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Improvement of diagnostic process for aircraft component damage

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Abstract: The paper examines current approaches to improving the diagnostic process for detecting damage in aircraft structural components under operational conditions. Particular attention is given to aircraft landing gear elements, which are subjected to significant cyclic, impact and vibration loads during take-off, landing and taxiing. The study analyses the influence of operational factors, including load intensity, climatic conditions and runway quality, on the accumulation of fatigue damage and the reduction of structural reliability.
A comprehensive diagnostic approach is proposed, combining vibration diagnostics with a software-based model for selecting the optimal inspection method depending on the type of structural element, material properties, operating conditions and nature of the suspected defect. The principles of vibration diagnostics based on the analysis of amplitude, frequency and energy characteristics of vibration signals are considered. The high sensitivity of vibration parameters to the early stages of structural degradation, including fatigue cracks, weakening of joints and microstructural defects, is substantiated.
The developed software model includes algorithms for analysing the diagnostic object, determining dominant degradation factors, generating informative diagnostic parameters and selecting the most effective inspection method. Comparative analysis of existing diagnostic methods demonstrates the advantages of vibration diagnostics in terms of early defect detection, automation capability and reduction of labour intensity. The proposed approach enables continuous monitoring of technical condition without dismantling structural components and supports the transition from scheduled maintenance to condition-based maintenance.
The implementation of the proposed diagnostic approach contributes to improving aircraft reliability, increasing flight safety, optimising maintenance schedules and reducing operational costs. The obtained results confirm the перспективность of integrating vibration diagnostics and intelligent software systems into modern aircraft maintenance processes.
Keywords: diagnostics, aircraft, damage, vibration diagnostics, landing gear, reliability

1. Introduction

Ensuring the reliability, durability and operational safety of aircraft structures remains one of the most important tasks of modern aviation engineering. The continuous growth of flight intensity, increasing operational loads and stricter international flight safety requirements significantly increase the demands placed on the technical condition monitoring of aircraft components. During long-term operation, aircraft structures are subjected to complex cyclic, vibration and impact loads, as well as adverse climatic and environmental influences, which lead to the gradual accumulation of fatigue damage, degradation of material properties and the initiation of hidden structural defects [1], [2].

The timely detection of structural damage is of critical importance for preventing emergency situations, reducing maintenance costs and increasing operational reliability. Fatigue cracks, local weakening of joints, corrosion processes and microstructural defects may significantly reduce the service life of aircraft structures and negatively affect flight safety. In many cases, the development of such defects occurs internally and remains undetected during routine maintenance inspections. Therefore, the development and implementation of highly sensitive diagnostic methods capable of identifying damage at early stages of development has become an important scientific and practical problem in aviation engineering [3].

Traditional aircraft diagnostic methods include visual inspection, capillary inspection, ultrasonic testing, radiographic inspection and other non-destructive testing techniques. Despite their widespread application in aviation maintenance practice, these methods possess several limitations associated with dependence on operator qualification, periodic inspection intervals and difficulties in detecting hidden defects during early stages of degradation. In addition, many traditional methods require partial dismantling of structural elements and considerable labour intensity, which increases maintenance complexity and operational costs [4], [5].

In recent years, the rapid development of intelligent maintenance technologies and digital diagnostic systems has significantly transformed approaches to aircraft technical condition assessment. Modern aviation increasingly requires the implementation of automated monitoring systems capable of continuously analysing the structural condition of aircraft components in real time. This tendency is closely related to the transition from scheduled maintenance concepts to condition-based and predictive maintenance strategies, which rely on continuous monitoring, intelligent data processing and early identification of degradation processes [6].

One of the most promising directions in modern aircraft diagnostics is the integration of Structural Health Monitoring (SHM) technologies, vibration analysis methods and intelligent software systems. These technologies enable

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continuous assessment of structural condition and provide the possibility of detecting hidden defects, fatigue damage and degradation processes long before critical structural failure occurs. The implementation of intelligent diagnostic systems contributes to improving maintenance efficiency, reducing aircraft downtime and enhancing overall flight safety [7], [8].

Among aircraft structural components, landing gear systems represent one of the most heavily loaded and operationally critical assemblies. During take-off, landing, braking and taxiing operations, landing gear structures are subjected to significant dynamic loads, vibration excitation and repeated cyclic stresses. Over time, these operational factors lead to the accumulation of residual stresses, fatigue microcracks and local weakening of structural elements. The highest stress concentrations are typically observed in joint areas, section transitions and shock-absorbing assemblies, where fatigue damage is most likely to initiate.

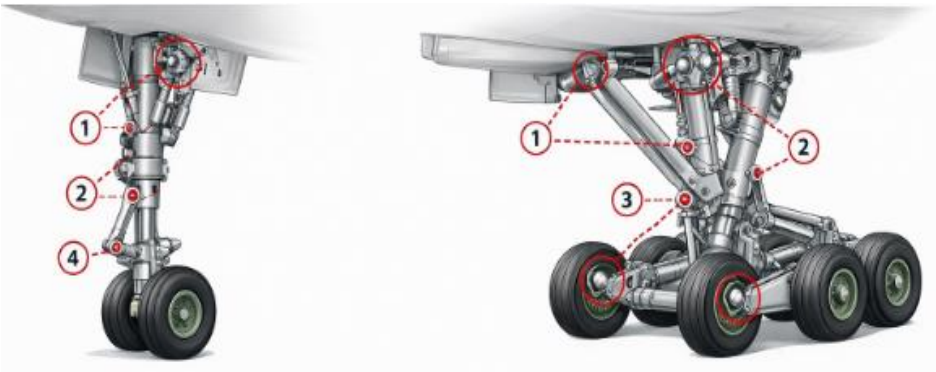

Fig. 1. Structural diagram and stress concentration zones of the aircraft landing gear components: 1 – shock absorber strut; 2 – lateral strut; 3 – cross members with spindles; 4 – bogie with wheels

The structural complexity of aircraft landing gear systems, the presence of stress concentrators and the use of high-strength materials necessitate the application of more advanced and highly sensitive diagnostic methods capable of identifying early-stage degradation processes. In this regard, vibration diagnostics is considered one of the most promising methods for assessing the technical condition of aircraft structures. The method is based on analysing changes in the dynamic characteristics of structural elements caused by defect development and stiffness reduction.

Another important problem in aircraft diagnostics is the selection of the most informative inspection method depending on operational conditions, material properties and the type of suspected defect. The effectiveness of technical condition assessment largely depends on the correct selection of diagnostic parameters and inspection techniques. Therefore, the development of intelligent software-based systems capable of analysing operational factors and automatically selecting optimal diagnostic methods represents an important scientific direction in modern aviation maintenance systems [5].

The present study proposes a comprehensive approach to improving the diagnostic process for aircraft component damage detection through the integration of vibration diagnostics and a software model for selecting inspection methods. The proposed approach aims to improve the reliability of technical condition assessment, increase the effectiveness of early defect detection and support the implementation of intelligent condition-based maintenance technologies in aircraft operation.

2. Research methodology

Vibration Diagnostics Principles

Vibration diagnostics is one of the most effective modern methods for assessing the technical condition of aircraft structural components. The method is based on the analysis of dynamic characteristics of structures during operation and allows hidden defects to be identified through changes in vibration parameters. Unlike conventional inspection techniques, vibration diagnostics enables continuous monitoring of structural condition without dismantling equipment, which significantly increases maintenance efficiency and reduces operational costs [9].

The principle of vibration diagnostics is based on the fact that the appearance and development of structural defects lead to changes in stiffness, mass distribution and damping characteristics of structural elements. These changes directly affect the vibration behaviour of the structure and result in variations of amplitude, frequency spectrum, phase characteristics and vibration energy distribution. Even relatively small defects may produce measurable deviations in dynamic response parameters, making vibration diagnostics highly sensitive to early stages of structural degradation [10], [11].

During aircraft operation, landing gear components are subjected to repeated cyclic and impact loads generated during take-off, landing, braking and taxiing processes. These loads lead to the gradual accumulation of fatigue damage, local weakening of joints and formation of microcracks in highly stressed areas. As the defect develops, the dynamic properties of the structure change, causing modifications in natural frequencies and vibration amplitudes. Monitoring these parameters enables the technical condition of structural components to be evaluated in real time [12].

The diagnostic effectiveness of vibration analysis depends on the correct interpretation of informative vibration parameters. The most commonly used diagnostic indicators include vibration amplitude, root mean square (RMS) value, peak vibration level, frequency spectrum characteristics and vibration energy distribution. An increase in vibration amplitude often indicates the development of looseness, imbalance or structural degradation, while shifts in natural frequencies may indicate stiffness reduction caused by crack propagation or fatigue damage.

Particular importance in vibration diagnostics is given to spectral analysis methods, which enable the identification of characteristic frequency components associated with specific defect types. The frequency spectrum of a healthy structural element differs significantly from that of a damaged structure. The appearance of additional harmonic components, sideband frequencies and increased energy concentration within certain frequency ranges may indicate the initiation and development of structural defects [13].

Figure 2 illustrates the characteristic evolution of vibration parameters during defect propagation. At the initial stage of degradation, vibration characteristics change insignificantly and remain close to nominal values. However, as fatigue damage accumulates and crack dimensions increase, a substantial rise in vibration activity and energy concentration is observed. These changes confirm the high sensitivity of vibration diagnostics to early-stage structural degradation processes.

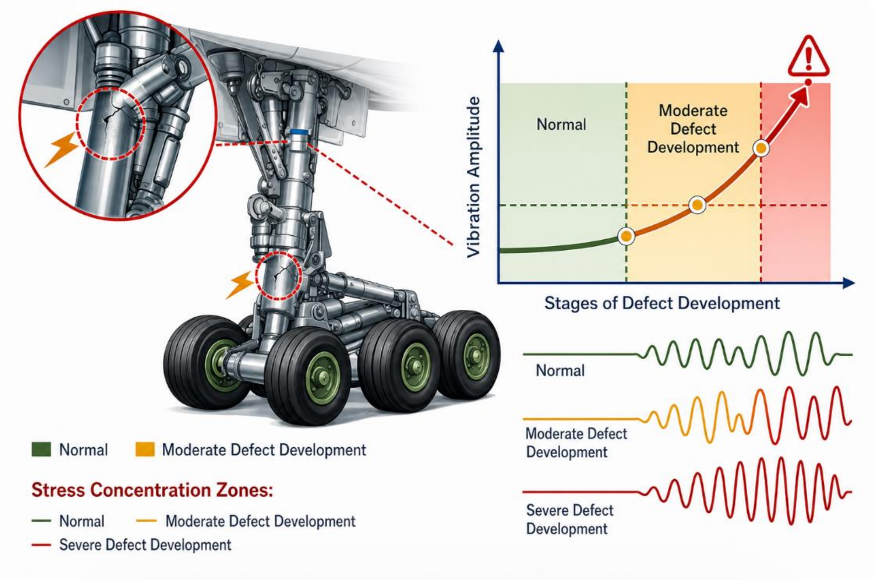

Fig. 2. Changes in vibration parameters as the defect develops

An important advantage of vibration diagnostics is the possibility of integrating diagnostic sensors with intelligent software systems for automated data processing and technical condition assessment. Modern digital diagnostic systems are capable of continuously monitoring vibration parameters, analysing large volumes of diagnostic information and automatically identifying abnormal operating conditions [14]. Such systems significantly reduce dependence on the human factor and improve the objectivity and reliability of diagnostic results.

Compared with conventional non-destructive testing methods, vibration diagnostics offers several significant advantages, including rapid data acquisition, suitability for automation, continuous monitoring capability and high sensitivity to hidden defects. These characteristics make vibration diagnostics a promising basis for the development of intelligent aircraft maintenance systems and predictive maintenance technologies [15].

Thus, the application of vibration diagnostics enables early detection of fatigue damage, optimisation of maintenance procedures and improvement of aircraft operational reliability. The integration of vibration analysis methods with intelligent software-based diagnostic systems creates favourable conditions for the implementation of condition-based maintenance concepts in modern aviation engineering.

Software Model for Diagnostic Method Selection

The effectiveness of aircraft diagnostics depends not only on the quality of inspection equipment but also on the correct selection of diagnostic methods according to the structural characteristics of aircraft components, operational conditions and the type of suspected defect. Different diagnostic techniques possess different levels of sensitivity, labour intensity and applicability. Therefore, the development of intelligent software systems capable of supporting the selection of optimal inspection methods represents an important scientific and practical direction in modern aviation maintenance systems [16].

In the present study, a software-based model for selecting diagnostic methods has been developed to improve the efficiency and reliability of aircraft structural condition assessment. The proposed model integrates several diagnostic approaches, including vibration diagnostics, ultrasonic testing and luminescent inspection methods, into a unified software environment. The system is intended to assist maintenance personnel in analysing technical condition and selecting the most informative inspection method depending on operational requirements and defect characteristics [17].

The software model performs comprehensive analysis of aircraft structural elements by considering operational loads, stress concentration zones, material properties and the probable nature of damage development. Based on the analysed information, the system determines which diagnostic method is most suitable for a particular inspection task. Such an approach increases diagnostic accuracy and reduces the probability of incorrect technical decisions [18].

Vibration diagnostics is used in the software model as one of the primary methods for detecting early-stage structural degradation. The method enables identification of changes in dynamic characteristics caused by fatigue cracks, loosening of joints, stiffness reduction and other hidden defects. Vibration analysis is especially effective for continuous monitoring of heavily loaded structural assemblies, including aircraft landing gear systems. The software system analyses vibration amplitude, frequency spectrum and energy characteristics to identify abnormal operating conditions and possible defect development [19].

Ultrasonic testing is included in the software model as a highly sensitive method for detecting internal defects and determining crack depth within structural materials. The ultrasonic method enables identification of hidden damage that cannot be visually observed on the surface of the component. In the developed software system, ultrasonic inspection data are used for уточнение defect localisation, assessment of defect dimensions and verification of vibration diagnostic results. Integration of ultrasonic testing significantly improves the reliability of technical condition assessment [20].

Luminescent inspection methods are also incorporated into the software model for detecting surface cracks and local structural defects. Luminescent control is widely applied in aviation maintenance practice due to its simplicity and high effectiveness for identifying small surface discontinuities. The developed system considers the results of luminescent inspection as an additional source of diagnostic information, particularly for evaluating surface damage in highly stressed landing gear elements and structural joints.

The software model combines information obtained from different diagnostic methods and performs integrated analysis of technical condition. Such an approach allows the advantages of each inspection technique to be utilised while compensating for their individual limitations. For example, vibration diagnostics provides early identification of abnormal structural behaviour, ultrasonic testing ensures accurate detection of internal defects, and luminescent inspection confirms the presence of surface cracks and local damage zones.

An important feature of the developed software system is its capability for intelligent selection of diagnostic methods depending on operational conditions and inspection objectives. For instance, in cases where early fatigue damage is suspected, the system prioritises vibration diagnostics due to its high sensitivity to changes in structural stiffness and dynamic behaviour. If detailed assessment of internal crack propagation is required, ultrasonic inspection methods are recommended. For rapid evaluation of surface defects during maintenance procedures, luminescent inspection methods are selected.

The software model also enables visualisation of diagnostic results through graphical interfaces and monitoring panels. Diagnostic information, including vibration characteristics, ultrasonic inspection data and defect status indicators, can be displayed in real time. Such visualisation improves the interpretability of diagnostic data and supports maintenance personnel in making technical decisions.

Another important advantage of the proposed system is the possibility of integrating diagnostic data into digital aircraft maintenance environments and intelligent monitoring platforms. Continuous accumulation and processing of inspection information enable analysis of degradation trends and improve maintenance planning efficiency. This contributes to the implementation of condition-based maintenance concepts and reduces unnecessary maintenance procedures [20].

Thus, the developed software model for selecting diagnostic methods represents a comprehensive intelligent diagnostic system integrating vibration diagnostics, ultrasonic testing and luminescent inspection methods. The proposed approach improves the reliability of aircraft structural condition assessment, increases the effectiveness of defect detection and contributes to enhancing aircraft operational safety.

Comparative Analysis of Diagnostic Methods

The effectiveness of aircraft structural diagnostics is strongly influenced by operational conditions and the correct selection of inspection techniques. Aircraft components operate under complex loading environments that include cyclic stresses, vibration excitation, impact loading and adverse climatic effects. Operational factors such as flight intensity, runway condition, humidity, temperature fluctuations and environmental contamination significantly affect the rate of structural degradation and accumulation of fatigue damage. These factors must be considered during the selection and application of diagnostic methods in order to ensure reliable technical condition assessment[3], [7].

Different diagnostic methods possess different levels of sensitivity, inspection complexity and suitability for automation. Therefore, comparative analysis of existing inspection techniques is necessary for determining the most effective approaches to aircraft structural diagnostics. Traditional inspection methods, including visual and capillary inspection, remain widely used in aviation maintenance practice due to their simplicity and relatively low cost. However, these methods are limited in their ability to detect hidden defects and early-stage fatigue damage.

Visual inspection is mainly used for detecting visible surface defects, corrosion traces, deformation and mechanical damage. Although this method requires minimal equipment and relatively low labour intensity, its effectiveness strongly depends on operator experience and inspection conditions. Hidden defects and internal structural degradation often remain undetected during visual examination.

Capillary inspection methods provide improved sensitivity for detecting small surface cracks and discontinuities. These methods are widely applied for inspection of highly stressed structural zones and welded joints. However, capillary inspection is limited to surface defects only and cannot provide information about internal structural condition. In addition, the inspection process requires careful surface preparation and considerable maintenance time [12], [13].

Ultrasonic inspection methods possess high sensitivity for detecting internal defects and determining crack depth within structural materials. Ultrasonic testing enables accurate localisation of hidden damage and is widely used in aircraft maintenance practice. Nevertheless, ultrasonic inspection often requires direct access to the inspected component and highly qualified personnel for interpretation of diagnostic results. The complexity of the inspection process and relatively high labour intensity may limit its application during rapid maintenance procedures.

Among modern diagnostic approaches, vibration diagnostics demonstrates significant advantages in terms of early defect detection and suitability for automation. The method enables identification of changes in structural stiffness and dynamic behaviour caused by fatigue damage, crack development and loosening of structural joints. Since vibration diagnostics can be performed without dismantling structural elements, it provides possibilities for continuous monitoring of technical condition during aircraft operation.

An additional advantage of vibration diagnostics is its compatibility with intelligent software systems and automated monitoring technologies. Modern digital diagnostic platforms are capable of continuously analysing vibration parameters, identifying abnormal operating conditions and generating diagnostic recommendations in real time. This significantly reduces dependence on the human factor and increases the reliability and objectivity of technical condition assessment[9], [14].

Table 1

Comparative characteristics of diagnostic methods for aircraft structures

Diagnostic method	Early defect detection	Suitability for automation	Labour intensity	Limitations
Visual inspection	Low	Low	Low	Dependence on human factors
Capillary inspection	Medium	Low	Medium	Surface defects only
Ultrasonic inspection	High	Medium	High	Requires access to the object
Vibration diagnostics	High	High	Low	Requires correct interpretation

The comparative analysis demonstrates that vibration diagnostics possesses considerable advantages for modern intelligent aircraft maintenance systems. The method combines high sensitivity to early-stage structural degradation with low labour intensity and broad possibilities for automation. These characteristics make vibration diagnostics particularly suitable for integration into condition-based maintenance and Structural Health Monitoring systems [15], [19].

At the same time, effective aircraft diagnostics should not rely on a single inspection method. The combination of vibration diagnostics, ultrasonic testing and conventional inspection techniques provides a more comprehensive assessment of structural condition and increases the reliability of defect detection. Integration of multiple diagnostic approaches into intelligent software systems enables optimisation of maintenance procedures and improves prediction of remaining service life for aircraft components.

Thus, taking operational factors and diagnostic method characteristics into account significantly improves the accuracy of technical condition assessment and enhances the effectiveness of aircraft maintenance processes. The obtained results confirm the перспективность of integrating vibration diagnostics and intelligent software systems into modern aviation diagnostic technologies.

3. Results and Discussion

The conducted analysis confirms that the combined application of vibration diagnostics, ultrasonic inspection and intelligent software-based diagnostic systems provides a comprehensive and effective approach to assessing the technical condition of aircraft structural components. Integration of different diagnostic methods enables more reliable identification of hidden defects, improves the accuracy of technical condition assessment and increases the effectiveness of maintenance procedures[9], [10].

The obtained results demonstrate that vibration diagnostics possesses high sensitivity to early-stage structural degradation processes. Even minor changes in stiffness and dynamic behaviour caused by fatigue damage lead to measurable variations in vibration parameters. This allows hidden defects and microstructural damage to be identified long before visually detectable signs of degradation appear. Such capabilities are particularly important for aircraft landing gear systems, which operate under significant cyclic and impact loading conditions.

One of the most important advantages of vibration diagnostics is the possibility of continuous monitoring of structural condition without dismantling aircraft components. Unlike traditional inspection techniques, vibration analysis can be performed during operation and does not require interruption of maintenance processes. This significantly reduces labour intensity and creates favourable conditions for implementing intelligent monitoring systems in aviation maintenance practice.

The research results also demonstrate that the effectiveness of diagnostic procedures significantly increases when vibration diagnostics is combined with ultrasonic and luminescent inspection methods. Vibration analysis enables early identification of abnormal structural behaviour, while ultrasonic inspection provides detailed information about internal defect localisation and crack dimensions. Luminescent inspection methods complement the diagnostic process by enabling reliable detection of surface cracks and local damage zones. The integration of these methods into a unified software environment improves the reliability and objectivity of technical condition assessment [17], [20].

Particular attention in the developed software model is given to the influence of operational factors on structural degradation processes. Flight intensity, runway condition, climatic influences and loading characteristics significantly affect the rate of fatigue damage accumulation in aircraft structures. The software system analyses these factors and adapts the selection of diagnostic methods according to specific operational conditions. Such an approach improves maintenance efficiency and reduces the probability of incorrect technical decisions.

The developed software model also demonstrates high potential for integration into intelligent aircraft maintenance systems and digital monitoring platforms. Automated processing of diagnostic information enables continuous analysis of structural condition and rapid identification of abnormal operating parameters. This contributes to reducing dependence on the human factor and increases the reliability of maintenance decision-making processes.

An important result of the study is the confirmation that the implementation of vibration diagnostics enables the transition from traditional scheduled maintenance concepts to condition-based maintenance strategies. This approach allows maintenance procedures to be planned according to the actual technical condition of aircraft components rather than fixed operational intervals. As a result, unnecessary inspections can be reduced while maintaining high levels of operational safety and structural reliability.

The research results further indicate that vibration diagnostics is most effective during the early stages of fatigue and microstructural damage development, when traditional inspection methods are not yet capable of identifying degradation processes. Early defect detection significantly reduces the risk of critical structural failure and contributes to increasing aircraft operational reliability [16], [19].

In addition, the integration of intelligent software systems with diagnostic technologies improves the visualisation and interpretation of inspection results. Real-time monitoring panels, graphical interfaces and automated defect indication systems simplify analysis of diagnostic information and improve interaction between maintenance personnel and diagnostic equipment.

Thus, the obtained results confirm the effectiveness and potential of integrating vibration diagnostics, ultrasonic inspection and intelligent software systems into modern aircraft maintenance technologies. The proposed approach contributes to improving aircraft operational reliability, optimising maintenance procedures, reducing maintenance costs and enhancing overall flight safety.

4. Conclusion

The conducted research demonstrates that the integration of vibration diagnostics, ultrasonic inspection and intelligent software-based diagnostic systems provides an effective approach to improving the process of aircraft structural condition assessment. Analysis of operational factors and degradation mechanisms confirms the necessity of applying highly sensitive diagnostic methods capable of detecting defects during the early stages of their development.

The study has shown that vibration diagnostics possesses significant advantages in terms of early defect detection, suitability for automation and continuous monitoring capability. Changes in vibration characteristics enable identification of hidden structural degradation processes, including fatigue damage, stiffness reduction and loosening of structural joints, long before visible defects appear. This makes vibration diagnostics a promising basis for the development of intelligent aircraft maintenance systems.

The developed software model for selecting diagnostic methods improves the reliability and objectivity of technical condition assessment by considering operational conditions, structural characteristics and defect types. Integration of vibration diagnostics with ultrasonic and luminescent inspection methods enables comprehensive analysis of aircraft structural condition and increases the accuracy of maintenance decision-making processes.

An important advantage of the proposed approach is the possibility of transitioning from traditional scheduled maintenance concepts to condition-based maintenance strategies. Continuous monitoring of diagnostic parameters enables optimisation of maintenance procedures, reduction of unnecessary inspections and improvement of aircraft operational efficiency. In addition, the use of intelligent software systems contributes to reducing dependence on the human factor and increases the effectiveness of technical diagnostics [19].

The obtained results confirm that the implementation of the proposed diagnostic approach contributes to improving aircraft reliability, reducing operational costs, optimising maintenance schedules and enhancing overall flight safety. The integration of intelligent diagnostic technologies into modern aviation maintenance systems represents a promising direction for further development of aircraft operational support and predictive maintenance concepts.

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