Research Progress on Structural Health State Monitoring and Evaluation of Aero-Engines (Postprint)

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Abstract

With the rapid development of China's aeronautical equipment technologies and industry, technologies for health state monitoring, fault diagnosis, trend prediction, and condition assessment of aero-engines are of critical importance to ensuring high performance, high stability, and high reliability of engine operation. Structural health monitoring of aero-engines enables continuous monitoring and assessment of the engine structural state throughout flight testing and the entire service life. By carrying out scientific fault diagnosis and isolation, structural health trend prediction, and state assessment, condition-based maintenance of engine structures can be realized, thereby enhancing engine reliability, maintainability, fault controllability, and the capability to respond to emergency conditions, while at the same time reducing the life-cycle cost-effectiveness ratio of the engine. Focusing on structural health monitoring and assessment technologies for aero-engines, this work systematically analyzes the necessity of engine health state monitoring for the healthy, stable, and safe operation of propulsion systems and aircraft, as well as its necessity for improving mission completion rates of equipment and reducing the cost-effectiveness ratio over the entire life cycle. It elaborates in detail the current research status of engine health state monitoring at home and abroad, reviews the research progress on advanced sensing technologies, monitoring systems and methods, typical fault feature extraction methods, and health state assessment methods applied to structural health state monitoring and assessment of aero-engines, and finally presents a perspective on the development trends of structural health monitoring and assessment technologies for aero-engines.

Full Text

Preamble

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Abstract: With the rapid development of China' s aviation equipment technology and industry, aero-engine health condition monitoring, fault diagnosis, trend prediction, and condition assessment technologies are critical for ensuring high performance, operational stability, and reliability. Aero-engine structural health monitoring enables continuous observation and evaluation of engine structural condition throughout flight testing and service life. Through scientific fault diagnosis and isolation, structural health trend prediction, and condition assessment, condition-based maintenance of engine structures can be achieved, enhancing engine reliability, maintainability, fault controllability, emergency response capability, and reducing life-cycle cost-effectiveness ratios. This paper systematically analyzes the necessity of engine health condition monitoring for ensuring healthy, stable, and safe operation of propulsion systems and aircraft, as well as for improving mission completion rates and reducing life-cycle costs. The research status of engine health condition monitoring both domestically and internationally is elaborated in detail, reviewing progress in advanced sensing technologies, monitoring systems and methods, typical fault feature extraction methods, and health condition assessment methodologies applied to aero-engine structural health monitoring and evaluation. Future development trends are also discussed.

Keywords: aero-engine; structural health; condition monitoring; advanced sensing; fault diagnosis; feature extraction; health baseline; condition assessment

1. Necessity of Engine Structural Health Monitoring

1.1 Enhancing Engine Performance Attenuation and Fault Controllability

Modern air combat aims to achieve air superiority and often involves complex battlefield situations. To accomplish such missions, equipment must maintain good performance without structural fault symptoms. When fault location is accurate, direct inspection and maintenance of faulty or potentially faulty components can be performed, eliminating comprehensive inspection and reducing maintenance time. This enhances equipment availability and improves mission readiness rates. Engine performance condition is a critical factor affecting mission completion. Achieving fault controllability through advanced technology to perceive engine health status can maximize mission success rates.

1.2 Reducing Engine Failure Risks

As the power component of aircraft, aero-engines operate in extremely harsh environments with complex compositions, high rotational speeds, and frequent failures with complex causes. Focusing on aero-engine health condition is crucial for improving mission completion rates. The higher the prediction accuracy, the more flight risks can be mitigated. Pilots and maintenance personnel must continuously master engine health status to ensure safe operation. Even during missions, when fault symptoms appear, pilots can take evasive actions such as degraded usage or early return to maximize flight safety.

1.3 Reducing Support Equipment and Personnel Requirements, Lowering Maintenance Costs

Aero-engines require significant support equipment and technicians for daily inspection and testing, increasing maintenance expenditures. Advanced health assessment technologies can substantially reduce ground support equipment configuration, improve equipment mobility, and integrate overall equipment health management into global networks. The Joint Strike Fighter (JSF/F-35) program proposed the Autonomic Logistics Global Sustainment (ALGS) system, which enables worldwide rapid support and maintenance with minimal manpower and equipment, effectively reducing cost-effectiveness ratios.

1.4 Reducing Unnecessary Maintenance and Spare Parts

Through fault location and prediction, component health condition assessment enables life management, planned replacement, parts logistics support, and supply chain simplification. Scientific evaluation and management approaches simplify on-site inspection, fault isolation, and replacement procedures, further reducing maintenance personnel and test equipment requirements. Accurate fault location reduces maintenance time and lowers cost-effectiveness ratios from both cost reduction and efficiency improvement perspectives.

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2. Domestic and International Research Status of Engine Health Monitoring

2.1 International Research Status

The concept of condition monitoring originated from U.S. commercial insurance companies analyzing aircraft accident statistics, finding that landing gear and engines (ATA32, ATA72) accounted for the most mechanical structure failures. This led to the development of health management concepts in aerospace equipment, representing a major innovation. The U.S. established distributed health management system architectures for aircraft, dividing functional domains into multiple subsystem health management areas including vehicle subsystem health management, structural health management, propulsion system health management, and software health management.

Since the 1990s, the U.S. implemented the Integrated High Performance Turbine Engine Technology (IHPTET) program and Versatile Affordable Advanced Turbine Engine (VAATE) program, with their advanced concepts embodied in the Joint Strike Fighter' s ISHM system. The U.S. Department of Defense recognized PHM technology as foundational for achieving weapon system readiness and affordability. The technology evolved into Health and Usage Monitoring Systems (HUMS), widely applied in U.S., British, and other helicopter fleets including Apache and Black Hawk models.

The F-35' s PHM system is a critical subsystem integrating particle monitoring, eddy current blade screening, ingested debris monitoring, and oil debris monitoring systems. It enables in-flight autonomous fault detection, engine operating condition adjustment, and component replacement preparation before landing. The system architecture includes on-board, regional manager, and enterprise levels, enabling real-time data transmission through the Multi-function Advanced Data Link (MADL) for deeper fleet-level analysis and complex predictive modeling.

Representative engine monitoring systems include ADEPT, IECMS, COMPASS, and others applied to various engine models (JT3D, JT8D, JT9D, PW4000, CF6, F110, F404, etc.). These systems provide performance parameter monitoring, vibration analysis, oil system monitoring, life consumption tracking, and integrated diagnostics.

2.2 Domestic Research Status

Domestic aero-engine health management research started later but has made progress. Researchers proposed principal factor models, baseline mining methods, and performance parameter forecasting techniques. Some systems have been applied in flight testing, but challenges remain in data perception, fault diagnosis prediction, system integration verification, and industry ecosystem foundation.

Key technical bottlenecks include: - **Data perception:** Limited measurement points and locations due to engine internal space constraints, unstable signal transmission for rotating components, and insufficient accuracy - **Fault diagnosis:** Difficulty in accurate fault location due to lack of complete forward design experience and mechanism model libraries, with insufficient performance prediction model accuracy - **System integration:** Complex fault mechanisms with strong multi-physics coupling, lack of test facilities simulating real extreme service environments, and incomplete verification platforms - **Industry ecosystem:** Health management technology is relatively separated from engine design processes, with insufficient forward design experience and R&D models often following specific models without long-term independent investment in core fundamental technologies

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3. Advanced Sensing Technologies for Engine Structural Health Monitoring

3.1 Strain Monitoring Sensing Technology

Strain monitoring enables measurement of structural mechanical properties. Resistance strain gauges and fiber Bragg gratings are commonly used strain monitoring technologies in mechanical structures. For high-temperature components operating in extreme environments, high-temperature strain measurement is particularly critical.

The F-35 has conducted flight tests with resistance strain gauges modified on critical load-bearing components. Research has been conducted on foreign object damage (FOD) monitoring based on engine rotor blade contact strain measurement, forming probability-based design criteria. Casing strain measurement methods have been used for real-time engine structural health monitoring, enabling rotor rub-impact fault identification. High-temperature strain sensors have been modified on nozzle unit critical load-bearing components to monitor nozzle structural health and verify mechanism integrity.

3.2 Fiber Optic Sensing Technology

Fiber optic sensors offer advantages including real-time monitoring, anti-interference capability, multi-parameter synchronous measurement, and predictive maintenance capability. Fiber Bragg Grating (FBG) sensors have been flight-tested on engines for strain, temperature, and acceleration measurement. Distributed fiber optic sensing technology has been applied to pressure pipeline crack identification and rotor blade vibration monitoring.

NASA applied distributed fiber optic sensors on X-33 vehicle fuel tank structures for multi-point temperature and strain measurement. High-resolution distributed fiber optic sensing networks on blade surfaces have successfully predicted fatigue crack initiation and propagation. Fiber optic sensors provide reliable, environmentally adaptable, multi-point distributed sensing for engine structural health monitoring.

3.3 MEMS Sensing Technology

MEMS (Micro-Electro-Mechanical System) sensors feature high integration, multi-parameter measurement, minimal impact on engine structure, and freedom from space constraints. MEMS technology enables intelligent health monitoring of engine typical components including structural health monitoring, combustion process control, and oil system health monitoring. Successful industrial applications in automotive airbags and anti-lock systems demonstrate MEMS potential for aviation engines.

3.4 Non-Contact Vibration Monitoring Sensing Technology

With advances in blade materials and manufacturing processes, blade fatigue damage remains a significant concern. Non-contact vibration monitoring offers substantial advantages over traditional contact methods. Blade tip timing (BTT) methods measure blade tip displacement intermittently, enabling real-time rotor blade vibration monitoring.

The U.S. Air Force Arnold Engineering Development Center (AEDC) pioneered non-intrusive stress measurement systems (NSMS). Hood Technology Corporation developed non-contact blade vibration monitoring systems using eddy current and optical sensors, applied to F100-PW-100, F405-RR-401, and other engines for high-cycle fatigue, foreign object damage, and compressor vibration monitoring.

Laser Doppler vibrometry measures blade vibration from Doppler frequency shift of light scattered from blade tips. Fiber laser Doppler displacement sensors have measured turbine blade tip clearance and vibration at rotor speeds up to 586 m/s and blade frequencies up to 21.7 kHz, showing superior accuracy compared to capacitive sensors.

3.5 Flexible Sensing Technology

Flexible sensors can measure physical or chemical quantities while conforming to complex surfaces without affecting the measured object. Flexible vibration sensors offer advantages including conformability to large-curvature surfaces, lightweight, and easy integration. They can be conformally attached to rotor blades and other typical structures to monitor vibration and stress parameters in real-time.

3.6 Other Advanced Sensing Technologies

Mechanical Waveguide Method: Proven for engine main shaft bearing health monitoring by measuring defect signals through waveguides and high-temperature vibration accelerometers.

Radar-Based Monitoring: The Engine Health Diagnostics Using Radar (EHDUR) system detects foreign object debris, classifying them as damaging or non-damaging, and provides early warning of blade problems by measuring individual blade vibration.

Acoustic Emission: Material deformation and crack damage release strain energy as acoustic emission waves. Acoustic emission sensors modified around engine bearings enable health monitoring and fault diagnosis.

Wireless Sensors: Wireless sensor networks with more sensors enable comprehensive monitoring data acquisition, overcoming wiring difficulties in engine internal environments.

[Figure 1: see original paper] F-35 system design diagram
[Figure 2: see original paper] Engine health monitoring system functional structure diagram
[Figure 3: see original paper] Aero-engine foreign object impact monitoring system based on blade surface strain measurement
[Figure 4: see original paper] Load measurement of engine temperature components based on high-temperature strain measurement
[Figure 5: see original paper] Transmission characteristics of fiber grating
[Figure 6: see original paper] X-33 aircraft fiber optic sensor distribution
[Figure 7: see original paper] High temperature turbine blade deformation measurement system based on optical fiber sensor
[Figure 8: see original paper] Eddy current sensor for monitoring component crack
[Figure 9: see original paper] Engine fatigue damage monitoring system based on wireless sensor
[Figure 10: see original paper] Vibration measurement of engine rotor based on laser Doppler principle
[Figure 11: see original paper] Non-contact blade tip vibration monitoring system diagram
[Figure 12: see original paper] Reliability flight schematic diagram of aero-engine foreign object impact monitoring system
[Figure 13: see original paper] Life prediction and health management of turbine blade disk based on non-contact vibration
[Figure 14: see original paper] Application of flexible vibration sensor in aero-engine health monitoring
[Figure 15: see original paper] Measurement and diagnosis of engine bearing defects based on mechanical waveguide method
[Figure 16: see original paper] Gasket foreign object impact test and detection results of EHDUR

[Figure 17: see original paper] Aero-engine system structure diagram
[Figure 18: see original paper] Structure of aero-engine dynamic stress flight measurement telemetry system
[Figure 19: see original paper] Aero-engine vibration monitoring system
[Figure 20: see original paper] Aero-engine airborne vibration monitoring system
[Figure 21: see original paper] Deformation measurement of engine blade based on technology
[Figure 22: see original paper] Deformation measurement of engine blade based on multi-vision digital image
[Figure 23: see original paper] Aero-engine mechanical fault feature extraction method classification
[Figure 24: see original paper] Aero-engine evaluation scheme
[Figure 25: see original paper] Aero-engine system structural health assessment model framework

Foreign typical engine condition monitoring and fault diagnosis systems
The engine and test bench projects participated by Hood Technology
Comparative analysis of different advanced sensing technologies

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4. Structural Health Monitoring Systems and Methods

4.1 Structural Strain Monitoring Systems

Strain monitoring systems are essential for engine structural health management. The U.S. conducted blade dynamic stress measurement during engine airworthiness certification flight tests for Boeing 777 engines, accumulating extensive test data and experience. Engine rotor blade dynamic stress measurement is crucial for design verification, improvement, life and reliability assessment, and safety monitoring.

Domestic researchers have designed engine elastic support stress monitoring systems for high-speed rotor rub-impact monitoring and fault diagnosis. Propeller blade root vibration stress monitoring methods have been validated through flight tests. Wireless near-field telemetry systems have enabled flight measurement of engine rotor blade vibration characteristics.

4.2 Structural Vibration Monitoring Systems

Vibration monitoring is a primary method for aero-engine condition monitoring, assessing mechanical performance through amplitude and frequency characteristics. Engine airborne vibration monitoring systems track high/low pressure fundamental and harmonic vibration components.

The Airborne Engine Diagnostic System (ATEDS) and other vibration monitoring systems enable real-time fault detection and cause discrimination. Statistical analysis shows structural strength faults account for 60%-70% of engine failures, with much fault information reflected in vibration features. Domestic researchers have developed vibration monitoring systems using wavelet and short-time Fourier transform methods for non-stationary signal analysis.

4.3 Structural Deformation Measurement Systems

Non-contact methods are most commonly used for blade deformation measurement, including laser speckle, holographic interferometry, machine vision, digital image correlation (DIC), and marker methods. DIC offers full-field measurement without requiring vibration isolation platforms, achieving high precision through control of detection point range and density.

DIC has been applied to measure deformation of helicopter rotor blades in flight and fan blades under maximum continuous thrust. Multi-vision DIC systems have accurately measured displacement and strain fields on rotor blade surfaces. While limited by camera frame rate and data processing speed for long-term fan rotor monitoring, DIC shows broad prospects with advancing computer technology.

4.4 Acoustic Emission Monitoring Systems

Acoustic emission (AE) refers to stress wave emission from strain energy release during material deformation or crack damage. AE sensors installed around engine bearings enable health monitoring and fault diagnosis. AE parameters including amplitude, duration, event count, and RMS voltage level effectively identify engine instability and crack propagation status.

4.5 Structural Fault Feature Extraction Methods

Fault feature extraction establishes correlations between fault types and characteristics. Methods are categorized into:

Time-domain analysis: Statistical parameters like RMS, crest factor, and kurtosis indicate bearing health trends. Improved time-domain feature sets enhance fault recognition rates.

Frequency-domain analysis: Power spectrum, cepstrum, and resonance demodulation methods extract fault-related frequency features. These work well for steady-state signals but not transient signals.

Time-frequency domain analysis: Short-time Fourier transform, empirical wavelet transform, and Wigner-Ville distribution characterize transient signals.

Entropy theory: Permutation entropy and other entropy methods have been applied to vibration monitoring for non-linear system signal features.

Deep learning: Automatic feature extraction from raw data eliminates manual feature design dependency. Neural networks can select optimal feature subsets from large feature sets, building powerful diagnostic and predictive models by learning performance degradation trends throughout complete flight cycles.

4.6 Engine Structural Health Condition Assessment Methods

Health assessment rapidly and accurately determines fault location and severity, enhancing maintenance decision-making and ensuring flight reliability and safety. Assessment approaches include:

Health status grading: Classifying equipment condition levels to determine maintenance and reliability levels, though lacking standardized criteria.

Health degree assessment: Quantifying individual engine health condition through comprehensive analysis of performance parameters, mechanical parameters, and operating environment. Health degree can be converted to failure rate for accurate trend prediction.

Model-based approaches: Observer models generate residual data in healthy conditions, with Mahalanobis distance calculated between current and baseline states, normalized as health degree. Matching matrices enable variable operating condition assessment by switching between different health evaluation models.

Data-driven approaches: GRNN and other neural network methods build health baselines from historical data, extracting feature sequences from time-domain residuals for health assessment.

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5. Conclusion

Aero-engine structural health monitoring and evaluation technologies are essential for propulsion system and aircraft health, stable and safe operation, improving mission completion rates, and reducing life-cycle cost-effectiveness ratios. This study systematically analyzed requirements, research status, advanced sensing technologies, monitoring systems and methods, fault feature extraction, and health assessment methodologies.

Future development trends include:

1. **Extreme environment sensing:** New sensing principles and materials for high-load, high-temperature environments, integrated structure-sensor manufacturing, and endogenous sensing for durability.
2. **Virtual sensing:** Soft measurement and physics-informed virtual sensors to overcome physical measurement point limitations, enabling indirect high-precision measurement of unmeasurable parameters.
3. **Sparse sensing with digital twins:** Optimal sensor placement and adaptive diagnostics driven by digital twins, providing self-awareness and self-diagnosis capabilities.
4. **High-precision models with limited data:** Establishing high-accuracy prediction and assessment models based on limited flight test

data, addressing the gap in complete life-cycle data for model validation.

5. **Multi-parameter fusion:** Multi-sensor measurement and multi-parameter data fusion diagnostic analysis, including deep learning-based multimodal fusion, physics-data driven fusion, small sample and uncertainty-oriented fusion, and lightweight edge computing fusion algorithms.
6. **AI and digital twins:** Deep integration of machine learning, artificial intelligence, cloud-edge collaboration, and digital twin technologies will enable predictive maintenance and autonomous health management. Digital twins represent the ultimate goal, dependent on breakthroughs in multi-physics modeling, real-time simulation, and data integration.
7. **Edge intelligence:** Solving the contradiction between computational resources and real-time requirements in airborne environments, forming the foundation for scalable health management systems.

These advancements will ultimately achieve precise perception, prediction, and decision-making for engine structural health, significantly enhancing flight safety and operational efficiency.

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