Specific features of aircraft maintenance based on their technical condition

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Abstract: The article analyzes the importance of a condition-based approach to improving the efficiency of the technical maintenance (TM) system for aircraft. Methods for optimizing TM processes through operational data analysis, failure forecasting, and the effective organization of preventive measures are examined. Issues related to the differences between preventive and reactive maintenance and the application of modern diagnostic technologies are highlighted. The approaches presented in the article help enhance flight safety and reduce maintenance costs.
Keywords: aircraft, system, aviation instruments, regular inspections, CAMP, technical maintenance, diagnostics, parameter, safety, airworthiness

1. Introduction

Currently, the rapid development of the aviation industry and the increasing complexity of aircraft operations demand new approaches to maintenance systems. The importance of maintenance based on assessing the technical condition of aircraft is growing to ensure their safety and uninterrupted operation. This approach allows for continuous real-time monitoring of aircraft conditions, early detection of malfunctions, and the effective implementation of preventive measures. This article analyzes the specific features of maintenance based on the technical condition of aircraft, modern diagnostic technologies, and methods for optimizing preventive measures. This approach is crucial not only for enhancing flight safety but also for reducing maintenance costs [1; 2].

Research analysis

Aircraft maintenance remains a cornerstone of aviation safety, reliability, and operational performance. The Maintenance, Repair, and Overhaul (MRO) sector is expected to reach $90.85 billion in 2024, with a projected compound annual growth rate (CAGR) of 4.75% between 2025 and 2030. Maintenance costs constitute a significant portion of operational expenses: in 2023, labor accounted for 31%, and fuel for 22%. Given this economic significance, the industry seeks innovative approaches to enhance maintenance efficiency, reduce costs, and improve fleet readiness.

Recent technological advancements have accelerated the shift from static, time-based maintenance practices to dynamic, data-driven strategies such as condition-based maintenance (CBM). CBM is defined as “preventive maintenance based on monitoring system physical conditions, analyzing data, and determining necessary actions.” This approach represents a proactive strategy that aligns maintenance activities with the actual condition of aircraft systems. By predicting failures, optimizing task intervals, and reducing excessive interventions, CBM enhances operational efficiency and safety.

2. Methods and materials

Condition-Based Maintenance (CBM) for aircraft is based on the regular monitoring, diagnostics, and forecasting of their actual condition. This approach provides several key advantages:

1. Early Fault Detection – Modern sensors and diagnostic technologies enable the continuous collection and analysis of data about the aircraft's condition..
2. Efficient Organization of Preventive Measures – Preventive actions aimed at avoiding faults and damages are carried out accurately and in a timely manner..
3. Cost Reduction – Economic efficiency is achieved by minimizing unplanned repairs and maintenance activities, as well as optimizing the use of spare parts.

Condition-Based Maintenance (CBM) is one of the most advanced and effective maintenance methods in the aviation industry. This approach is based on the continuous monitoring and analysis of the technical condition of aircraft during their operation and organizing maintenance activities based on precise data. The CBM system plays a critical role in the efficient organization of maintenance by enabling early fault detection, implementing preventive measures, and ensuring accurate and timely maintenance operations.

1. Early Fault Detection and Prevention [4].

The key advantage of condition-based maintenance (CBM) is its ability to detect faults and technical errors before they occur. Through modern sensors, diagnostic technologies, and automated data analysis systems, precise information about the condition of each aircraft component is collected. This data is analyzed to predict the technical state and prevent potential failures before they happen. For instance, changes in engine temperature or vibration can be used to identify potential engine malfunctions.

2. Reducing Technical and Time Costs.

The condition-based approach is a method aimed at achieving both effective and cost-efficient maintenance. For example, compared to traditional preventive maintenance methods that rely on fixed intervals, CBM ensures that maintenance is performed only when specific faults or needs are identified in the aircraft. This reduces unnecessary and

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inefficient repairs, spare part replacements, and ambiguous costs. As a result, aviation companies can lower expenses and utilize resources more effectively.

3. Ensuring Continuity and Safety.

The CBM system plays a critical role in ensuring continuity and safety. By regularly monitoring the technical condition of an aircraft, any malfunction or hazardous situation can be quickly identified and effectively addressed beforehand. For instance, minor issues in complex components are resolved early, preventing major failures and mitigating threats to operational safety. This approach helps to avoid numerous safety risks during the operation of aircraft, ensuring smooth and secure operations.

4. Extending Airworthiness.

Condition-Based Maintenance plays a crucial role in extending the airworthiness of aircraft. When the technical condition is accurately and efficiently monitored, components are repaired in a timely manner, prolonging their operational lifespan. This approach ensures the extension of airworthiness certificates and the overall operational life of the aircraft. Additionally, it reduces the need for new aircraft, leading to significant economic benefits.

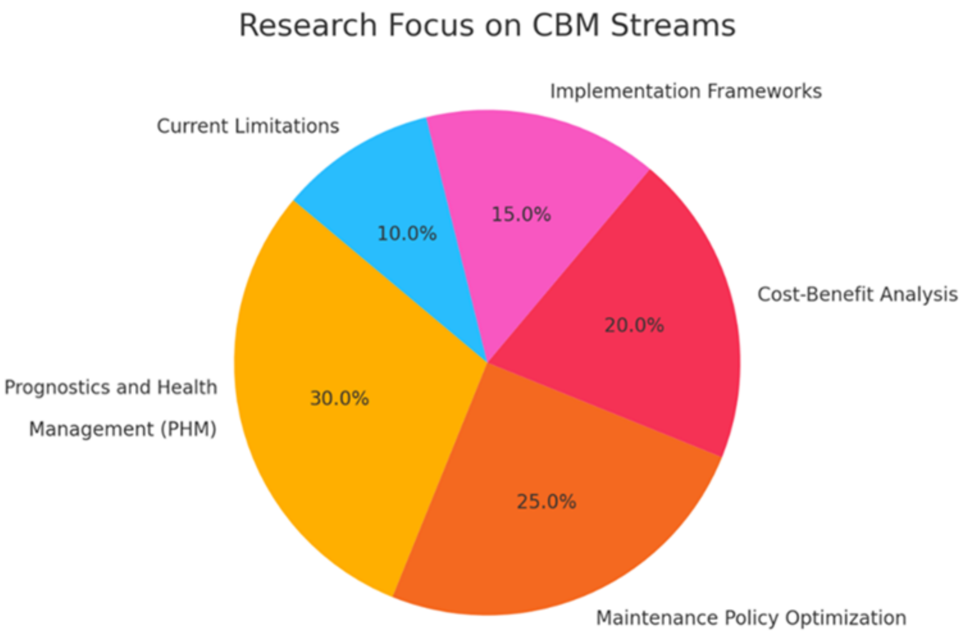

Fig. 1. Research on Condition-Based Maintenance

5. Innovative Technologies and Specialized Methods.

Another important aspect of condition-based maintenance is its reliance on modern innovative technologies and diagnostic methods. Techniques such as sensors, real-time monitoring, ultrasonic analysis, and vibration diagnostics provide accurate information about the technical condition. These methods and technologies offer professional aviators precise and reliable data on the current state of the aircraft, enabling efficient and prompt decision-making.

The three main elements of CBM are as follows.

1. Monitoring the Technical Condition of the Aircraft.

This involves the systematic collection of data about the physical condition of the aircraft. Such data can be collected using the following methods:

- Onboard System Sensors: Collecting continuous or periodic data such as vibration levels, engine temperature, and structural stress.;
- Non-Destructive Testing (NDT): Utilizing methods such as visual inspection, acoustic vibration testing, and liquid penetrant testing..

This data provides critical diagnostic indicators and forms the basis for assessing and predicting the technical condition [3; 5].

1. Aircraft Health Management (AHM).

AHM, also known as Integrated Aircraft Health Management (IAHM), analyzes the collected data to evaluate the current and future technical condition of the aircraft.

- System Operations (Prognostics and Health Management - PHM): Focused on detecting system-level faults and predicting the Remaining Useful Life (RUL) of components;
- Structural Operations (Structural Health Monitoring - SHM): Detecting, assessing, and predicting structural damage.

AHM uses physics-based and data-driven methods to accurately schedule maintenance periods.

1. Maintenance Planning.

Based on the assessment of the technical condition, it determines the following:

- Required Actions: Identifies what maintenance is needed based on the expected conditions.
- Scheduling: Determines a schedule that minimizes operational disruptions.
- Resource Allocation: Ensures the availability of necessary personnel, tools, and spare parts. Figure 1.

Research Directions in CBM.

Academic research covers various aspects of CBM and focuses on the following directions:

1. Prognostics and Health Management (PHM):

This direction focuses on developing models and algorithms for predicting system and structural element failures and assessing the Remaining Useful Life (RUL).

These frameworks utilize advanced data analysis techniques and machine learning to improve prediction accuracy.

2. Maintenance Policy Optimization:

Research focuses on optimizing maintenance schedules based on cost, reliability, and availability. Key directions include:

- Scheduling line maintenance
- Minimizing unscheduled maintenance
- Fleet-level planning to reduce operational costs.

2. Cost-Benefit Analysis:

Research evaluates the economic impact of implementing CBM, highlighting its role in reducing asset downtime and maintenance costs.

3. Implementation Frameworks (Amalga Oshirish Ramkalari):

Research focuses on addressing challenges encountered in implementing CBM in practice. For example, the Open System Architecture for Condition-Based Maintenance (OSA-CBM) standard defines six functional blocks, including data acquisition, health assessment, and recommendation generation.

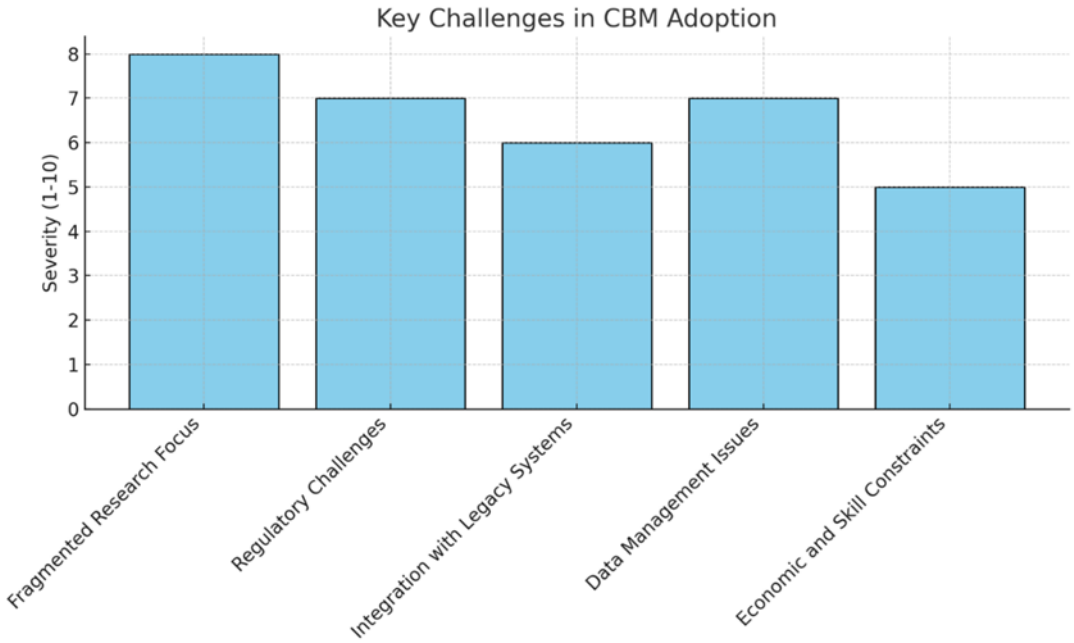

Fig. 2. Key Challenges in CBM adoption

Practical Limitations and Gaps.

Despite advancements in CBM, several significant limitations persist:

•Fragmented Research Directions:

Many studies focus on specific components of CBM, such as PHM or SHM, but do not consider the comprehensive lifecycle-based framework of CBM.

• Challenges in Regulatory and Standardized Approaches:

The aviation industry is governed by stringent regulatory standards that lag behind technological advancements. The lack of standard protocols for implementing CBM complicates certification processes.

• Integration with Legacy Systems:

Many airlines operate mixed fleets that lack modern sensors and data acquisition systems. Upgrading these aircraft to support CBM is expensive.

• Data Management Challenges:

CBM relies on collecting and analyzing large volumes of data. Issues with data quality, storage, and compatibility between different systems can complicate analyses.

• Limited Collaboration:

The gap between academic research and practical application is widening due to insufficient collaboration within the industry.

• Economic Issues:

The initial investments required to implement CBM technologies can be expensive for smaller operators [7].

• Skill and Workforce Shortages:

Transitioning to CBM requires skilled personnel in data analysis, sensor technologies, and predictive strategies. Figure 2.

3. Conclusion

Condition-based maintenance (CBM) of aircraft is one of the emerging and significant directions in the aviation industry. Unlike traditional preventive and reactive maintenance methods, this approach focuses on enhancing the efficiency of maintenance through condition-based monitoring and diagnostics. This type of CBM is primarily aimed at analyzing the individual condition of each aircraft, which helps ensure safety in the aviation sector, extend operational lifespan, and reduce maintenance costs. The main advantages of condition-based maintenance include early fault detection, effective implementation of preventive measures, and organizing maintenance according to the precise condition. This approach enables direct identification of various faults and technical errors during the operation of aircraft, thereby preventing accidents and significant technical failures.

Moreover, the use of modern technologies and diagnostic tools further improves the efficiency of CBM. Advanced methods such as sensors, automated data analysis, ultrasonic diagnostics, and vibration diagnostics provide aviators with comprehensive and reliable real-time information about the condition of aircraft. This enables them to make effective decisions. In the future, the widespread adoption of condition-based maintenance will benefit airlines and aviation organizations not only by ensuring safety but also by providing economic advantages. By coordinating maintenance, implementing modern methods and technologies, and enhancing efficiency, safety, and continuity, the aviation industry can achieve significant advancements. This approach plays a vital role in further developing and modernizing maintenance systems in the aviation sector.

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