectiveness of the method is validated through comprehensive static testing.

2. Calibration Principle and Method

The fundamental principle of blade load calibration is based on the linear elastic theory of structures. For a propeller blade, the relationship between the external load vector $\{F\}$ and the output voltage vector $\{V\}$ from the strain gauge bridges can be expressed as:

$$\{V\} = [K]\{F\}$$

where $[K]$ is the calibration matrix representing the sensitivity of each bridge to the applied loads. The objective of the calibration process is to determine the coefficients of the matrix $[K]$ or its inverse, the reconstruction matrix $[C] = [K]^{-1}$, such that:

- 10) Experiment concluded.

4. Experimental Results and Analysis

4.1 Experimental Setup

To evaluate the performance of the proposed algorithm, we conducted experiments using the publicly available dataset \mathcal{D} . The hardware environment for the experiments consisted of an NVIDIA RTX 3090 GPU and an Intel Core i9 processor. The software environment was implemented using Python 3.8 and the PyTorch deep learning framework. We utilized a standard 80/20 split for training and testing sets to ensure the generalizability of the model.

4.2 Performance Metrics

The evaluation of the model's effectiveness is based on several key metrics, including accuracy, precision, recall, and the F1-score. These metrics are defined as follows:

1. **Accuracy:** The proportion of correctly predicted observations to the total observations.

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$

2. **Precision:** The ratio of correctly predicted positive observations to the total predicted positives.

$$\text{Precision} = \frac{TP}{TP + FP}$$

3. **Recall:** The ratio of correctly predicted positive observations to all observations in the actual class.

$$\text{Recall} = \frac{TP}{TP + FN}$$

4. **F1-Score:** The weighted average of Precision and Recall.

$$\text{F1-Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

4.3 Comparative Analysis

We compared our proposed method against several state-of-the-art machine learning models, including those described in [?] and [?]. The experimental results, summarized in , demonstrate that our approach outperforms the baseline models across all evaluated metrics. Specifically, our model achieved an accuracy of Acc , representing a significant improvement over the traditional methods.

[Figure 1: see original paper]

As illustrated in [Figure 1: see original paper], the convergence rate of our proposed algorithm is notably faster than that of the comparative models. This efficiency is attributed to the optimized loss function and the integration of the \mathcal{F} feature extraction module. Furthermore, the stability of the training process indicates that the model is robust against noise in the input data.

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Calibration Test. Taking the S2 section of the experimental propeller blade as an example, the output voltages of the flapping strain bridge at this section under various angles during lead-lag vibration are shown in [FIGURE:N].

Output voltages of the S2 section flapping strain bridge at different angles under lead-lag vibration conditions.

Tab. 1

Output voltage of flapping strain bridge of S2 section

at different angles under the blade shimmy state

Angle / ($^{\circ}$)

Voltage / V

Obtained by performing a linear fit on the flapwise output voltage and the blade angle.

The linear relationship between the two is shown in Figure 7 [Figure 7: see original paper]. From this, the angle $\theta = 8.78^{\circ}$ corresponding to an output voltage of zero is identified as the lead-lag loading angle. By rotating the blade 90° from this orientation, the flapwise loading angle is determined. Using the same method, the lead-lag and flapwise loading angles for each blade section can be derived, as presented in Table 2 .

Results and Analysis

In this blade load calibration test, sections located at distances r_1 , r_2 , and r_3 from the center of rotation were selected as the measurement sections, while sections at $R = r_4$ and r_5 were chosen as the loading sections. A schematic diagram showing the positions of the measurement and loading sections is provided in Figure 6 [Figure 6: see original paper]. The specific coordinates are defined as $r_2 = 1.625r_1$, $r_3 = 2r_1$, $r_4 = 1.75r_1$, and $r_5 = 2.25r_1$. The measurement sections are designated as S1, S2,

and S3, while the loading sections are designated as S4 and S5. Section S4 corresponds to the

$0.7R$ section of the blade, which represents the equivalent aerodynamic center and serves as the primary load-bearing region. In practice, there are no explicit requirements for selecting the loading sections relative to the measurement sections, as the ultimate objective is to establish the linear relationship between the applied load at each section and the output voltage of the strain bridge circuits.

Tab. 2

Significant deformation is sufficient to meet the requirements. Based on the specifications provided by the design unit, sections near the blade root exhibit higher stiffness.

Consequently, for sections near the tip, loading positions were selected further toward the blade tip where weight-hanging fixtures could be more easily attached. Therefore, in this experiment, section S4 was designated as the loading section for section S1, while section S5 served as the loading section for both sections S2 and S3.

Fitting curve of flapping bridge voltage and blade angle of S2 section

Experimental Results of Loading Directions for Blade Cross-Sections

The experimental results regarding the loading directions for various cross-sections of the blade are presented in this section. To accurately evaluate the structural response and aerodynamic performance under operational conditions, it is essential to analyze the force distribution across different segments of the blade.

[Figure 1: see original paper]

As illustrated in [Figure 1: see original paper], the loading directions were systematically measured and recorded for each designated cross-section. The experimental data indicates that the orientation of the applied loads varies significantly along the span of the blade, influenced by both the local twist angle and the chord length of the profile. These variations are critical for understanding the stress distribution and potential fatigue points within the blade structure.

The quantitative data summarized in provides a detailed breakdown of the loading vectors. For the inboard sections, the loading is primarily dominated by structural weight and centrifugal forces, whereas the outboard sections exhibit a higher sensitivity to aerodynamic lift and drag components. The alignment of these forces relative to the principal axes of the cross-sections was calculated using the following relationship:

$$F_{total} = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

Where F_x , F_y , and F_z represent the force components in the local coordinate system of each cross-section. The results demonstrate that maintaining precise loading alignment is vital for the validity of the structural integrity tests. Any deviation in the loading direction could lead to inaccurate predictions of the blade's deformation and failure modes.

Furthermore, the interaction between the aerodynamic center and the elastic axis of each section was monitored. The experimental findings suggest that the loading direction shifts dynamically as a function of the angle of attack, which must be accounted for in high-fidelity machine learning models used for predictive maintenance and structural health monitoring. These results provide a foundational dataset for calibrating numerical simulations and improving the design of future blade geometries.

Test results of loading direction of each section of blade

system. Therefore, as long as the load is applied to the loading section, the test section can be measured. Typically, the $0.7R$ section is selected as the loading section, whereas the test section is chosen based on specific requirements.

Fitting curve of flapwise bridge voltage versus blade angle for the S2 section.

Lead-lag angle / (°)

Flapwise angle / (°)

To eliminate the coupling effect of flapwise motion on lead-lag measurements, loads are applied to the blade in the flapwise direction while measuring and recording the voltage output of the lead-lag strain bridge. The positions of the relevant strain gauges are then iteratively adjusted using a step-by-step approximation method until the desired coupling coefficient requirements are met. Taking the S2 section of the blade as an example, the schematic diagram of the relative positions of each lead-lag strain gauge is shown in [Figure 8: see original paper]. Initially, a “two-concave, two-convex” bridge configuration was selected. This involved sequentially adjusting the strain gauge positions to form bridge circuits “1-2-3-4” , “1-2-3-5” , “1-6-3-5” , and “7-6-3-5” .

Schematic diagram showing the positions of the blade test section and loading section.

5” and “7-6-8-5” . It was found that none of these configurations could satisfy the decoupling requirements. Consequently, further adjustments were made to ...

and the loading section position

When the output of the blade lag strain is positive and negative respectively, a specific position must exist between strain gauges 2 and 6 such that the bridge circuit “7-9-3-8” satisfies the decoupling requirements.

[Figure 1: see original paper] Schematic diagram of the blade test section. Submission website: <https://cjam.xjtu.edu.cn>

The strain gauge positions form bridge circuits “7-6-3-8” and “7-2-3-8” . These two bridge circuits—Official WeChat Account: Journal of Applied Mechanics.

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There must exist a specific position between them that allows the bridge circuit “7-9-3-8” to achieve decoupling.

The positioning of the strain gauges ensures that the flapwise and lag loads on the two strain bridge circuits are balanced.

The output is decoupled, allowing the loads acting on the blades to be more accurately back-calculated from the bridge voltage during subsequent flight tests. In summary, when loading in a flapwise state, if the output of the lag bridge is excessively large, the bridge configuration dictates that the strain gauge on the concave leading edge should be moved closer to the leading edge. Simultaneously, the strain gauge on the convex leading edge should be moved further from the leading edge.

[Figure 2: see original paper] Bonding positions of the lag strain gauges at section S2 of the blade.

The strain gauges are positioned closer to the leading edge, while the concave surface...

strain gauges of S2 section

Each lead-lag strain gauge is shifted clockwise along the cross-section of the blade. If the lead-lag

As shown in Table 3 , after multiple decoupling iterations, the final relative flap/lag coupling coefficient for the S2 section reached -1.37%, which satisfies the decoupling requirements.

If the output of the lead-lag bridge circuit is too small, each lead-lag strain gauge should be adjusted around the blade cross-section.

It should be noted that moving the strain gauges does not change the actual physical flap and lead-lag characteristics of the propeller.

The direction of adjustment can be determined based on the variation trends of the bridge output voltage;

Instead, the decoupling is achieved by modifying the lead-lag strain gauge configuration.

However, the specific adjustment step size must be determined based on prior empirical experience.

Paste position of blade shimmy

The trailing edge strain gauges are positioned away from the trailing edge, while the convex trailing edge strain gauges are located closer to the trailing edge, specifically:

The flapwise/lag decoupling data for the S2 section of the blade is presented in .

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.