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A mathematical model for assessing damage and selecting diagnostic methods for aircraft landing gear components

K.K. Kadirbekova[1][a], Sh.T. Ermukhamedova[1][b]
[1]Tashkent state transport university, Tashkent, Uzbekistan

Abstract: This paper presents an integrated computational and diagnostic model for assessing the technical condition of aircraft landing gear components based on stress–strain analysis, fracture mechanics principles and fatigue life prediction. The relevance of the study stems from the high loads placed on landing gear components and the need to improve the reliability of their operation.
Unlike traditional non-destructive testing methods, which are mainly focused on detecting already developed defects, the proposed approach enables early-stage damage detection, quantitative evaluation of defect parameters and prediction of crack propagation. The model incorporates the calculation of nominal and local stresses considering stress concentration effects, determination of stress intensity factors and estimation of fatigue life under cyclic loading conditions.
A key feature of the study is the development of an algorithm for selecting the optimal diagnostic method based on the current structural condition, type of defect and operational parameters. This allows the transition from reactive diagnostics to predictive maintenance strategies.
The results of numerical analysis for IL-76 landing gear components made of titanium alloys demonstrate that accounting for stress concentration and crack parameters significantly increases the accuracy of damage assessment and enables early identification of critical zones. The proposed model can be implemented in software systems and integrated into modern structural health monitoring and digital twin platforms.
The practical significance of the work lies in improving diagnostic reliability, reducing maintenance costs and enhancing flight safety.
Keywords: mathematical modelling, aircraft diagnostics, aircraft landing gear, stress-strain state, crack resistance, fatigue failure, non-destructive testing, service life prediction, selection of diagnostic methods, predictive maintenance

1. Introduction

Aircraft structures operate under complex and highly variable loading conditions, which impose strict requirements on their reliability, safety and service life **[1]**. Among all structural elements, the landing gear system represents one of the most critically loaded assemblies, as it is subjected to combined static, dynamic and impact loads during take-off, landing and taxiing operations **[2]**. These conditions lead to the accumulation of fatigue damage, the initiation of microcracks and the formation of stress concentration zones, which significantly increase the risk of structural failure.

In modern aviation practice, ensuring the airworthiness of aircraft requires the implementation of effective diagnostic methods capable of detecting defects at early stages of their development. However, traditional diagnostic approaches, including visual inspection, luminescent testing and ultrasonic methods, are primarily focused on identifying already formed defects [3]. As a result, their effectiveness in detecting early-stage damage remains limited. Furthermore, these methods do not provide a quantitative assessment of the severity of damage or allow reliable prediction of defect evolution, which complicates maintenance decision-making.

The problem becomes particularly critical for landing gear components, which are typically manufactured from high-strength steels and titanium alloys and operate under cyclic loading conditions [4], [5]. The presence of geometric discontinuities, joints and stress concentrators further increases the likelihood of crack initiation and propagation. In such conditions, even minor defects can lead to a significant redistribution of stresses and accelerate the failure process.

In recent years, the aviation industry has been moving towards advanced maintenance strategies, such as Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM), which require the integration of diagnostic methods with analytical and predictive models [6]. These approaches are aimed not only at detecting defects but also at assessing the current technical condition of the structure and predicting its remaining useful life.

Despite significant progress in the development of non-destructive testing techniques and structural health monitoring systems, many existing approaches do not fully account for the physical mechanisms of damage formation and evolution. In particular, insufficient attention is paid to the role of stress concentration, fracture mechanics parameters and fatigue behaviour in the diagnostic process [7], [8]. This limits the accuracy of condition assessment and reduces the effectiveness of maintenance planning.

Therefore, there is a need to develop an integrated computational and diagnostic approach that combines stress–strain analysis, fracture mechanics and fatigue life prediction into a unified framework. Such an approach should enable the quantitative assessment of structural

[a] https://orcid.org/0009-0009-0167-0907
[b] https://orcid.org/0009-0008-0503-3924

condition, identification of critical zones and prediction of defect growth under real operating conditions.

In this study, a computational and diagnostic model is proposed for assessing the technical condition of aircraft landing gear components. The model is based on the analysis of stress distribution, crack parameters and fatigue characteristics, and includes an algorithm for selecting the optimal diagnostic method depending on the current state of the structure. The proposed approach allows a transition from traditional reactive diagnostics to predictive maintenance, thereby improving the reliability, safety and efficiency of aircraft operation.

2. Research methodology

Computational and diagnostic model

The development of an advanced computational and diagnostic model is a fundamental requirement for improving the reliability and effectiveness of assessing the technical condition of aircraft landing gear components. Unlike conventional diagnostic approaches, which rely primarily on periodic inspections and the application of isolated non-destructive testing techniques, the proposed model establishes an integrated analytical framework that combines stress analysis, fracture mechanics and fatigue behaviour into a unified system [5].

Such an approach enables not only the identification of existing defects but also the prediction of their initiation and evolution under real operational conditions, which is essential for the transition to predictive maintenance strategies.

Aircraft landing gear components operate under complex loading conditions that include axial forces, bending moments, impact loads and vibration-induced stresses. The superposition of these effects leads to a highly non-uniform stress distribution, particularly in structurally critical zones.

The resulting stress state is described by:

$$\sigma = \frac{F}{A} + \frac{M \cdot y}{I}$$

This relationship accounts for both direct and bending stresses, allowing a more realistic representation of operational conditions.

However, in practical engineering applications, nominal stress values alone are insufficient for accurate damage assessment. This is because real structures contain geometric discontinuities such as holes, fillets and welded joints, which act as stress concentrators.

To capture the influence of local geometric irregularities and defects, a stress concentration factor is introduced:

$$\sigma_{max} = K_t \cdot \sigma$$

The parameter K_t reflects the amplification of stress in local regions and is highly sensitive to defect geometry and size. In landing gear structures, where multiple joints and transitions exist, the value of K_t may significantly exceed unity, resulting in local stresses that are several times higher than nominal values.

This phenomenon is critical because crack initiation is strongly correlated with peak stress values rather than average stresses. Therefore, the use of σ_{max} provides a more conservative and physically justified criterion for damage assessment.

The next stage of the model involves the application of fracture mechanics principles to evaluate defect criticality. The stress intensity factor is used as the governing parameter:

$$K_I = Y \cdot \sigma_{max} \cdot \sqrt{\pi a}$$

This parameter establishes a direct relationship between stress level, crack size and structural geometry. Unlike traditional diagnostic indicators, the stress intensity factor provides a physically meaningful measure of crack propagation potential.

The comparison of K_I with the material's fracture toughness K_{IC} allows classification of the structural condition into distinct regimes:

- Stable condition ($KI < KIC$)
- Critical condition ($K_I \approx K_{IC}$)
- Failure condition ($K_I > K_{IC}$)

This classification forms the basis for risk-oriented diagnostics.

Given that landing gear components are subjected to repeated loading cycles, fatigue is the dominant failure mechanism. Therefore, the model incorporates a fatigue life prediction module based on the well-established power-law relationship:

$$N = C(\Delta\sigma)^{-m}$$

This equation reflects the inverse relationship between stress amplitude and fatigue life. Even a small increase in stress level can lead to a significant reduction in the number of cycles to failure.

The integration of fatigue analysis enables the estimation of residual life and supports long-term maintenance planning.

To enhance practical applicability, the model introduces an integrated damage parameter combining stress, fracture and fatigue characteristics:

$$D = \frac{K_I}{K_{IC}} + \frac{\sigma_{max}}{\sigma_{lim}} + \frac{N_{ref}}{N}$$

This dimensionless parameter provides a unified measure of structural condition and allows ranking of components based on their damage severity.

An important advantage of the proposed model is its adaptability to various operational scenarios. By incorporating real input data such as:

- load spectra;
- environmental conditions;
- material properties;
- defect characteristics

the model can be calibrated for specific aircraft types, including IL-76 landing gear systems.

Furthermore, the model is suitable for implementation in software environments, enabling real-time diagnostics and integration with:

- Structural Health Monitoring (SHM) systems;
- Digital twin platforms;
- Predictive maintenance frameworks.

This significantly enhances its practical value and opens opportunities for automation.

The proposed computational and diagnostic model provides several important advantages:

- quantitative assessment of structural condition;
- early detection of defect initiation;
- prediction of crack propagation;
- integration of physical and diagnostic parameters;
- reduction of uncertainty in maintenance decisions.

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The developed computational and diagnostic model represents a comprehensive analytical framework for assessing the technical condition of aircraft landing gear components under real operating conditions. Unlike traditional diagnostic approaches, which are primarily focused on the detection of already developed defects, the proposed model enables a transition to a fundamentally different paradigm based on quantitative evaluation and predictive analysis of structural degradation processes.

A key feature of the model is the integration of multiple physical and mechanical principles, including stress–strain analysis, stress concentration effects, fracture mechanics and fatigue behaviour. The combination of these approaches allows for a more realistic representation of the structural response to complex loading conditions, which is particularly important for landing gear components subjected to cyclic, impact and vibration loads [7], [8].

The use of maximum local stresses instead of nominal values significantly enhances the accuracy of damage assessment, as it reflects the actual conditions under which crack initiation occurs. The incorporation of the stress intensity factor provides a physically justified criterion for evaluating defect criticality and enables the identification of potentially dangerous zones before the onset of catastrophic failure. Furthermore, the inclusion of fatigue life prediction makes it possible to estimate the residual service life of structural elements and to analyse the long-term evolution of damage under repeated loading [9], [10].

An important contribution of the proposed model is the introduction of an integrated damage parameter, which combines stress, fracture and fatigue characteristics into a single dimensionless index. This parameter simplifies the interpretation of diagnostic results and allows for a comparative evaluation of different structural elements in terms of their damage severity and risk level.

Another significant advantage of the model is its adaptability to different operating conditions and structural configurations. By incorporating real operational data, such as load spectra, environmental factors and material properties, the model can be calibrated for specific aircraft types, including heavy transport aircraft landing gear systems. This ensures a high level of reliability and applicability in practical engineering tasks.

The model is also designed with a strong emphasis on implementation in modern digital environments. Its structure allows integration into software-based diagnostic systems, structural health monitoring platforms and digital twin technologies. This enables automated data processing, real-time condition assessment and the development of intelligent maintenance systems based on predictive analytics.

From a practical perspective, the application of the proposed model contributes to improving diagnostic accuracy, reducing maintenance costs and enhancing operational safety. By enabling early detection of defects and reliable prediction of their development, the model supports the transition from scheduled maintenance to condition-based and predictive maintenance strategies.

Thus, the developed computational and diagnostic model can be considered not only as a theoretical tool for analysing structural behaviour, but also as a practical instrument for improving the efficiency and reliability of aircraft maintenance systems. Its implementation provides a solid foundation for the development of next-generation intelligent diagnostic systems in the aviation industry.

Algorithm for selecting a diagnostic method

The selection of an appropriate diagnostic method is a critical component of aircraft maintenance, directly influencing the reliability, safety and cost-effectiveness of operation. In conventional practice, diagnostic procedures are performed according to predefined regulations, without sufficient consideration of the actual structural condition [11], [12]. Such an approach leads to redundant inspections in some cases and insufficient diagnostic sensitivity in others.

To overcome these limitations, an adaptive algorithm for selecting a diagnostic method is proposed, based on the quantitative assessment of the structural condition obtained from the computational model. The algorithm integrates stress analysis, fracture mechanics parameters and fatigue characteristics into a unified decision-making framework.

The proposed algorithm operates as a multi-stage decision system, where each stage refines the selection of the diagnostic method based on progressively detailed information about the structural condition. The main input parameters include:

- maximum stress σ_{max}
- stress intensity factor K_I
- crack length a
- fatigue life N
- damage index D

Based on these parameters, the algorithm determines the most appropriate diagnostic technique for a given structural element.

A key step in the algorithm is the classification of the structural condition into distinct damage levels. This classification is based on threshold values of the calculated parameters:

- Low damage level: $D < D_1$
- Medium damage level: $D_1 \leq D < D_2$
- High damage level: $D \geq D_2$

This approach enables a systematic interpretation of the structural condition and simplifies decision-making.

The selection of an appropriate diagnostic method within the proposed algorithm is based on a comprehensive evaluation of the structural condition, taking into account both physical and operational parameters. Unlike traditional approaches, where diagnostic methods are applied according to fixed procedures or regulatory schedules, the proposed framework determines the most suitable inspection technique through a continuous analysis of stress state, defect characteristics and damage evolution.

At the core of the decision-making process lies the relationship between the calculated mechanical parameters and the detectability of defects using different diagnostic methods. In particular, the level of maximum stress, the magnitude of the stress intensity factor and the size and location of the defect play a decisive role in determining which inspection technique can provide the most reliable results. The analysis begins with the evaluation of the stress state of the structural element, as stress distribution directly influences both the initiation and propagation of defects. In regions where stress levels remain relatively low and do not exceed permissible limits, the probability of significant defect growth is minimal. Under such conditions, simple diagnostic methods are generally sufficient to confirm the absence of critical damage, as the structural integrity is not significantly compromised [3].

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However, as stress levels increase and approach critical values, the likelihood of defect formation and propagation grows considerably. In such cases, the selection of diagnostic methods must take into account not only the presence of defects but also their internal characteristics. For instance, surface-level defects, which are typically associated with minor mechanical damage or early-stage fatigue cracks, can often be detected using relatively simple inspection techniques that rely on surface sensitivity. Nevertheless, these methods become ineffective when defects develop within the internal volume of the material, where their detection requires the application of more advanced diagnostic technologies capable of penetrating the structure.

The decision-making process becomes particularly critical when the calculated stress intensity factor approaches the material's fracture toughness. In this regime, even small defects may lead to rapid crack propagation and potential structural failure. Therefore, the algorithm prioritises the use of high-precision diagnostic methods that can accurately determine defect size, orientation and growth rate. This ensures that the structural condition is assessed with sufficient reliability to support safe operation.

In addition to the static evaluation of stress and defect parameters, the algorithm also incorporates the dynamic behaviour of the structure. The evolution of defects over time is considered through fatigue analysis, which provides insight into the rate of damage accumulation and the remaining service life of the component. As a result, the selection of the diagnostic method is influenced not only by the current condition of the structure but also by its expected future state. This allows the algorithm to anticipate critical conditions and to recommend more advanced inspection techniques before the defect reaches a dangerous level.

Furthermore, the decision criteria are influenced by practical considerations related to inspection efficiency and operational constraints. The algorithm aims to achieve an optimal balance between diagnostic accuracy and resource utilisation, avoiding unnecessary application of complex methods in cases where simpler techniques are sufficient, while ensuring that critical conditions are not overlooked. This optimisation is particularly important in aviation maintenance, where both safety and cost-effectiveness are of paramount importance.

Thus, the proposed decision-making framework establishes a direct link between the physical state of the structure and the selection of diagnostic methods. By integrating stress analysis, fracture mechanics and fatigue behaviour into the decision process, the algorithm ensures a rational and adaptive approach to diagnostics. This significantly enhances the reliability of defect detection, improves maintenance planning and supports the transition towards predictive and condition-based maintenance strategies in modern aviation systems.

A distinctive and fundamentally important feature of the proposed algorithm is its adaptive and predictive capability, which significantly differentiates it from conventional diagnostic approaches. Traditional diagnostic systems are generally based on static inspection schedules and predefined criteria, which do not account for the actual operational condition of structural elements or the dynamic evolution of damage. As a result, such systems often fail to detect defects at early stages or lead to unnecessary inspections, increasing maintenance costs without improving reliability.

In contrast, the proposed algorithm incorporates adaptive mechanisms that continuously adjust the diagnostic strategy based on the current and predicted state of the structure. This adaptability is achieved through the integration of real-time or periodically updated input parameters, including stress levels, crack size, fatigue life and damage index. By analysing these parameters, the algorithm dynamically modifies the selection of diagnostic methods, ensuring that the inspection process remains relevant to the actual condition of the component.

A key element of the predictive capability is the incorporation of fatigue life estimation and crack growth modelling. Using relationships between stress amplitude, number of load cycles and crack propagation rate, the algorithm is able to forecast the future state of the structure over a given time horizon. This allows not only the detection of existing defects but also the identification of zones where damage is likely to initiate in the near future.

The predictive aspect can be formalised by introducing a time-dependent damage function:

$$D(t) = D_0 + \int_0^t f\big(\sigma(t), N(t), a(t)\big)dt$$

where *D(t)* represents the accumulated damage over time, and the function f describes the rate of damage evolution depending on stress, loading cycles and crack growth. This formulation enables the estimation of the remaining useful life (RUL) of the structural element and supports long-term maintenance planning.

Furthermore, the algorithm can incorporate probabilistic elements to account for uncertainties in loading conditions, material properties and measurement errors. By applying statistical or reliability-based approaches, it becomes possible to evaluate the probability of failure and to prioritise inspection actions accordingly. This enhances the robustness of the diagnostic system and reduces the risk of unexpected failures.

Another important aspect of adaptability is the ability of the algorithm to learn from accumulated operational data. When integrated with digital monitoring systems, the algorithm can update its parameters based on historical observations, improving the accuracy of predictions over time. This creates a foundation for the implementation of intelligent diagnostic systems based on machine learning and data-driven models.

The integration of adaptive and predictive features enables a transition from conventional reactive maintenance strategies to advanced maintenance concepts such as Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM). In this context, diagnostic decisions are no longer based solely on fixed intervals or threshold values, but on a comprehensive analysis of the structural condition and its expected evolution.

From a practical perspective, the implementation of such an adaptive and predictive algorithm provides significant benefits, including early detection of critical conditions, optimisation of maintenance schedules, reduction of downtime and minimisation of operational costs. It also contributes to enhancing flight safety by ensuring timely intervention before the occurrence of catastrophic failures.

Thus, the adaptive and predictive capabilities of the proposed algorithm represent a key advancement in the field of aircraft diagnostics, enabling the development of intelligent, flexible and efficient maintenance systems aligned with modern aviation requirements.

An essential advantage of the proposed algorithm for selecting a diagnostic method is its compatibility with modern digital technologies, which enables its effective implementation within advanced aircraft maintenance and monitoring systems. In contrast to traditional diagnostic approaches, which are typically performed as isolated procedures, the developed algorithm is designed to operate within an integrated digital environment, allowing continuous assessment of structural condition and automated decision-making.

The integration of the algorithm with digital systems begins with the incorporation of data obtained from structural health monitoring (SHM) technologies. These systems provide real-time or periodically updated information on key parameters such as stress levels, vibration characteristics, temperature variations and operational loading conditions. By continuously receiving and processing this data, the algorithm is able to dynamically update the assessment of the structural condition, ensuring that diagnostic decisions are based on the most актуальной and accurate information available.

A particularly important aspect of this integration is the compatibility of the model with digital twin technology. A digital twin represents a virtual representation of a physical structural component that reflects its current state, operational history and predicted future behaviour. By embedding the proposed computational and diagnostic model into a digital twin framework, it becomes possible to simulate the evolution of structural damage under various operating scenarios. This enables not only the identification of existing defects but also the forecasting of potential failure modes and the evaluation of alternative maintenance strategies.

The interaction between the algorithm and digital systems also supports the implementation of data-driven approaches. The accumulation of historical operational data allows for the refinement of model parameters and the improvement of prediction accuracy over time. In such a framework, the algorithm can be enhanced through machine learning techniques, which enable the identification of hidden patterns in data and the adaptation of diagnostic criteria to specific эксплуатационные conditions. This leads to a gradual transition from deterministic models to hybrid systems combining physical modelling and artificial intelligence.

Another important aspect of digital integration is the automation of the diagnostic decision-making process. The algorithm can be implemented as a software module within aircraft maintenance management systems, where it performs continuous analysis of incoming data and automatically selects the most appropriate diagnostic method for each structural element. This significantly reduces the influence of human error, increases the speed of decision-making and ensures consistency in maintenance procedures.

From an operational perspective, the integration of the algorithm with digital systems enables the implementation of advanced maintenance concepts such as Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM). In these approaches, maintenance actions are performed based on the actual condition of the structure and its predicted evolution, rather than on fixed schedules. This leads to more efficient resource utilisation, reduced downtime and improved safety.

Furthermore, the use of digital platforms facilitates the visualisation of diagnostic results and structural condition indicators. Engineers and maintenance personnel can access real-time information on stress distribution, defect parameters and risk levels through intuitive interfaces, which improves situational awareness and supports informed decision-making.

Thus, the integration of the proposed algorithm with modern digital systems represents a significant step towards the development of intelligent diagnostic environments. By combining computational modelling, real-time monitoring and data-driven analytics, the algorithm provides a robust and flexible tool for managing the technical condition of aircraft landing gear components. This integration not only enhances diagnostic accuracy but also supports the transition to next-generation maintenance systems characterised by adaptability, efficiency and predictive capabilities.

The developed algorithm provides several key advantages:

- adaptability to real operating conditions
- reduction of unnecessary inspections
- improved accuracy of defect detection
- integration of physical and diagnostic parameters
- support for predictive maintenance strategies

The proposed algorithm for selecting a diagnostic method represents an integrated and adaptive decision-making framework that fundamentally transforms the traditional approach to aircraft structural diagnostics. Unlike conventional methods based on predefined inspection schedules and standardised procedures, the developed algorithm operates on the basis of quantitative assessment of the structural condition, allowing diagnostic decisions to be directly linked to the actual state of the component.

A key feature of the algorithm is the incorporation of multiple interrelated parameters that describe the physical condition of the structure, including stress distribution, crack characteristics, fatigue behaviour and the overall damage level. The simultaneous consideration of these parameters ensures that the diagnostic process reflects the complex nature of damage formation and evolution in aircraft landing gear components, which are subjected to cyclic, impact and vibration loading.

The integration of stress–strain analysis with fracture mechanics provides a physically grounded basis for evaluating defect criticality. In particular, the use of the stress intensity factor allows for the identification of conditions under which crack propagation becomes unstable, thereby enabling early detection of potentially hazardous situations. At the same time, the inclusion of fatigue life estimation ensures that the algorithm takes into account not only the current condition of the structure but also its expected degradation over time.

An important aspect of the algorithm is its adaptability, which allows it to respond dynamically to changes in operational conditions and structural parameters. By continuously analysing input data and updating the assessment of the structural condition, the algorithm ensures that the selected diagnostic method remains relevant and effective throughout the service life of the component. This adaptive behaviour significantly improves the efficiency of diagnostic procedures and reduces the likelihood of both undetected defects and unnecessary inspections.

Furthermore, the algorithm supports predictive capabilities by incorporating models of damage

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accumulation and crack growth. This enables the estimation of the future state of the structure and the identification of critical time intervals for inspection and maintenance. As a result, diagnostic activities can be planned in advance, reducing downtime and improving resource utilization [14], [15].

The compatibility of the algorithm with digital diagnostic systems further enhances its practical value. When integrated with structural health monitoring systems and digital twin technologies, the algorithm can operate in a real-time environment, processing large volumes of data and providing automated recommendations for diagnostic actions. This significantly reduces the influence of human factors and ensures consistency in maintenance decision-making.

From an operational perspective, the implementation of the proposed algorithm enables a transition from traditional maintenance strategies to advanced concepts such as condition-based and predictive maintenance. This transition is associated with improved safety, reduced operational costs and increased reliability of aircraft systems.

Thus, the developed algorithm can be regarded as a comprehensive and intelligent diagnostic tool that combines physical modelling, data analysis and decision-making processes into a unified system. Its application provides a robust foundation for improving the effectiveness of aircraft diagnostics and for developing next-generation maintenance systems based on adaptability and predictive capabilities.

Simulation results

The simulation results obtained using the developed computational and diagnostic model make it possible to identify patterns in the evolution of the stress state and defect parameters in aircraft landing gear components under various operating conditions. The analysis carried out has shown that the behaviour of the structure is distinctly non-linear, particularly in stress concentration zones, where accelerated damage accumulation is observed.

During the modelling process, it was established that as operational loads increase, there is a disproportionate rise in maximum stresses, leading to a significant acceleration in crack propagation. In the initial stages of damage, the change in the stress state is insignificant and is not accompanied by pronounced external signs of a defect, making it impossible to detect them using traditional inspection methods. However, the computational model allows these changes to be recorded through the analysis of local parameters, thereby enabling early damage diagnosis [9].

Particular attention was paid to analysing the dependence of the stress intensity factor on crack length. The results obtained showed that upon reaching a certain critical value of the defect length, there is a sharp increase in the K_I parameter, indicating that the structure has entered a zone of unstable failure. This pattern confirms the need to take into account not only the current size of the defect, but also its potential development dynamics.

$$K_I = Y \cdot \sigma_{max} \cdot \sqrt{\pi a}$$

Analysis of the simulation results also showed that traditional diagnostic methods have limited sensitivity in the early stages of damage. In particular, visual and luminescent inspection do not allow defects to be detected until they reach a certain size, whereas the computational model enables the condition of the structure to be assessed on the basis of indirect parameters, such as changes in stress and stress concentration factor.

Furthermore, it was established that taking fatigue life into account significantly improves the accuracy of structural condition forecasting. As the number of loading cycles increases, a gradual reduction in residual life is observed, with the rate of this reduction depending on the level of applied stresses. Under conditions of increased loads, failure may occur well before the design service life, which confirms the need for an individual approach to assessing the condition of each element.

The simulation results confirm that the most hazardous areas are those of local stress concentration, where defects originate and develop. Even a slight increase in the concentration factor can lead to a significant rise in maximum stresses and, consequently, accelerate failure.

An important finding is the establishment of a relationship between the calculated state parameters and the effectiveness of diagnostic methods. It has been shown that, at low stress levels and with small defect sizes, it is appropriate to use simple inspection methods, whereas as damage parameters increase, more accurate and comprehensive diagnostic approaches are required[13], [14].

Thus, the simulation results demonstrate the high effectiveness of the developed computational and diagnostic model, which enables the early detection of defects, the assessment of their severity, and the prediction of their future development. The data obtained confirm the advisability of moving from traditional diagnostic methods to integrated computational and analytical systems, which make it possible to significantly improve the operational reliability of aviation equipment. The scientific novelty of this study lies in the development of an integrated computational and diagnostic approach to assessing the technical condition of aircraft landing gear components, based on the combination of methods from the fields of strength of materials, fracture mechanics and diagnostic theory into a single analytical system.

Unlike existing methods, which are primarily focused on identifying defects that have already formed, the proposed model provides a quantitative assessment of the level of structural damage based on an analysis of the stress-strain state and crack resistance parameters. This enables a shift from a qualitative interpretation of inspection results to a well-founded numerical assessment of the technical condition of chassis components.

A key innovation is the integration of design parameters into the process of selecting a diagnostic method. In the developed model, the diagnostic decision is made not on the basis of regulatory requirements, but taking into account the current condition of the structure, including stress levels, defect characteristics and the degree of risk of failure. This approach ensures the adaptability of the diagnostic system and enhances its effectiveness under real-world operating conditions [10].

An additional aspect of the scientific novelty is the consideration of the dynamics of defect development. The proposed model allows not only the current condition of the structure to be recorded, but also the prediction of changes in damage parameters over time based on an analysis of stresses and fatigue life. This enables the early identification of potentially hazardous areas and the prevention of a defect from reaching a critical state.

A key finding is the identification of a correlation between the design's calculated characteristics and the effectiveness of various diagnostic methods. The modelling carried out demonstrates that the choice of diagnostic method should depend on the stress state and the defect parameters—factors that were not fully taken into account in traditional approaches.

Furthermore, the developed model is designed for software implementation and integration into digital diagnostic systems. This opens up prospects for the creation of intelligent diagnostic systems capable of automatically assessing the technical condition of a structure and generating recommendations for its continued operation.

Thus, the scientific novelty of the research lies in the transition from isolated diagnostic methods to a comprehensive computational and analytical model that provides a quantitative assessment of the condition, predicts the development of defects, and enables a well-founded selection of diagnostic solutions depending on operating conditions.

Practical significance

The practical significance of this study is determined by the applicability of the developed computational and diagnostic model for improving the efficiency, reliability and economic performance of maintenance processes for aircraft landing gear components under real operating conditions. Unlike conventional diagnostic approaches, which are primarily based on scheduled inspections and the detection of already developed defects, the proposed model enables a fundamentally different approach based on the quantitative assessment of structural condition and the prediction of damage evolution.

One of the key practical outcomes of the model is the ability to identify critical zones in advance based on calculated stress distribution, stress concentration effects and crack parameters. This makes it possible to focus diagnostic efforts on the most critical regions of the structure, thereby reducing unnecessary inspection operations. As a result, maintenance procedures become more targeted and efficient, leading to a reduction in labour intensity and inspection time.

The integration of fatigue life prediction into the model further enhances its practical value. By estimating the remaining useful life of structural elements, maintenance decisions can be made on a scientifically justified basis rather than relying on conservative assumptions or fixed service intervals. This enables a transition from time-based maintenance strategies to condition-based maintenance, where interventions are performed only when necessary. Such an approach ensures more efficient use of component resources and reduces the likelihood of both premature replacement and unexpected failure.

From an economic perspective, the implementation of the proposed model contributes to a reduction in operational costs. The optimisation of diagnostic procedures reduces inspection frequency, minimises downtime and decreases the need for unnecessary disassembly and testing operations. At the same time, improved accuracy in damage assessment reduces the risk of critical failures, which are associated with high repair costs and operational disruptions [5], [13].

Another important practical advantage is the possibility of implementing the model as part of a software-based diagnostic system. The algorithm can be integrated into modern aircraft maintenance management systems, where it performs automated analysis of input data and generates recommendations for diagnostic actions. This automation reduces the influence of human factors, improves consistency in decision-making and increases the overall efficiency of maintenance processes.

Furthermore, the developed model is fully compatible with modern digital technologies, including structural health monitoring systems and digital twin platforms. This allows continuous monitoring of structural condition and real-time updating of diagnostic decisions. The combination of computational modelling with real-time data processing provides a powerful tool for managing the technical condition of aircraft structures in dynamic operating environments.

The results of this study are also of practical importance for education and training in the field of aviation engineering. The model can be used as a basis for simulation systems, enabling students and engineers to analyse structural behaviour, assess damage levels and select appropriate diagnostic methods in a controlled environment. This contributes to improving the quality of professional training and the development of practical skills.

Thus, the practical significance of the proposed computational and diagnostic model lies in its ability to enhance diagnostic accuracy, optimise maintenance processes, reduce operational costs and improve the overall safety and reliability of aircraft operation. Its implementation provides a strong foundation for the development of advanced maintenance systems based on predictive analytics and intelligent decision-making.

3. Conclusion

This study addresses the important scientific and engineering problem of improving the effectiveness of diagnostic methods for aircraft landing gear components through the application of computational and analytical approaches. In the course of the research, an integrated computational and diagnostic model has been developed, combining stress–strain analysis, fracture mechanics and fatigue life prediction into a unified framework for evaluating structural condition.

Unlike conventional diagnostic methods, which are primarily focused on detecting already developed defects, the proposed approach enables a quantitative assessment of damage level and allows the influence of operational loads, geometric characteristics and material properties to be taken into account. This ensures a more accurate and physically justified evaluation of the structural condition, thereby improving the reliability of diagnostic decisions.

A key result of the study is the development of an adaptive algorithm for selecting diagnostic methods based on calculated structural parameters [11], [12]. The implementation of this algorithm enables a transition from traditional schedule-based diagnostics to a condition-oriented approach, where inspection methods are selected according to the actual state of the component. This significantly enhances diagnostic efficiency and reduces unnecessary inspection operations.

The results of computational modelling demonstrate that the evolution of damage in landing gear components follows a nonlinear pattern, with accelerated crack growth occurring as stress levels approach critical values. The proposed model allows the identification of potentially hazardous zones at early stages, which is not achievable using traditional inspection techniques. This confirms the effectiveness of integrating computational analysis with diagnostic procedures.

An additional advantage of the developed model is its ability to predict damage progression and estimate the remaining useful life of structural elements. This enables the implementation of predictive maintenance strategies, reducing operational risks and improving resource utilisation. The compatibility of the model with modern digital technologies, including structural health monitoring systems and digital twin platforms, further enhances its practical applicability.

From an engineering perspective, the application of the proposed model contributes to improving diagnostic accuracy, optimising maintenance processes, reducing operational costs and enhancing flight safety. The model provides a foundation for the development of intelligent diagnostic systems capable of real-time condition assessment and automated decision-making.

In summary, the developed computational and diagnostic approach represents a significant advancement in the field of aircraft structural diagnostics. Its implementation supports the transition to next-generation maintenance systems based on adaptability, data-driven analysis and predictive capabilities, thereby ensuring a higher level of reliability and safety in aircraft operation.

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Information about the author

Kutpinisa Kadirbekova	Tashkent State University of Transport, Doctor of Technical Sciences, Professor in the Department of Aviation Engineering. E-mail: niso_51@mail.ru Tel: +998903522340 https://orcid.org/0009-0009-0167-0907
Shakhnozakhon Ermukhamedova	Tashkent State University of Transport PhD candidate in the Department of Aviation Engineering E-mail: shaxnozaxonermuxamedova@gmail.com Tel: +998977743544 https://orcid.org/0009-0008-0503-3924

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