

Multi-source reliability evaluation method of aircraft mechanism performance considering wear-plasticity accumulative damage

Yao-Jia Han, Bai-Yang Zheng , Cheng-Wei Fei ^{*} 

Department of Aeronautics and Astronautics, Fudan University, Shanghai 200433, China

ARTICLE INFO

Keywords:

Aircraft mechanism
Coupled motion
Synergistic damage degradation
Multi-source uncertainty
Reliability analysis

ABSTRACT

The lifting mechanism of an aircraft cargo door is a critical component that ensures both cargo handling safety and flight reliability. Multi-source reliability evaluation method of aircraft cargo door lifting mechanism performance is proposed considering the synergistic effect of wear and plasticity accumulation. Firstly, the kinematic relationships of mechanism are derived based on the coupled mechanism of spatial drive and planar motion. Synergistic damage evolution model is then established by integrating contact wear theory with cyclic plasticity criteria, mapping equivalent geometric variations into key motion accuracy errors. Subsequently, the influence of multi-source uncertainties on mechanism reliability, which involve geometric parameters, material properties, operational loads and performance margins, was investigated. Finally, numerical simulation and reliability sensitivity analysis are conducted. From this study, it is demonstrated that after 100 000 cycles, the synergistic effect of wear and plasticity leads to greater performance degradation than single-factor effects, thereby validating the effectiveness of the proposed method. The efforts of this work provide a promising reliability assessment for aircraft cargo door lifting mechanism performance degradation, which is helpful for the theoretical support and guidance of the reliability design, manufacturing and maintenance of complex mechanism system.

1. Introduction

The cargo door lifting mechanism of an aircraft is a multi-component motion system connected by revolute pairs. It is necessary to maintain reliable operation during whole life cycle, and thus ensure both the normal operation of cargo and the structural integrity of aircraft. The failure of mechanisms directly impairs the standard opening and closing of cargo door, which will seriously threat flight safety. As illustrated from the statistic of aviation accidents, lifting mechanism failures have shown a rising trend recently [1]. In some historical cases, severe accidents, including catastrophic crashes, have been attributed to design flaws in cargo doors [2]. Due to the influence of multi-source information such as manufacturing errors, assembly deviations, service environments, operational loads, and so forth, the lifting mechanism is subject to significant uncertainties. With service time, cumulative wear and material plastic deformation progressively degrade the mechanism's motion accuracy and reliability, potentially leading to functional failure. Therefore, it is imperative to perform the comprehensive reliability analysis of aircraft cargo door lifting mechanism performance degradation induced by wear-plasticity accumulation in combination with multi-source uncertainties, to prevent failures and safeguard flight operations.

^{*} Corresponding author.

E-mail address: cwfei@fudan.edu.cn (C.-W. Fei).

In recent years, numerous researchers have systematically investigated various factors influencing the performance of mechanical systems. Li et al. [3] proposed a degradation-based reliability framework incorporating performance margins to quantify the failure risk of landing gear door locks under combined multi-source uncertainties and wear. Jiang et al. [4] developed a coupled wear-impact-creep model to reveal the effects of progressive damage and multi-factor interactions on performance degradation. Shu et al. [5] investigated friction-corrosion-induced sticking failure in marine environments, integrating simulation and experimental methods to enhance response surface modeling for improved reliability assessment efficiency. Wang et al. [6], Zhang et al. [7], and Gao et al. [8] further improved the accuracy and efficiency of reliability evaluation by optimizing response surface methods or extreme error models. Sun et al. [9] performed a failure mechanism analysis of door lock systems and established a functional reliability model for door unlocking, along with sensitivity analysis.

In multibody motion mechanisms, contact wear leads to a continuous increase in clearance at revolute joints over time, resulting in a decline in motion accuracy. Regarding the degradation mechanism, Jiang et al. [10] investigated the nonlinear response differences before and after wear in a six-link multibody model. Zhao et al. [11] derived an angular error expression for a multi-loop deployable mechanism and validated the error evolution through both numerical simulation and experimental testing. Bai et al. [12] developed dynamic equations incorporating multiple clearances, revealing the influence of inter-clearance coupling on system dynamic responses. Liang et al. [13] employed a Monte Carlo simulation to quantify the effects of irregular wear on reliability degradation and nonlinear dynamic characteristics. Xue et al. [14] and Ren et al. [15] used finite element modeling and experimental validation to demonstrate the competitive and co-dominant roles of fretting wear and fretting fatigue in failure mechanisms. Varedi et al. [16] applied a particle swarm optimization approach to reduce impact forces caused by clearances in slider-crank mechanisms.

Irreversible cyclic plastic deformation is another key mechanism contributing to the degradation of mechanism performance. Focusing on material-level constitutive modeling and parameter calibration, Basan et al. [17] characterized the rate-dependent isotropic hardening saturation range of Chaboche model for 42CrMo4 steel through loading experiments. Agius et al. [18] employed multi-objective genetic algorithm to optimize the Chaboche model parameters for 7075-T6 aluminum alloy and validated the sensitivity to fatigue life prediction. Subasic et al. [19] experimentally constructed multiple constitutive models for 316L stainless steel. Agius et al. [20] and Kourousis et al. [21] captured the mean stress relaxation behavior and cyclic hysteresis evolution of 7075-T6 and 7050-T7451 aerospace-grade aluminum alloys. Das et al. [22] proposed multi-objective cyclic plasticity model to capture the cyclic hardening/softening behavior of tubular materials under different strain amplitudes.

Mechanical systems are inevitably affected by various sources of uncertainty during manufacturing and service stages. Wei et al. [23] established an index system to evaluate the impact of input perturbations and their interactions on time-dependent reliability. Fei et al. [24] proposed a CNN-DNN-based approach for probabilistic modeling and prediction of low-cycle fatigue life in integrally bladed turbines under parameter uncertainty, demonstrating superior accuracy and efficiency. Su et al. [25] identified uncertain parameters within dynamic equations incorporating a Stribeck friction model and developed a multi-objective reliability optimization method. Zeng et al. [26] and Wang et al. [27] employed quasi-Monte Carlo simulation and a unified framework, respectively, to handle mixed uncertainties and improve motion reliability analysis methods. Fei et al. [28] integrated multiple algorithms to construct an Enhanced Network Learning Method (ENLM), significantly improving the precision and efficiency of motion reliability evaluation for flexible two-link manipulators under highly nonlinear and time-varying conditions. Jiang et al. [29] introduced Copula, Wiener process, and Vine-Copula techniques to realize degradation path fitting, residual life prediction, and key damage identification. Several investigations [30–32] have systematically addressed the interrelation between uncertainty and reliability, and many other studies have focused on reliability assessment methods [33–35].

In summary, current works still focus on single degradation mechanisms or idealized conditions, although substantial theoretical progress has been gained in the performance degradation and reliability of mechanical system. In this case, it is insufficient in unified modeling approaches for the synergistic degradation effects of multiple factors and system-level uncertainties. The challenges are illustrated as follows. (1) Kinematic modeling is only conducted by either purely planar or purely spatial mechanisms, and is not simulated and validated by spatially driven and planar-following mechanisms in engineering applications. (2) The reliability analysis of mechanism systems did not fully consider the stochastic characteristics of multi-source parameters at different degradation stages, thus it is difficult for the reliability results to accurately describe the performance degradation of mechanism systems under multi-factor coupling. (3) Most of existed reliability works only focus on theoretical evaluation, so that it is difficult to provide the strong support for the reliability design and maintenance planning of products.

To accurately evaluate the performance reliability of aircraft cargo door lifting mechanism, the multi-source reliability analysis method is discussed in respect of the synergistic degradation resulting of wear-plasticity accumulation. The coupling kinematic theory of space driven and planar followed movement is adopted to develop the precise kinematic model of driving mechanism by combining numerical and analytical approaches. And the established model is validated by multibody dynamic simulations and bench testing, to ensure the consistency between theoretical derivation and engineering application, and provide the theoretical foundation for modeling complex mechanisms. The uncertainty of parameters in manufacturing defects, material properties, operational loads and performance margins is introduced into the established synergistic kinematic model, to improve the adaptability and predictive capability of the model under variable real-world conditions. The unified framework of system reliability analysis is proposed with regard to the combined effects of wear and plasticity on mechanism performance, which is promising to precisely reflect the performance evolution law in service and provide the theoretical support for the performance degradation modeling and reliability assessment of complex mechanical systems.

The remainder of this paper is organized as follows. Section 2 introduces reliability theory and methods besides the multi-source reliability analysis framework of lifting mechanism regarding synergistic degradation. Section 3 presents and validate the kinematic model of coupled mechanism spatial driven and planar followed motion, by multibody dynamic simulation. Section 4 develops a

performance margin model in line with the combined effects of wear and plasticity accumulation. Section 5 analyzes multi-source uncertainty and quantifies the associated parameter distributions. Section 6 applies the proposed method to the reliability sensitivity analysis of one numerical case, i.e., aircraft cargo door lifting mechanism. Section 7 summarizes the main conclusions of this study.

2. Theory and methods

Reliability refers to the ability of a product to perform its intended function within a specified period and under given conditions [36]. The fundamental scientific principles of reliability involve performance margin equation $\mathbf{M}$, degradation equation $\mathbf{P}$ and reliability metric equation $\mathbf{R}$, which are expressed as:

$$\begin{cases} \mathbf{M} = G(\mathbf{P}, \mathbf{P}_{th}) > 0 \\ \mathbf{P} = F(\mathbf{X}, \mathbf{Y}, \mathbf{T}) \\ \mathbf{R} = \mu(\tilde{\mathbf{M}} > 0) \end{cases} \quad (1)$$

where $\mathbf{M}$ is the performance margin vector; $\mathbf{P}$ is the performance parameter vector; $\mathbf{P}_{th}$ is the corresponding threshold vector of the system; $\mathbf{X}$ denotes internal factors (e.g., geometric dimensions, material properties); $\mathbf{Y}$ represents external factors (e.g., operational stress); $\mathbf{T}$ is the time vector; and $\mathbf{R}$ denotes reliability. The performance margin $\tilde{\mathbf{M}}$ is a random vector with uncertainty, and μ is a mathematical measure. When $\mathbf{M} > 0$, the system operates normally and can perform the required functions. This reliability theory has been applied to the reliability assessment of aviation organizations [3,4].

Based on reliability theory, novel reliability analysis framework is developed based on performance margin, which incorporates the synergistic degradation effects of wear and plasticity accumulation, as well as multi-source uncertainties, as illustrated in Fig. 1.

As shown in Fig. 1, the process of the multi-source reliability analysis framework of lifting mechanism regarding synergistic degradation involves three steps. Firstly, the functional analysis of cargo door lifting mechanism is conducted to establish performance margin equation. Subsequently, a kinematic modeling approach is proposed for the lifting mechanism, based on the coupling between spatial driving and planar followed motion. The cumulative wear volume and cyclic plastic strain are then modeled separately, and the “equivalent linkage length” method is adopted to map degradation effects into performance margin domain, and thereby form a degradation–margin coupled model. Next, the four categories of multi-source uncertainty parameters are systematically analyzed and quantified, including manufacturing defects, material property variations, operational load fluctuations and threshold deviations. Finally, by integrating the degradation model with the stochastic parameters, a reliability analysis model is constructed by simultaneously considering the synergistic effects of wear–plasticity accumulation and multi-source uncertainties.

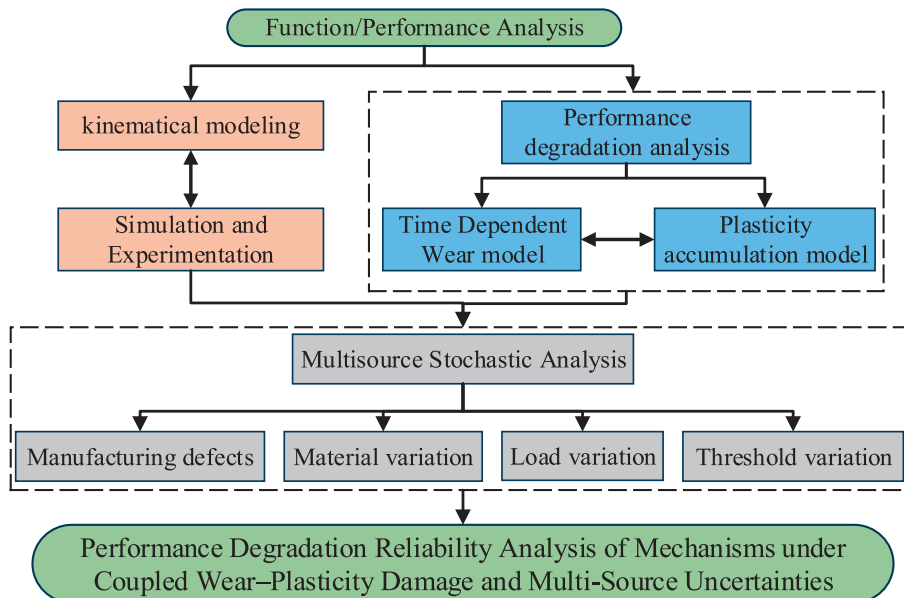


Fig. 1. Multi-source reliability analysis framework of lifting mechanism regarding synergistic degradation.

3. Kinematic analyses of cargo door lifting mechanism

3.1. Cargo door lifting mechanism

An aircraft cargo door lifting mechanism is selected as the subject of kinematic analysis. The mechanism mainly comprises four hinge points, one crank, one cargo door, one rocker arm and one drive shaft that rigidly connected to the rocker and oriented perpendicular to the plane of motion. The opening and closing motions define the two main operational stages of the mechanism, as shown in Fig. 2. During the opening phase, the motor activates and drives the shaft to rotate about its axis via a reduction gear. Because the shaft is rigidly connected to the rocker, its rotational angle is directly transferred to the rocker, which attempts to rotate by the same angle. However, the hinges are constrained by the crank and cargo door to follow circular arcs centered at their respective pivot points. As a result, the spatial rotation of the rocker is converted into planar rotation of the cargo door through closed-loop geometric constraints. When the drive shaft reaches a specified angle, the cargo door becomes fully open. In the closing phase, the motor reverses direction, causing the reduction gear to rotate the drive shaft accordingly. The rocker then rotates in the opposite direction, by transmitting motion through the same kinematic chain. The cargo door rotates back along its original path and fully closes when the drive shaft returns to its initial position.

The spatial–planar coupled mechanism effectively addresses the limitations of traditional planar linkages. By positioning the drive shaft perpendicular to the motion plane, the spatial interference between driving unit and cargo door structure is eliminated. In addition, the three-dimensional (3D) input from the drive shaft is accurately transformed into the planar motion of four-bar linkage through rigid connections at the hinge points. As a result, compact and efficient power transmission is achieved, to enable the kinematic coupling between 3D input and two-dimensional output.

3.2. Kinematic modeling and constraints

3.2.1. Coordinate system and position definition

The lifting mechanism is simplified as shown in Fig. 3, where the solid lines represent the fully closed position of the cargo door, and the dashed lines correspond to the fully opened position. Since the motion of the cargo door lifting mechanism ACDB is constrained within a single plane, a fixed Cartesian coordinate system $\{O, X, Y\}$ is established, with the fixed hinge point A defined as the origin O . The X-axis is aligned along the direction of link AB, and the Y-axis is defined to be perpendicular to the X-axis and pointing upward, following the right-hand rule. A local coordinate system $\{D, X, Y\}$ is defined at point D, where the origin is located at point D, the x-axis remains parallel to the global X-axis, and the y-axis remains parallel to the global Y-axis. This coordinate system translates with point D but does not rotate.

The minimal coordinate set $q = [\alpha, \beta, \varphi_D]$ is selected to describe the mechanism configuration, where counterclockwise rotation is defined as positive. The variable α denotes the rotation angle of crank AC relative to the X-axis, β represents the rotation angle of the cargo door BD relative to the X-axis, and φ_D is the angle of rocker CD measured in the local coordinate system $\{D, X, Y\}$. Since the local coordinate system does not rotate relative to the global coordinate system, φ_D also represents the angle of rocker CD in the global coordinate system.

In the global coordinate system, the position vectors of all hinge points are defined as

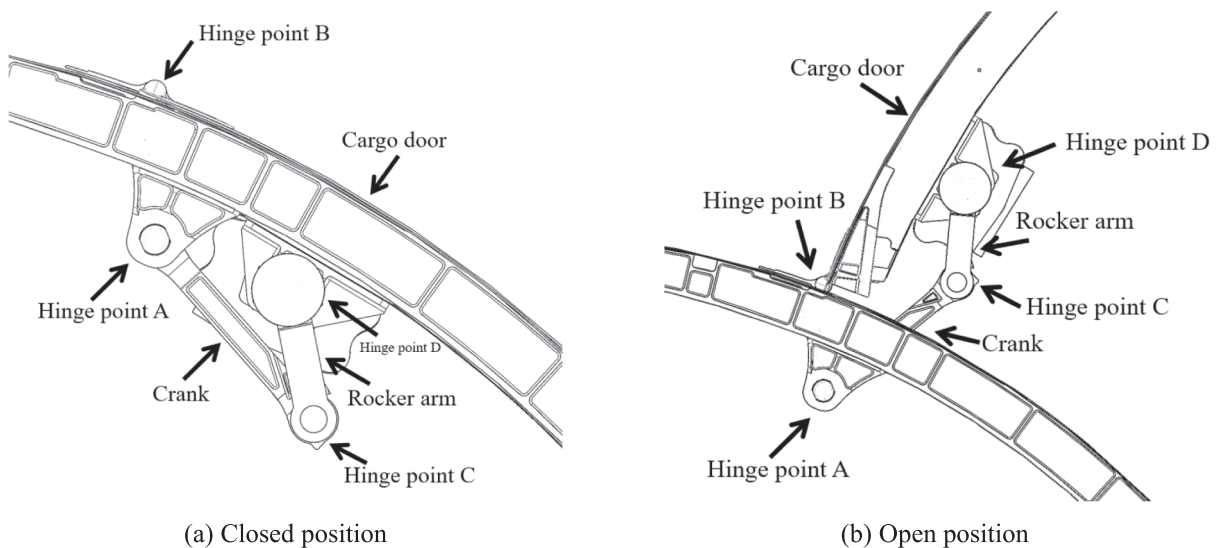


Fig. 2. Conceptual diagram of aircraft cargo door in closed and open positions.

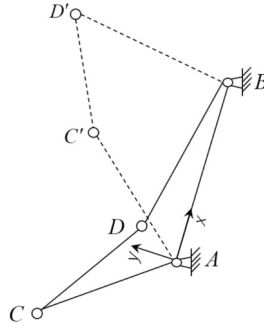


Fig. 3. Simplified diagram of aircraft cargo door lifting mechanism.

$$\vec{r} = [\vec{r}_A, \vec{r}_B, \vec{r}_C, \vec{r}_D] = \begin{bmatrix} 0 & L_{AB} & L_{AC}\cos\alpha & L_{AB} + L_{BD}\cos\beta \\ 0 & 0 & L_{AC}\sin\alpha & L_{BD}\sin\beta \end{bmatrix} \quad (2)$$

In the local coordinate system, the relative position of point C is given by

$$\vec{r}_{C \rightarrow D} = [L_{CD}\cos\varphi_D, L_{CD}\sin\varphi_D]^T \quad (3)$$

Its transformation into the global coordinate system is expressed as

$$\vec{r}_C = \vec{r}_D + \vec{r}_{C \rightarrow D} = \vec{r}_D + [L_{CD}\cos\varphi_D, L_{CD}\sin\varphi_D]^T \quad (4)$$

3.2.2. Formulation of constraint equations

The kinematic constraint equations consist of physical angle constraints and drive coupling constraints. For the physical angle constraint, point C must simultaneously lie on both crank AC and rocker CD. Subject to the two constraint conditions shown in Eqs. (2) and (4), therefore, the expressions of point C derived from the crank AC and rocker CD is

$$\begin{bmatrix} L_{AC}\cos\alpha \\ L_{AC}\sin\alpha \end{bmatrix} = \begin{bmatrix} L_{AB} + L_{BD}\cos\beta \\ L_{BD}\sin\beta \end{bmatrix} + \begin{bmatrix} L_{CD}\cos\varphi_D \\ L_{CD}\sin\varphi_D \end{bmatrix} \quad (5)$$

For the drive coupling constraint, the initial state of the lifting mechanism corresponds to the fully closed position of the cargo door. In this state, by the initial geometric relationship, the local coordinates of rocker CD are determined as

$$\varphi_D^{(0)} = \arctan(y_C^{(0)} - y_D^{(0)}, x_C^{(0)} - x_D^{(0)}) \quad (6)$$

Once the drive shaft begins to rotate, the angle of rocker CD in the global coordinate system is given by

$$\varphi_D = \beta + \varphi_D^{(0)} + \Delta\varphi_D \quad (7)$$

here φ_D represents the rotational input angle of the drive shaft DE.

By substituting Eq. (7) into Eq. (5), and projecting the resulting vector equation onto the X-axes and Y-axes, the scalar form of the constraint equations is

$$f_1(\alpha, \beta) = L_{AC}\cos\alpha - L_{AB} - L_{BD}\cos\beta - L_{CD}\cos(\beta + \varphi_D^{(0)} + \Delta\varphi_D) = 0 \quad (8)$$

$$f_2(\alpha, \beta) = L_{AC}\sin\alpha - L_{BD}\sin\beta - L_{CD}\sin(\beta + \varphi_D^{(0)} + \Delta\varphi_D) = 0 \quad (9)$$

Eqs. (8) and (9) together form a nonlinear equation system with two unknowns. Let $\theta \in [\alpha, \beta]^T$, then:

$$\mathbf{F}(\theta) = \begin{bmatrix} f_1(\alpha, \beta) \\ f_2(\alpha, \beta) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

3.2.3. Numerical solution

Given the nonlinear nature of the constraint Eq. (10), the Newton–Raphson iteration method [37] is employed to numerically solve the generalized coordinates $q = [\alpha, \beta]^T$ under a specified driving angle.

Let the solution at the k -th iteration be $\theta^k = [\alpha^k, \beta^k]^T$. At this point, the constraint equations are expanded using a Taylor series, retaining only the first-order terms:

$$\mathbf{F}(\theta^{(k+1)}) \approx \mathbf{F}(\theta^k) + \mathbf{J}(\theta^k)(\theta^{(k+1)} - \theta^k) \quad (11)$$

here J denotes Jacobian matrix which is defined as

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_\alpha} & \frac{\partial f_1}{\partial \theta_\beta} \\ \frac{\partial f_2}{\partial \theta_\alpha} & \frac{\partial f_2}{\partial \theta_\beta} \end{bmatrix} \quad (12)$$

The partial derivatives are computed as follows

$$J = \begin{bmatrix} -L_{AC}\sin\alpha & L_{BD}\sin\beta + L_{CD}\sin(\beta + \varphi_D^{(0)} + \Delta\varphi_D) \\ L_{AC}\cos\alpha & -L_{BD}\cos\beta - L_{CD}\cos(\beta + \varphi_D^{(0)} + \Delta\varphi_D) \end{bmatrix} \quad (13)$$

The Newton–Raphson iteration formula is given by

$$\theta^{(k+1)} = \theta^k - J^{-1}(\theta^k)F(\theta^k) \quad (14)$$

The iteration process continues until the convergence criterion is satisfied

$$\|\theta^{(k+1)} - \theta^k\| < \delta \quad (15)$$

in which δ denotes the predefined error tolerance, set as $\delta = 1 \times 10^{-8}$ in this study.

The numerical method provides the robust solution of kinematic equations while maintaining high accuracy. The solution strategy fully leverages the kinematic characteristics of mechanism, to enable the precise analysis of its motion behavior under specified driving inputs, which provides the theoretical foundation of the design and analysis of lifting mechanism.

3.3. Experimental and simulation validation

To validate the accuracy of the previously developed kinematic model and numerical solution, a kinematic experiment of the cargo door lifting mechanism was conducted. In addition, a dynamic model of the lifting mechanism was constructed on a multibody dynamic simulation platform for comparative analysis.

Test rig was constructed based on the geometric and structural parameters of the aircraft fuselage section. The initial closed and fully open positions of the cargo door are shown in Fig. 4. The drive shaft was actuated by a rotary motor to provide angular displacement input, while the rotational angle of the cargo door served as the output motion. These two key parameters were measured using absolute angular encoders with a resolution of 0.01° and a measurement accuracy of $\pm 0.02^\circ$. The installation locations and fixation methods of the angle sensors are illustrated in Fig. 5. The sensor for measuring the door rotation was mounted near the upper hinge, ensuring precise alignment of the measurement axis with the theoretical axis of rotation. To minimize random errors, each angular input was measured three times to calculate their mean value. The final test curves are obtained by removing the high-frequency noise.

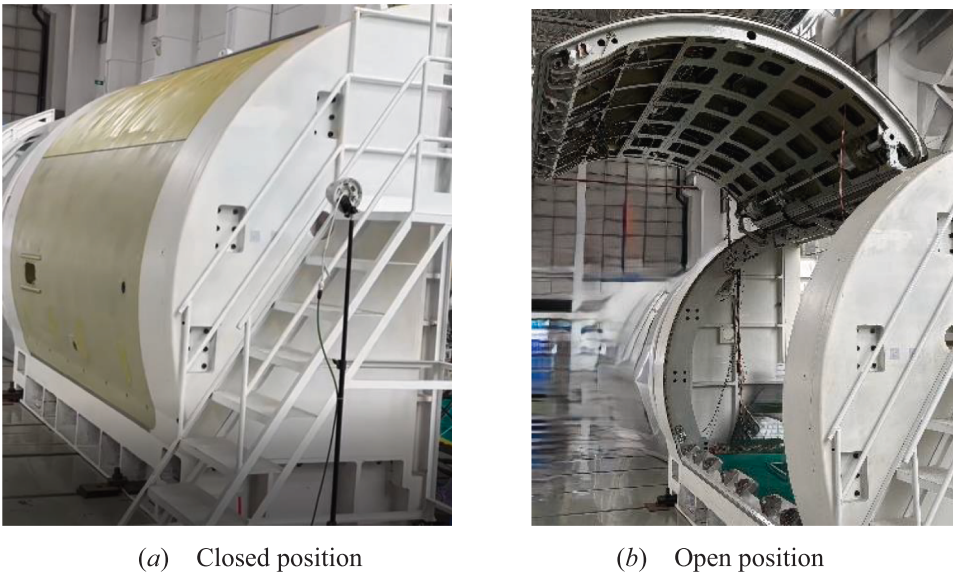


Fig. 4. Experimental setup of the cargo door.

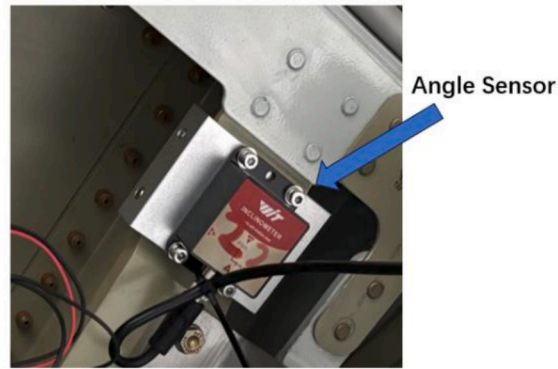


Fig. 5. Installation of the rotational angle sensor on the cargo door.

Fig. 6 compares the output angle curves obtained from the NR-based numerical analysis, multibody dynamic simulation and test bench experiment within the input range of $0 \leq \theta \leq 119^\circ$.

To quantitatively evaluate the consistency, the three methods are adopted to present the representative cargo door angle values as listed in Table 1.

In light of Fig. 6 and Table 1, obviously, the overall trends of output angle curves from the three methods are consistent, which validate the rationality and accuracy of multibody simulation, numerical analysis and experimental measurements. The root-mean-square (RMS) error between analytical and ADAMS results is 2.87° , and between analytical and experimental results is 3.42° , confirming the good quantitative agreement among the three methods. The theoretical solution, derived from ideal geometric assumptions and frictionless conditions, yields slightly higher output values. In contrast, the experimental data are lower due to frictional losses, manufacturing tolerances and measurement errors, which prevent the cargo door to achieve the ideal opening angle under real conditions. The multibody dynamic simulation, which incorporates friction at selected joints, produces intermediate results. The experimental curve exhibits response delay in the initial phase, mainly caused by nonlinear effects such as clearance elimination, static friction breakaway and inertia-induced lag. Once the system enters the steady-state driving phase, the agreement among the three methods improves significantly. Therefore, the proposed kinematic model not only ensures the sufficient engineering accuracy but also greatly enhances the computational efficiency. The validity of kinematic constraint equations, numerical solution algorithm and underlying physical assumptions are demonstrated, which provide a solid theoretical foundation for engineering applications of cargo door lifting mechanism.

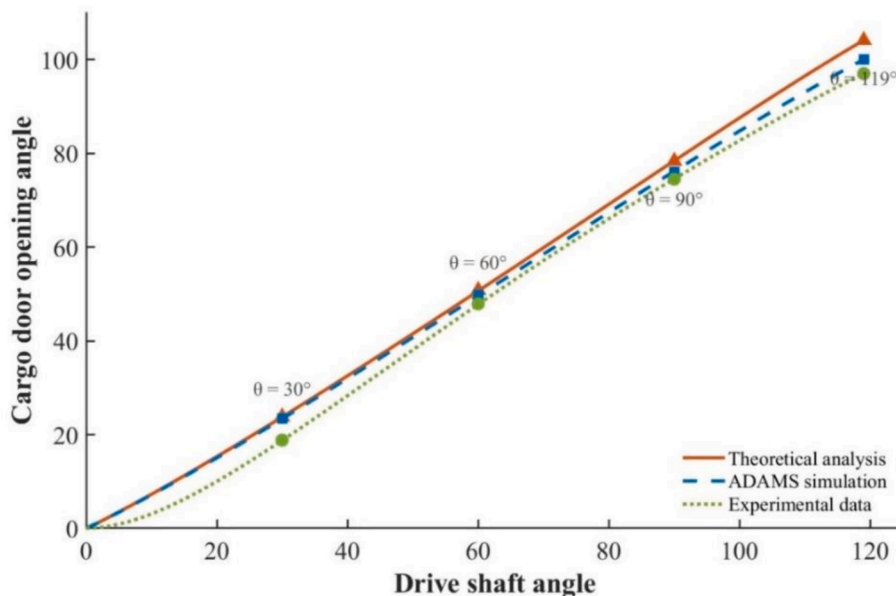


Fig. 6. Comparison of results obtained by three methods.

Table 1
Comparison of angle values obtained by the three methods.

θ (°)	ADAMS (°)	NR (°)	Experimental (°)
30	23.43	23.81	18.83
60	49.76	50.79	47.92
90	76.13	78.36	74.51
119	100.03	104.12	97.10

4. Performance margin degradation modeling

4.1. Time-Dependent wear modeling

The lifting mechanism of the cargo door is composed of revolute joints at the hinge positions. Relative rotation between the sleeves and shafts at the four hinge points (A, C, D, and B) during motion causes wear on the contact surfaces. As a result, the clearance between the sleeves and shafts increases with the number of operational cycles, which in turn affects the rotation angle of the cargo door (BD) and degrades the motion accuracy and reliability of the mechanism.

The wear between sleeve and shaft is commonly modeled using Archard model [3,4], which is widely employed to relate wear depth to applied load, as well as to the material and geometric properties of sliding components. Assuming uniform wear at the hinge joints, the Archard model is adopted to describe the time-dependent evolution of wear depth at each hinge point, i.e.,

$$h_i(t) = t \left(\frac{K_{1i}}{H_{1i}} + \frac{K_{2i}}{H_{2i}} \right) \sigma_{\max,i} S_i \quad (16)$$

where H_{1i} and H_{2i} are the Brinell hardness values; ν_{1i} and ν_{2i} are the Poisson's ratios; K_{1i} and K_{2i} wear coefficients.

According to Hertzian contact theory, the contact between the sleeve and the shaft can be modeled as the interaction between two coaxial cylindrical surfaces. The maximum contact stress $\sigma_{\max,i}$ is expressed by

$$\sigma_{\max,i} = 0.5642 \sqrt{\frac{2F_i}{\tau_i} \frac{D_i - d_i}{D_i d_i \left(\frac{1-\nu_{1i}^2}{E_{1i}} + \frac{1-\nu_{2i}^2}{E_{2i}} \right)}} \quad (17)$$

The relative sliding distance S_i between sleeve and shaft during one operating cycle is expressed as

$$S_i = d_i |\theta_i(\Delta\varphi_D) - \theta_i(0)|, \quad i = A, C, D, B \quad (18)$$

where $\theta_i(0)$ and $\theta_i(\Delta\varphi_D)$ denote the hinge angles at the start and end positions of the drive shaft.

The clearance $c_i(t)$ between sleeve and shaft at one hinge point increases with the accumulated wear $h_i(t)$, i.e.,

$$c_i(t) = c_{0i} + h_i(t) \quad (19)$$

To account for the influence of time-accumulated wear damage on the rotation of cargo door, an equivalent link model is employed, which can analyze the influence of joint clearance in motion mechanisms on motion performance.

The effective length L^e of the component can be described as:

$$L^e = \sqrt{(L^a + x)^2 + y^2} \quad (20)$$

where x and y are the coordinates of the random shaft center position in the local coordinate system. Due to the contact force between the sleeve and the shaft, x and y satisfy the following condition:

$$x^2 + y^2 = c_i(t)^2 \quad (21)$$

where $c_i(t)$ is the joint clearance, which can be determined from Eq. (19).

4.2. Analysis of cyclic plasticity accumulation

During the cargo door opening process, the crank AC and rocker CD, which function as the primary load-bearing components of the lifting mechanism, are subjected to predominantly compressive cyclic loading caused by the gravitational force of the door. This loading induces gradually accumulated plastic deformation, with each cycle producing a slight but irreversible plastic compression. Although the residual strain per cycle is minimal, the cumulative effect over hundreds of thousands of cycles can become significant. As a result, the linkages undergo effective axial shortening, ultimately reducing the motion accuracy of the mechanism.

The evolution of the material yield surface under classical hardening models includes isotropic hardening, kinematic hardening, and their combination. To quantitatively evaluate the influence of cyclic plasticity accumulation on the effective shortening of the linkage and to estimate the residual plastic compression generated during each loading cycle, this section adopts the Chaboche mixed

hardening model [17,18], which integrates both isotropic and kinematic hardening behaviors. This model enables a more comprehensive representation of material plasticity under cyclic loading.

This model is one of the commonly used material models for describing cyclic plasticity behavior at the microscale. It is formulated under the assumption of isothermal conditions and is developed within the framework of small-strain theory for material behavior. Considering that the yield function incorporates both kinematic and isotropic hardening, the von Mises yield surface can be appropriately expressed in the deviatoric stress space when the plastic yielding criterion is satisfied:

$$f = \sqrt{\frac{3}{2}(S - X) : (S - X) - \sigma_0 - R} = 0 \quad (22)$$

where S is the deviatoric stress tensor; X is the back stress tensor defining the center of the yield surface; R is the isotropic hardening variable; σ_0 is the initial yield strength.

The plastic flow follows the associated flow rule:

$$d\epsilon^p = d\lambda \frac{\partial f}{\partial \sigma} \quad (23)$$

where $d\lambda$ is the plastic multiplier determined from the consistency condition $df = 0$. The standard Karush–Kuhn–Tucker (KKT) conditions are satisfied, i.e.

$$d\lambda \geq 0, \quad f \leq 0, \quad d\lambda f = 0 \quad (24)$$

The kinematic hardening behavior of materials is described by decomposing X into three components $\{X_i\}(i = 1, 2, 3)$. The back stress tensor is expressed as the superposition of three individual components, i.e.,

$$X = \sum_{i=1}^3 X_i \quad (25)$$

The stress evolution law is

$$dX_i = \begin{cases} \frac{2}{3}a_i\gamma_i d\epsilon^p - \gamma_i X_i dp & i = 1, 2 \\ a_3 d\epsilon^p & i = 3 \end{cases} \quad (26)$$

where a_i and γ_i are the back stress modulus and the back stress evolution parameter.

The isotropic hardening behavior of materials is described by the following evolution law:

$$dR = b(R_\infty - R)dp \quad (27)$$

where R_∞ is the saturation value of isotropic hardening; b is the hardening rate parameter. This formulation accounts for both the asymptotic limit and the evolution rate of isotropic hardening, effectively capturing the non-uniformity of isotropic hardening behavior during cyclic loading.

The equivalent plastic strain increment is given by:

$$dp = \sqrt{\frac{2}{3} d\epsilon^p : d\epsilon^p} = d\lambda \quad (28)$$

This definition allows the evolution equations in Eqs. (27) and (28) to depend solely on the scalar dp , which facilitates numerical integration.

For N loading cycles, the accumulated plastic strain is given by:

$$\epsilon_r(N) = \sum_{i=1}^N \int_i d\epsilon^p \quad (29)$$

The deformation of the crank AC and the rocker CD caused by plastic strain accumulation is given by:

$$\Delta L_p(N) = \epsilon_r(N)L_0 \quad (30)$$

By numerically integrating the above expression over loading cycles, the plastic accumulation-induced deformation of the crank AC and rocker CD can be obtained. This results in irreversible axial deformation of the linkages, with the accumulation rate depending on the stress level, cyclic loading characteristics, and material parameters. Unlike linearly accumulating wear, the ratcheting strain predicted by the Chaboche three-component back stress model exhibits saturation behavior. The corresponding uniaxial material responses have been experimentally validated [17,18], providing a theoretical foundation for evaluating the long-term performance degradation of the mechanism.

4.3. Performance margin modeling considering degradation

During the cyclic operation of the cargo door lifting mechanism, sliding friction at hinge locations causes surface wear on the components. At the same time, plastic deformation under high loads introduces irreversible geometric deviations in the primary load-bearing members. Together, these effects result in cumulative errors in the mechanism's output motion. The degradation at each part of the mechanism over repeated cycles can be quantified using the wear model and cyclic plasticity accumulation model. By applying the kinematic relationships of the mechanism, variations in linkage lengths and angular deviations can be propagated to the output motion. Considering the coupled effects of wear degradation and plasticity accumulation, the effective lengths of all linkages in the lifting mechanism can be determined. By replacing the nominal link lengths with these effective lengths and substituting them into Eqs. (8) and (9), a modified kinematic model of the lifting mechanism can be derived as:

$$f_1(\alpha, \beta) = L_{AC}^e \cos \alpha - L_{AB}^e - L_{BD}^e \cos \beta - L_{CD}^e \cos(\beta + \varphi_D^{(0)} + \Delta \varphi_D) = 0 \quad (31)$$

$$f_2(\alpha, \beta) = L_{AC}^e \sin \alpha - L_{BD}^e \sin \beta - L_{CD}^e \sin(\beta + \varphi_D^{(0)} + \Delta \varphi_D) = 0 \quad (32)$$

In practical applications, the cargo door reaches its fully open position when the drive shaft rotates to its maximum angle. At this point, the door opening angle error δ is of particular concern. Taking into account the time-dependent variations caused by wear loss and cyclic plastic deformation, the error can be expressed as:

$$\delta(t) = |\beta(\Delta \varphi_D) - \beta^e(\Delta \varphi_D, t)| \quad (33)$$

Assuming that the allowable limit error for $\delta(t)$ is ε , the performance margin model considering degradation can be expressed in terms of the relative angle as:

$$M(t) = \frac{\varepsilon - \delta(t)}{\varepsilon} \quad (34)$$

Eq. (34) ensures that the cargo door lifting mechanism operates normally and reliably when $M(t) > 0$.

5. Analysis and quantification of multi-Source uncertainties

Mechanical systems are generally subjected to various uncertainties during entire life cycle, which may compromise the fulfillment of their intended design functions. For the aircraft cargo door lifting mechanism, the significant sources of randomness can be categorized into four types: manufacturing and machining errors, variations in material properties, fluctuations in operational loads, and uncertainties in performance thresholds. Manufacturing and machining errors affect the initial configuration of the mechanism, while variations in material properties and operating loads influence the degradation behavior of damage-related factors. In this section, each source of uncertainty is analyzed in terms of its characteristics, and corresponding probabilistic distributions are assigned to quantify the uncertainties.

For the quantification of parameter uncertainties, different types of probabilistic distributions are selected based on the availability of prior information and data. For well-studied parameters, such as manufacturing errors, assembly deviations, and material properties, established statistical models from published literature can be directly adopted. For parameters with available experimental or simulation-based measurements, appropriate probabilistic distributions can be fitted to the data. For parameters that are not well-studied and lack sufficient data, the probability distribution types can be assumed based on prior knowledge and expert judgment.

5.1. Manufacturing and machining errors

In the manufacturing, machining, and assembly processes of the aircraft cargo door lifting mechanism, dimensional variations are introduced due to inherent limitations, including machining accuracy, assembly precision, and geometric deviations. These variations originate from factors such as machine tool geometric errors, tool wear, thermal deformation, and measurement resolution. Generally, the dimensional parameters of components can be modeled as random variables following a normal probability distribution [38,39]. For the cargo door lifting mechanism, the dimensional parameters including sleeve diameter D_i , shaft diameter d_i , link length L_i and angular offset θ are all assumed to follow normal distributions.

To control such dimensional errors, a standardized tolerance system known as the International Tolerance (IT) grade is typically implemented. This system provides a unified method for evaluating and controlling dimensional deviations. In each hinge joint, an appropriate clearance fit between the shaft and the sleeve must be ensured to allow free rotational motion. In the basic hole system, the tolerances of sleeve diameter D_i and shaft diameter d_i is defined as

$$\begin{cases} T_{D_i} = ES_i - EI_i \\ T_{d_i} = es_i - ei_i \end{cases} \quad (35)$$

Since manufacturing tolerances represent the allowable limits of dimensional deviations, the means of sleeve diameter D_i and shaft diameter d_i can be derived as

$$\begin{cases} \mu_{D_i} = \frac{T_{D_i}}{2} \\ \mu_{d_i} = es_i - \frac{T_{d_i}}{2} \end{cases} \quad (36)$$

According to the 6σ limit in mechanical design standards, the standard deviations σ_D and σ_d of sleeve diameter D_i and shaft diameter d_i can be calculated as

$$\begin{cases} \sigma_{D_i} = \frac{1}{6}T_{D_i} \\ \sigma_{d_i} = \frac{1}{6}T_{d_i} \end{cases} \quad (37)$$

Similarly, the length error of link is controlled according to the IT grade. The length tolerance of link is

$$T_{L_j} = ES_j - EI_j \quad (38)$$

Generally, it is assumed that the tolerance zone of link length is symmetrically distributed around the zero line with $\mu_i = 0$. According to the 6σ criterion, the standard deviations σ_L and σ_θ for link length and angular dimension are calculated by

$$\begin{cases} \sigma_{L_j} = \frac{1}{6}T_{L_j} \\ \sigma_{\theta_i} = \frac{1}{6}T_{\theta_i} \end{cases} \quad (39)$$

5.2. Variations in material properties

In the entire material processing chain, inherent variations in material properties arise from multiple sources. Differences in microstructure introduced by processes such as smelting, heat treatment, and machining lead to fluctuations in elastic modulus, hardness, and hardening parameters. Material property parameters can be treated as random variables that follow normal distributions [1,2]. Various materials are used in different components of the cargo door lifting mechanism. For the wear analysis of hinges, two materials are considered: 40CrA steel and QA19-2 leaded bronze. The material parameters include the elastic moduli E_{1i} and E_{2i} , Brinell hardness values H_{1i} and H_{2i} , Poisson's ratios ν_{1i} and ν_{2i} , and wear coefficients K_{1i} and K_{2i} of the sleeve and shaft in the hinge joints. For the cumulative cyclic plasticity analysis of the linkages, material parameters directly affect the accumulation rate of plastic deformation and wear. Two materials are used: 7075-T6 aluminum alloy and 42CrMo4 steel (546 HV). Relevant material parameters include the elastic modulus E , initial yield stress σ_0 , saturation values of the back stress components a_1, a_2, a_3 , hardening rates of the back stress γ_1, γ_2 , isotropic hardening saturation value R_∞ , and isotropic hardening rate parameter b . All of these parameters are assumed to follow normal distributions.

5.3. Variations in operational loads

In practical applications, the operation of an aircraft cargo door lifting mechanism represents a typical dynamic process, in which parameters such as operational loads and working conditions vary randomly over time. During the door-opening phase, the rotation of the drive shaft influences the internal force transmission within the lifting mechanism and causes variations in the contact forces at the hinge joints. These variations, in turn, affect the wear behavior between the sleeves and shafts, resulting in fluctuations in the cargo door's output rotation angle. Based on dynamic simulation data, the contact forces F_i at each hinge point are found to follow normal distributions.

5.4. Uncertainty in performance thresholds

The uncertainty of performance thresholds typically arises from the imprecise identification of functional boundaries within the system. In practice, the allowable angular deviation for the cargo door in the fully open position is often not a fixed deterministic value. Therefore, uncertainty is embedded in ϵ , which is treated as a random variable assumed to follow a normal distribution.

Table 2

Nominal parameters of each component in the mechanism.

Parameters	Nominal values	Parameters	Nominal values	Parameters	Nominal values
$L_{0,AC}$	310(mm)	$L_{0,CD}$	170(mm)	$L_{0,BD}$	300(mm)
$L_{0,AB}$	180(mm)	$\theta_{AC,0}$	1.05(rad)	$\theta_{BD,0}$	2.53(rad)
$d_{0,A}$	30(mm)	$d_{0,B}$	12(mm)	$d_{0,C}$	38(mm)
$d_{0,D}$	40(mm)	τ_A	18(mm)	τ_B	120(mm)
τ_C	48(mm)	τ_D	25(mm)	A_{AC}	706.8(mm ²)
A_{CD}	1661.9(mm ²)	—	—	—	—

6. Numerical simulations

6.1. Parameter configuration

All nominal dimensional parameters of the aircraft cargo door lifting mechanism were obtained from actual digital model measurements. The accuracy of these parameters has been validated by comparing the kinematic simulation results with experimental measurements, ensuring engineering fidelity of the numerical case study. The nominal values of all dimensions are listed in Table 2. The manufacturing tolerance for the linkages is classified as IT8, and the engineering fit between shafts and holes at all hinge joints follows the H8/f8 specification. The parameters of the standard distributions were calculated based on the tolerances and engineering fits using the corresponding formulations.

The material property parameters were determined based on the actual material specifications used in the mechanism. The crank AC, located at the linkage section, is made of aluminum alloy (7075-T6), while the rocker CD is fabricated from high-strength steel (42CrMo4–546HV). All sleeves are made of leaded bronze (QA19-2), and all shafts are composed of alloy steel (40CrA). The mean values of the normally distributed material properties listed in Tables 3 and 4 were directly obtained from material data, with a coefficient of variation set at 0.1.

The contact forces at the hinge joints are assumed to independently follow normal distributions. The mean values are derived from multibody dynamic simulation results, reflecting the load distribution characteristics of mechanism during actual operation. A coefficient of variation of 0.1 is applied. The detailed settings of hinge joint contact forces are summarized in Table 5.

The allowable angular deviation of the cargo door in the fully open position is assumed to follow a normal distribution, denoted as $\varepsilon \sim N(0.035, 0.0026^2)$ rad.

6.2. Reliability analysis based on performance margin

The reliability of the cargo door lifting mechanism is evaluated using the Monte Carlo method, with the core metric based on performance margin. Random samples of system parameters are generated according to their probability distributions. For each sample, the ideal output angle of the mechanism is calculated using the established kinematic model. Subsequently, the degraded output angle is determined by applying the wear and plasticity accumulation models. The angular error and performance margin are then computed. Finally, the system reliability is obtained by calculating the proportion of samples with a positive performance margin, as illustrated in Fig. 7, where N_{MC} denotes the total number of Monte Carlo samples used for reliability estimation.

Fig. 8 presents the reliability degradation curves under three different degradation mechanisms: coupled progressive damage (wear and plasticity accumulation), wear-only degradation, and plasticity-only degradation. The Monte Carlo simulation was performed with a sample size of $N_{MC} = 1 \times 10^5$ to ensure stable reliability estimation.

As shown in Fig. 8, during the early stage of operation (when the number of operating cycles is less than 50,000), the reliability under all three degradation scenarios remains at a high level (greater than 0.95). However, as the number of cycles continues to increase, the impact of different degradation mechanisms on reliability becomes increasingly pronounced. When only plasticity accumulation is considered, reliability exhibits a relatively slow linear decline and eventually approaches a saturation plateau. This is attributed to the strain-hardening effect of the material during plastic deformation. In the case of wear-only degradation, a moderate rate of reliability decay is observed. When the coupled effects of wear and plasticity accumulation are considered, the reliability degrades most rapidly, falling significantly below both single-mechanism curves after 100,000 operating cycles. This observation confirms the existence of a strong synergistic acceleration effect between wear and plastic deformation, which results in a compounded adverse impact on system reliability. These findings provide a theoretical basis for the reliability-oriented design and maintenance strategies of cargo door lifting mechanisms, underscoring the necessity of accounting for synergistic degradation mechanisms in practical engineering applications.

In this section, the evolution characteristics of the cargo door opening angle error under different numbers of operating cycles are analyzed using a probability density function (PDF) fitting method. The Monte Carlo sampling technique is employed to estimate the probability density distributions of the opening angle error at various operational stages. The results are illustrated in Fig. 9.

As shown in Fig. 9, the distribution of cargo door opening angle error exhibits several notable trends as the number of operation cycles increases. First, the mean of the error distribution rises steadily from an initial value of approximately 10 mrad. Once the operation cycle count exceeds 80,000, the rate of increase accelerates, and by 150,000 cycles, the mean surpasses the performance threshold of 35 mrad. Second, the variance of the error distribution expands with the number of cycles, indicating increased response uncertainty and a broader range of variation. Third, the peak value of the probability density function decreases progressively, reflecting reduced data concentration. Fourth, the probability of the error falling into the failure domain increases gradually. When the

Table 3
Distribution of material properties related to wear.

Parameters	Distributions	Parameters	Distributions
E_{1i}	$N(120, 12^2)$ (GPa)	ν_{1i}	$N(0.37, 0.037^2)$
E_{2i}	$N(210, 21^2)$ (GPa)	ν_{2i}	$N(0.29, 0.029^2)$
H_{1i}	$N(85, 8.5^2)$ (HB)	K_{1i}	$N(4.07 \times 10^{-3}, (4.07 \times 10^{-4})^2)$ (mm ³ /(N·m))
H_{2i}	$N(174, 17.4^2)$ (GPa)	K_{2i}	$N(2.1 \times 10^{-2}, (4.07 \times 10^{-3})^2)$ (mm ³ /(N·m))

Table 4

Distribution of material properties related to plasticity.

Parameters	Distributions	Parameters	Distributions	Parameters	Distributions
E_{AC}	$N(69,6.9^2)(\text{GPa})$	$\sigma_{0,AC}$	$N(465,46.5^2)(\text{MPa})$	$a_{1,AC}$	$N(41,4.1^2)(\text{MPa})$
$a_{2,AC}$	$N(71,7.1^2)(\text{MPa})$	$a_{3,AC}$	$N(2100,210^2)(\text{MPa})$	$\gamma_{1,AC}$	$N(35.304,3.53^2)$
$\gamma_{2,AC}$	$N(242,24.2^2)$	$R_{\infty,AC}$	$N(15,1.5^2)(\text{MPa})$	b_{AC}	$N(6.8,0.68^2)$
E_{CD}	$N(197,19.7^2)(\text{GPa})$	$\sigma_{0,CD}$	$N(1070,107^2)(\text{MPa})$	$a_{1,CD}$	$N(105,10.5^2)(\text{MPa})$
$a_{2,CD}$	$N(225,22.5^2)(\text{MPa})$	$a_{3,CD}$	$N(464,46.4^2)(\text{MPa})$	$\gamma_{1,CD}$	$N(122,12.2^2)$
$\gamma_{2,CD}$	$N(574,57.4^2)$	$R_{\infty,CD}$	$N(-420,42^2)(\text{MPa})$	b_{CD}	$N(7,0.7^2)$

Table 5

Distribution of operational load parameters.

Parameters	Distributions	Parameters	Distributions
F_A	$N(16780,1678^2)(\text{N})$	F_B	$N(30620,3062^2)(\text{N})$
F_C	$N(16750,1675^2)(\text{N})$	F_D	$N(20100,2010^2)(\text{N})$

operation cycles are below 80,000, virtually no samples fall into the failure region, implying high system reliability. In contrast, at 300,000 cycles, a substantial portion of the distribution enters the failure domain, resulting in a clear decline in reliability. These observations suggest that under the combined influence of multiple stochastic factors and progressive damage mechanisms, the stability of the cargo door lifting mechanism degrades over time. Compared with decoupled analysis methods, the system demonstrates a continuously deteriorating reliability trend when subjected to coupled effects.

Fig. 10 illustrates the influence of different progressive damage mechanisms on system performance evolution, and the computational results quantify the impact of each damage type on the functional integrity of the mechanism.

Fig. 10 shows apparent differences in the wear progression of the hinge joints. Wear at hinge A is the most severe, increasing rapidly and nearly linearly. Hinge B shows a moderate level of wear, followed by hinge D, while hinge C exhibits the least wear accumulation. The overall order of wear severity is $A > B > D > C$. The observed differences can be attributed to multiple interacting factors, including load distribution, material characteristics, structural configuration, and assembly accuracy. Despite varying degrees of wear, all hinge joints exhibit a similar pattern of progression. Under steady operational conditions, this behavior indicates that the rate of wear across joints tends to follow a stable and foreseeable path.

The accumulation of cyclic plastic strain typically follows a saturation pattern. At the onset of loading, the strain increases rapidly, but with continued cyclic application, the accumulation rate diminishes progressively until it stabilizes into a steady-state response. This characteristic behavior arises from the nonlinear development of both the back stress tensor and the isotropic hardening variable, which together govern the material's gradual adaptation to repeated plastic deformation. The process reflects an intrinsic material tendency toward saturation under sustained cyclic loading. This phenomenon indicates that under long-term service conditions, irreversible plastic deformation induced by sustained loading may become a critical driving factor for system reliability degradation.

The interplay among multiple progressive damage mechanisms governs the staged evolution of key reliability indicators over time. In the early phase of operation, when load cycles are still low, the system exhibits stable performance. Once the number of cycles exceeds a critical threshold, performance metrics begin to change nonlinearly and gradually approach saturation, marking the onset of the degradation phase. This evolution suggests that although the impact of individual damage modes may be limited initially, their combined effects intensify with time and accelerate performance deterioration. This process reveals the inherent lag and abrupt transition features that characterize reliability degradation in complex systems.

6.3. Reliability sensitivity analysis

In this section, the reliability $R(30,000)$ of the aircraft cargo door lifting mechanism was evaluated, and a one-at-a-time (OAT) sensitivity analysis was conducted, treating the distribution parameters as independent variables to compare and rank parameter importance.

6.3.1. Reliability sensitivity analysis of manufacturing-related parameters

To understand how dimensional accuracy impacts system-level reliability, a sensitivity study is conducted that centers on the tolerances and fit specifications of several structurally important components. This evaluation focuses on the main load-transmitting elements within the drive assembly, namely the rods, bushings, shafts, and hinge connections, where small deviations in geometry can propagate and influence the mechanism's long-term functional behavior. Standard tolerance grades (IT7, IT8, and IT9) are considered for links, sleeves, and shafts, while typical engineering fits (H7/g7, H8/g8, and H9/g9) are applied to hinge joints. The impact of various manufacturing parameters on the reliability index $R(30,000)$ after 30,000 operation cycles is illustrated in Fig. 11.

Fig. 11 demonstrates that system reliability is strongly influenced by manufacturing precision, with evident variability across structural components. Among the rods, CD shows the most incredible sensitivity to changes in tolerance levels, where a drop in dimensional accuracy leads to an apparent reduction in reliability. For the sleeves, Sleeve B maintains relatively stable reliability across tolerance grades, while Sleeves A and D display greater susceptibility to manufacturing variations. In the shaft group, Shaft D

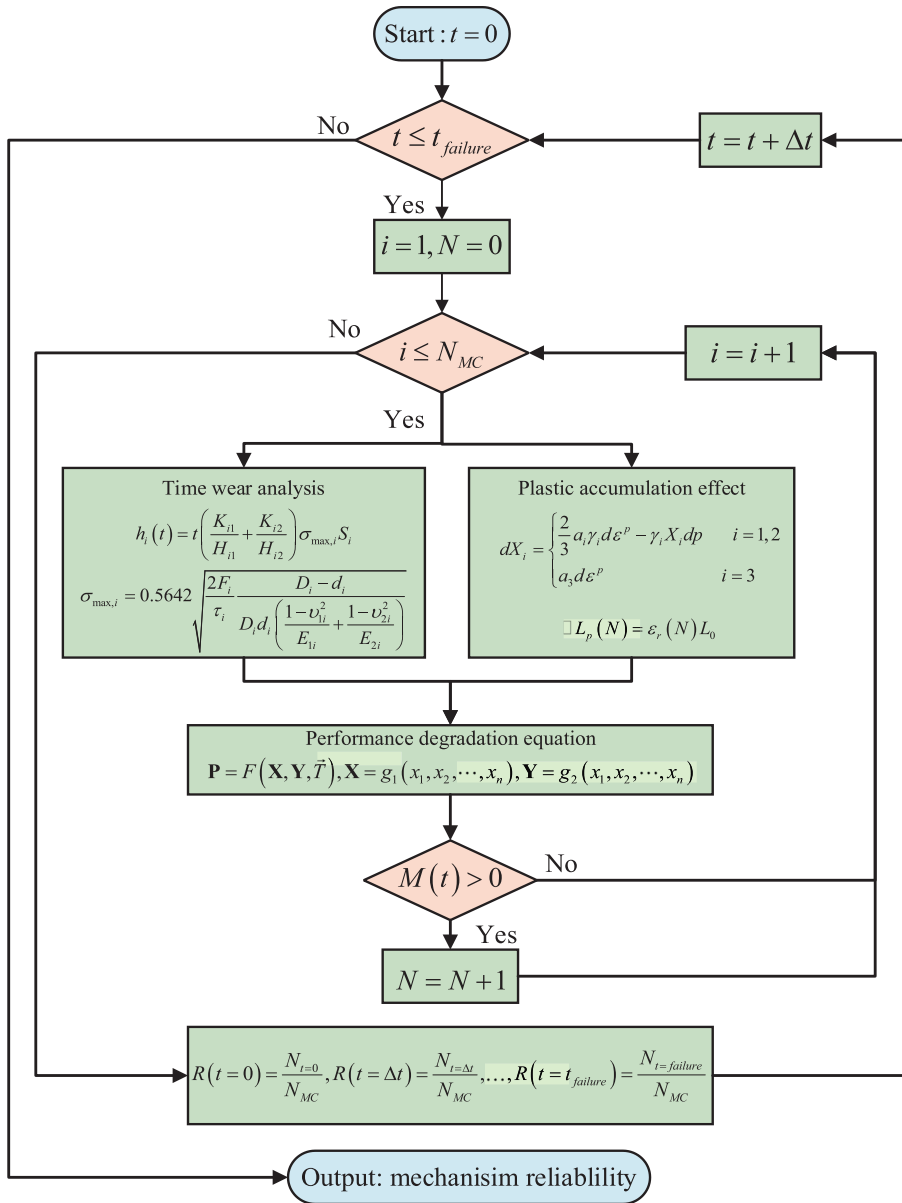


Fig. 12. Reliability evaluation flowchart based on the Monte Carlo method.

exhibits a pronounced sensitivity to precision changes, implying its location along a primary load-bearing path. Regarding hinge joints, the analysis indicates that Hinges B and C are particularly affected by fit deviations.

Differences in reliability sensitivity primarily reflect the distinct structural roles and force-transmitting responsibilities of each component within the mechanism. Components that participate directly in motion or bear major loads tend to exhibit stronger sensitivity because even small geometric deviations in these parts are more likely to propagate through the system, leading to a measurable decline in reliability. Given these findings, it is technically sound to apply stricter dimensional control to critical parts such as Rod CD, Shaft D, and Hinges B and C during the design and manufacturing stages, for components whose sensitivity is relatively low, moderately wider tolerances may be allowed, enabling a more efficient trade-off between production cost and overall system performance.

6.3.2. Reliability sensitivity analysis of material-related parameters

This section investigates how uncertainty in material properties affects the reliability of the system. The focus is placed on the role of material characteristics at each hinge joint, especially regarding wear behavior. Four parameters are considered for both the sleeve and the shaft: elastic modulus, Brinell hardness, Poisson's ratio, and wear coefficient. Sensitivity analysis is conducted from two

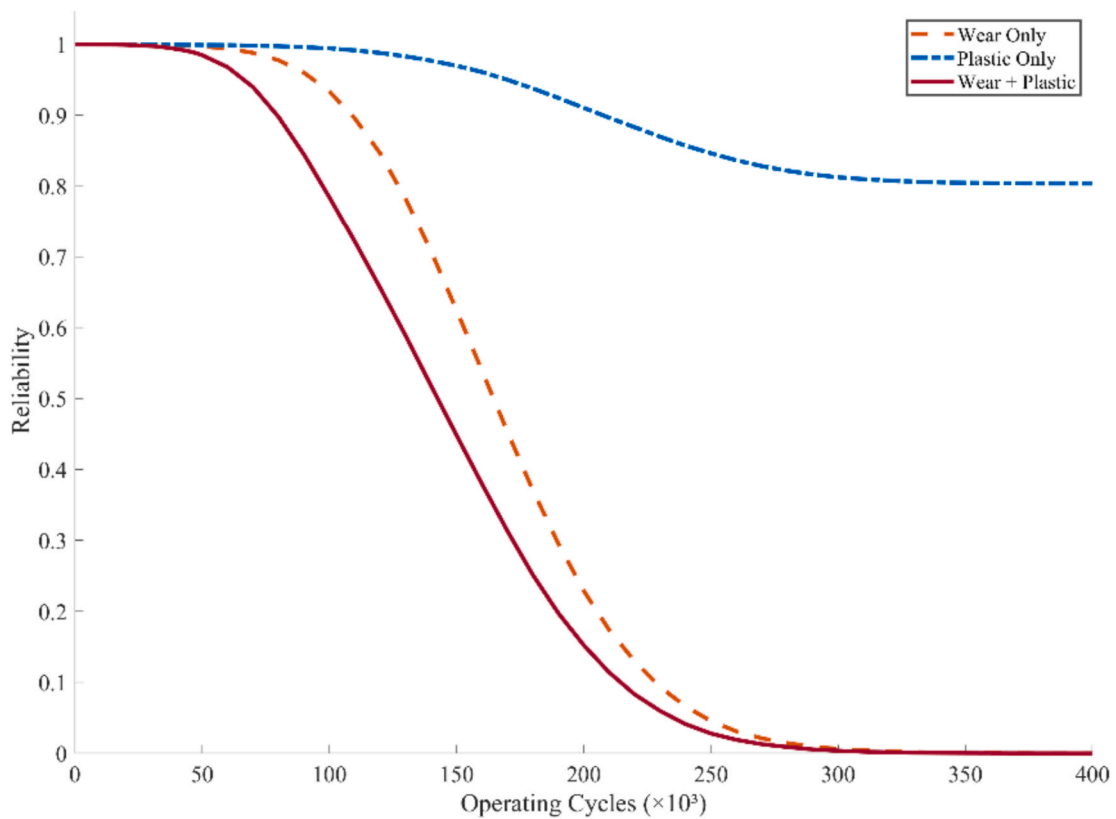


Fig. 13. Reliability of the aircraft cargo door lifting mechanism.

perspectives: the mean values and the coefficients of variation.

The influence of variations in the mean values of different material properties on system reliability is first evaluated. Each material parameter is individually set to 0.8 times and 1.2 times from its nominal value, while all other parameters are held constant. The resulting trends in key performance metrics are analyzed, as illustrated in Fig. 12.

As shown in Fig. 12, the reliability of the sleeve material exhibits a clearly differentiated response to various parameters. The elastic modulus has the most significant impact on reliability, followed by Brinell hardness, indicating that both the deformation resistance and surface strength of the sleeve collectively determine the rate of wear progression. Accordingly, the sensitivity of reliability to the mean values of sleeve material properties can be ranked as follows: elastic modulus, Brinell hardness, Poisson's ratio, and wear coefficient. In comparison, the reliability of the shaft material shows relatively higher sensitivity to Brinell hardness and elastic modulus, while the effects of Poisson's ratio and wear coefficient are less pronounced. This indicates that the dominant wear mechanisms for the shaft material differ from those of the sleeve during the contact wear process.

To further evaluate the impact of material property variability on system reliability, the coefficients of variation for each material parameter were increased to 1.5 and 2 times their original values while keeping the mean values constant. The analysis results are presented in Fig. 13.

The results in Fig. 13 indicate that the variability of material parameters has a significant impact on system reliability. The sleeve material exhibits a moderate sensitivity to the variability of all parameters, with the fluctuations in wear coefficient and Poisson's ratio showing relatively more pronounced effects on reliability. This highlights the importance of material consistency in ensuring stable contact performance. In contrast, the shaft material shows a more pronounced response to parameter variability, especially in terms of Brinell hardness and elastic modulus, which substantially influence system reliability. The sensitivity ranking of the shaft material's coefficient of variation is as follows: Brinell hardness, elastic modulus, Poisson's ratio, and wear coefficient. This indicates that fluctuations in the mechanical properties of the shaft material tend to induce nonlinear propagation of wear, posing a greater threat to system reliability.

In the analysis of plastic strain accumulation, primary attention is given to the main load-bearing rods AC and CD. During operation, the linkages are subjected to cyclic loading, and the plastic properties of the material determine their cumulative deformation behavior under such loading. Nine key plasticity-related parameters are selected for sensitivity analysis, including yield strength, fast saturation strength, medium saturation strength, and various hardening parameters. The analysis is conducted with respect to the mean values, examining the influence of three representative levels—0.8, 1.0, and 1.2 times the nominal mean—on system reliability. The results are shown in Fig. 14.

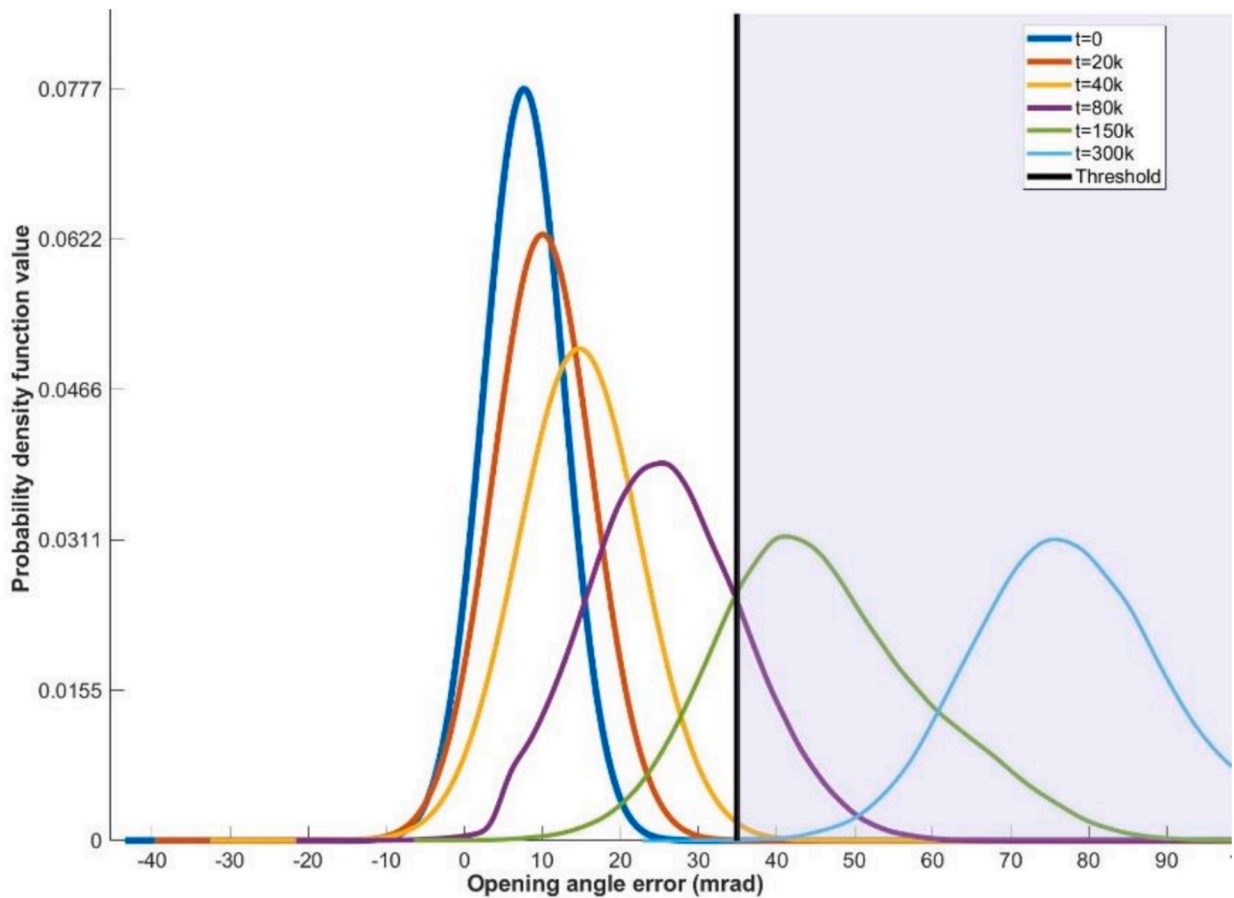


Fig. 14. Probability density distributions of different opening angle errors.

As shown in Fig. 14, yield strength exhibits the highest sensitivity to system reliability, with both rods AC and CD demonstrating pronounced dependence on this parameter. As the critical stress marking the onset of plasticity, higher yield strength helps delay the occurrence of plastic deformation, significantly mitigating the degree of strain accumulation and enhancing service reliability. The medium saturation strength parameter also shows a high level of sensitivity, indicating the significant influence of plastic hardening behavior on structural reliability. In contrast, the elastic modulus exhibits the lowest sensitivity, consistent with elastoplastic theory, which suggests that in failure modes dominated by plastic deformation, variations in elastic properties have a limited impact on system reliability. Furthermore, the effects of hardening variables—such as the fast and medium saturation rates and the isotropic hardening parameter—exhibit non-monotonic response patterns, reflecting the coupled and competing mechanisms of different hardening behaviors during plastic accumulation. It is also noteworthy that the overall sensitivity of the CD rod (42CrMo4 steel) under all parameter perturbations is significantly lower than that of the AC rod (7075-T6 aluminum alloy), suggesting that high-strength steels offer better stability and reliability in controlling plastic deformation and resisting cumulative damage.

Reinforcing material property uniformity proves essential to maintaining system reliability, as revealed by the combined sensitivity analyses. Increased variability in material behavior tends to amplify performance degradation risks, with individual components responding differently to specific property changes. Tight control over material consistency during manufacturing is essential to limiting intra-batch variability. When necessary, processes such as heat treatment or surface strengthening may be employed to enhance long-term system reliability further.

6.3.3. Reliability sensitivity analysis of operational load parameters

To evaluate the influence of the statistical characteristics of contact forces on system reliability, sensitivity analysis was conducted for each hinge joint. While keeping all other parameters constant, the mean of contact forces $\{F_i\}$ change to 0.8 times and 1.2 times from their original values, and the coefficients of variation change to 1.5 times and 2 times from their original levels. The analysis results are shown in Fig. 15.

As displayed in Fig. 15, the statistical characteristics of contact forces significantly influence system reliability. Reliability decreases with the increasing contact force, with the sensitivity ranking as follows: $A > D > B > C$. Point A reveals the highest sensitivity to mean variations, while point D, serving as the motion input end and bearing larger loads, also shows high sensitivity. Similarly, reliability

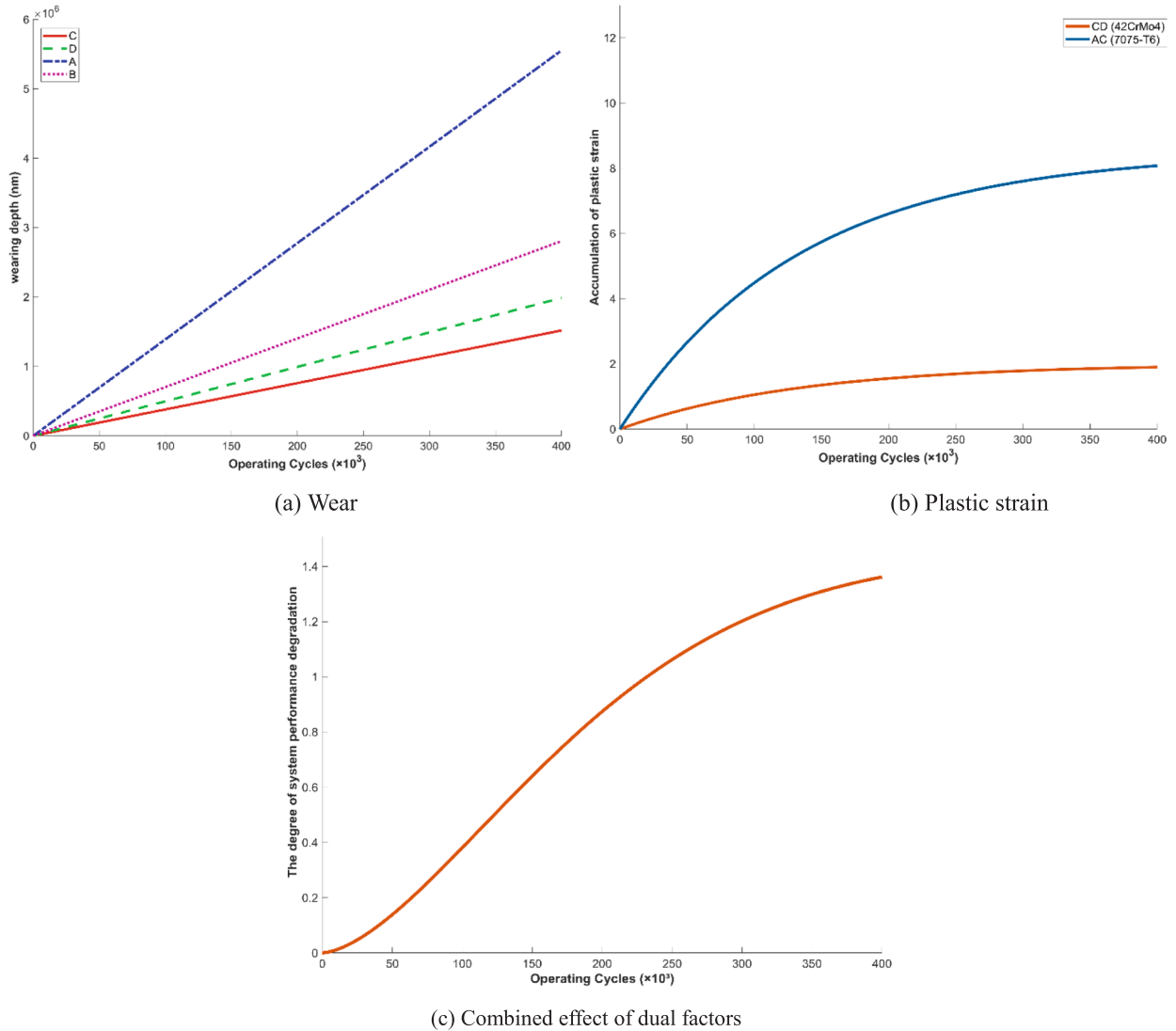


Fig. 15. Effect of progressive damage on mechanism functionality.

decreases with the increasing variability of contact forces, with the sensitivity ranking as follows: $A > C > B > D$. It is noted that the markedly different sensitivity rankings of points C and D from the above analyses indicate that the mean and variability of loads influence the reliability of systems through distinct mechanisms.

In summary, the reliability of the lifting mechanism is closely tied to how contact forces are distributed and vary during operation. Among the hinge joints, the points A and D display the most sensitivity to force fluctuations, indicating their priority in condition monitoring and preventive maintenance efforts. To maintain long-term performance, it is essential to identify the dominant load contributors and refine operating conditions to stabilize both the magnitude and variability of contact interactions.

6.3.4. Reliability sensitivity analysis of performance threshold parameters

The reliability sensitivity analysis of performance threshold parameters is performed to gain the effects of performance threshold ε on reliability index $R(30,000)$. In the distribution of performance threshold, the mean μ_ε varies from its original value to its 80 % and to 120 %, and the standard deviation δ_ε from its original value to 1.5 times and 2.0 times respectively, while keeping the other parameters unchanged. The results of the sensitivity analysis are illustrated in Fig. 16.

As shown in Fig. 16, the reliability of system consistently increases with the expansion of performance threshold tolerance. Conversely, the increase of standard deviation results in a continuous decline in reliability degree. These conclusions agree with physical trend. The sensitivity analysis of performance threshold parameters provides the critical guidance for the rational specification of performance requirements, which is promising to weight functional requirements and reliability constraints and support the study of threshold uncertainty and time dependence.

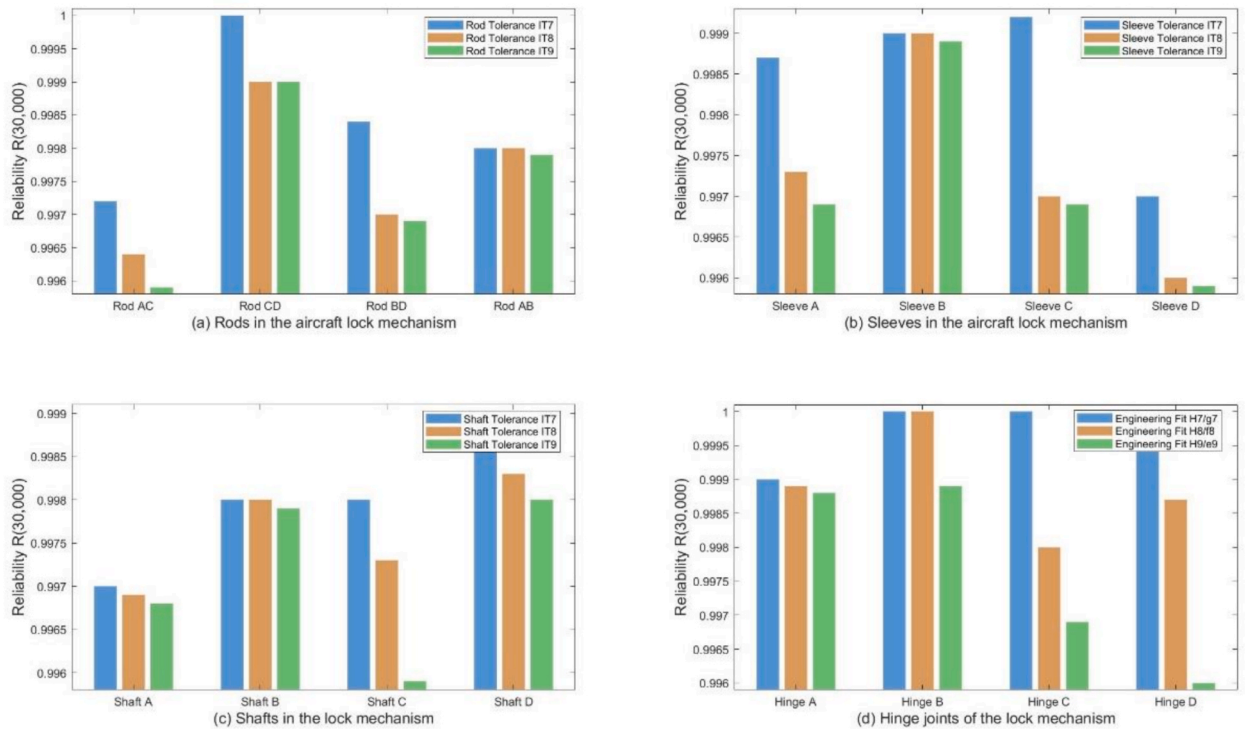


Fig. 16. Reliability sensitivity analysis results for manufacturing tolerances.

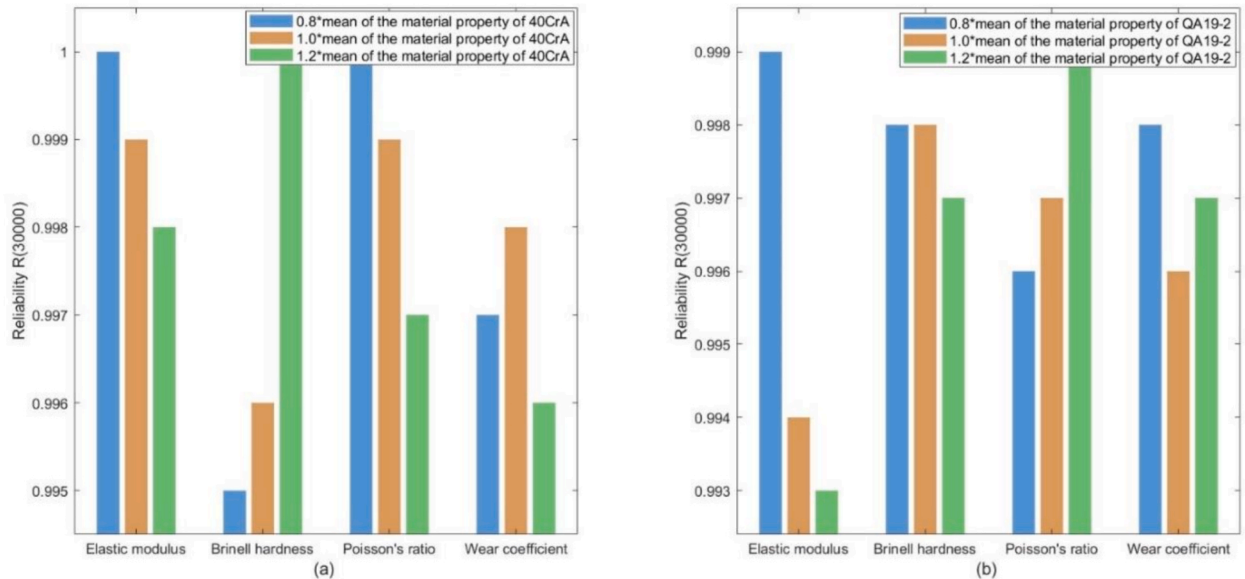


Fig. 17. Reliability sensitivity analysis for the mean values of wear-related material properties: (a) 40CrA; (b) QA19-2.

7. Conclusions

The aim of this paper is to develop the multi-source reliability evaluation method of aircraft cargo door lifting mechanism with the consideration of the synergistic effect between wear and plastic accumulation and multi-source uncertain information, to precisely reflect the performance degradation of cargo door lifting mechanism. From this study, the main conclusions are summarized as follows:

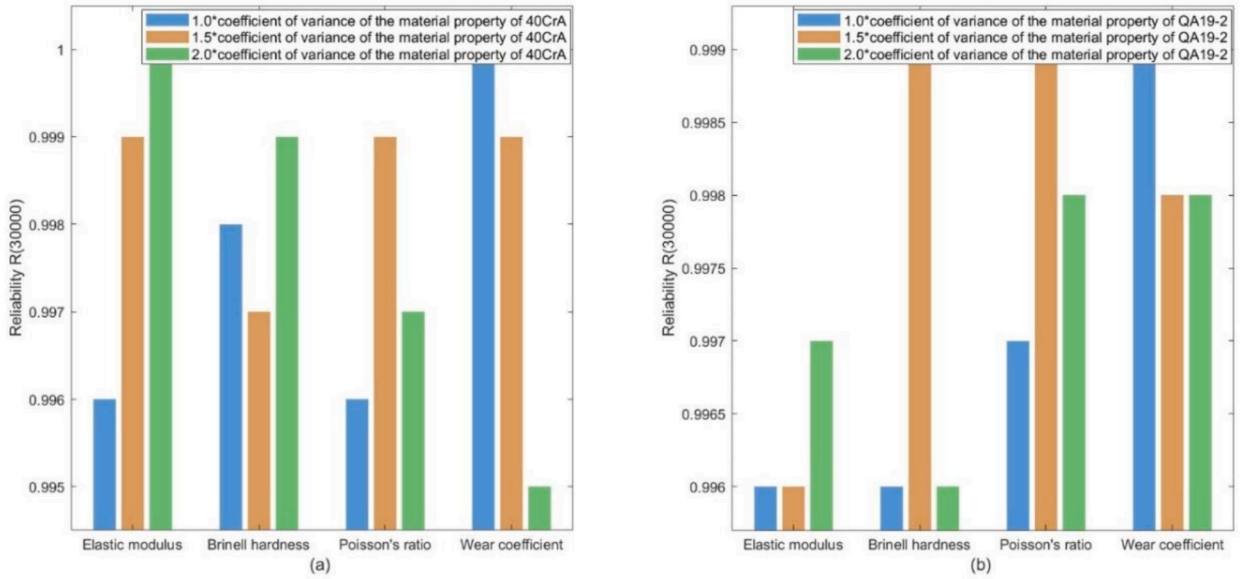


Fig. 18. Reliability sensitivity analysis for the coefficients of variation of wear-related material properties: (a) 40CrA; (b) QA19-2.

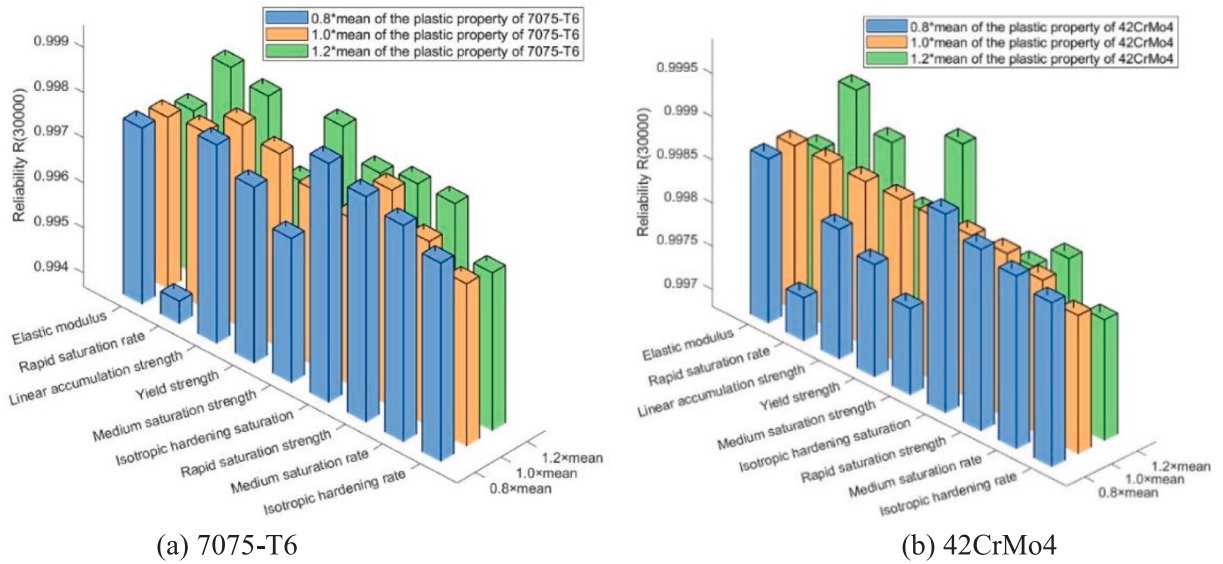


Fig. 19. Reliability sensitivity analysis for the mean values of plasticity-related material properties.

(1) The developed kinematic model with the coupling characteristics of spatial driving and followed planar is higher precision with the fast solving based on Newton–Raphson method, which effectively support performance degradation modeling and reliability analysis.

(2) The wear-plastic cumulative synergistic evolution equation based on Archard wear model and Chaboche mixed hardening model, accurately map physical damage into performance margin domain.

(3) The proposed unified modeling framework reveals the nonlinear degradation feature of mechanism system reliability under the coupling effect of wear and plastic accumulation.

(4) From the reliability analysis, it is demonstrated that wear has the most significant impact on the variability of system reliability, while cyclic plasticity leads to a gradual reduction in the overall reliability level. Their synergistic interaction obviously accelerates the degradation process of mechanism performance, and results in the reliability curve to sharply decline during the later stages of service.

(5) As shown from the one-at-a-time (OAT) sensitivity analysis of the parameters on aircraft cargo door mechanism performance, the parameters such as Rod CD and Hinges B/C are highly sensitive, which have the largest influence on the degradation of cargo door mechanism performance.

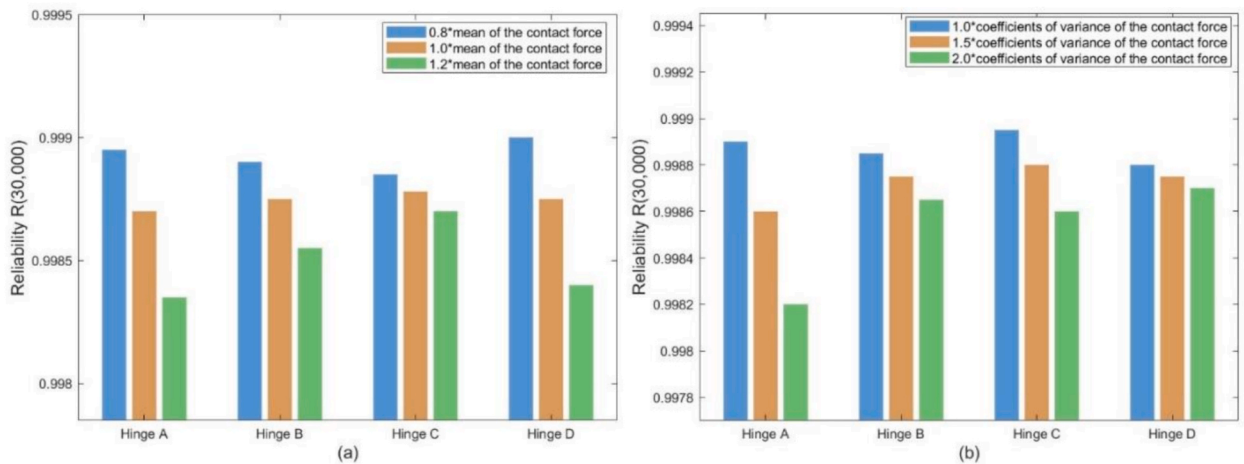


Fig. 20. Reliability sensitivity analysis of contact forces at hinge joints: (a) mean value; (b) coefficient of variation.

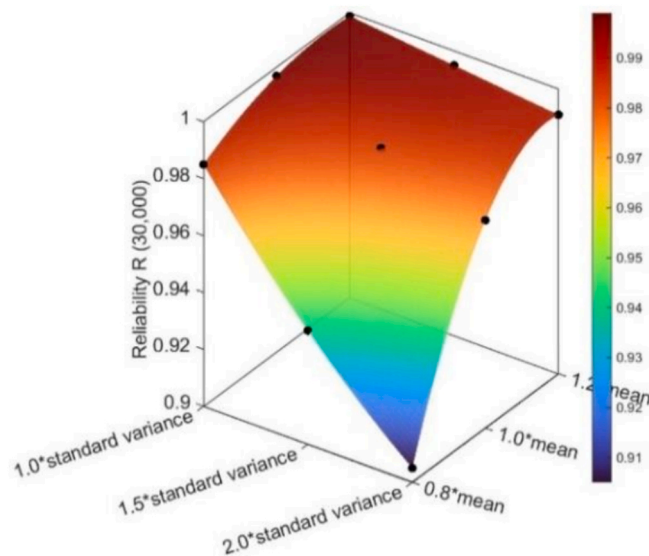


Fig. 21. Sensitivity analysis results of threshold parameters.

Although the theoretical modeling and quantitative analysis of aircraft cargo door mechanism performance was deeply investigated in this study, the difference between the theory and practical requirement still exists in reliability assurance. In this case, future research should further promote reliability optimization design based on performance margin involving the collaborative modeling of multiple failure mechanisms, the quantification of multi-source uncertainties and the integration of engineering constraints. Besides, multi-location and multi-factor functional failure analysis will further be performed with regard to the various progressive damage mechanisms like corrosion under service conditions, to structure more comprehensive degradation modeling framework and enhance the accuracy and applicability of reliability predictions. Although the current analysis provides theoretical and numerical insights, experimental validation and parameter calibration are still required to confirm the degradation models and improve the engineering reliability prediction of the cargo door lifting mechanism.

CRedit authorship contribution statement

Yao-Jia Han: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Bai-Yang Zheng:** Writing – review & editing, Visualization, Validation, Data curation. **Cheng-Wei Fei:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is co-supported by National Natural Science Foundation of China (Grant No. 52375237), National Science and Technology Major Project (Grant J2022-IV-0012). The authors would like to thank them.

Data availability

Data will be made available on request.

References

- [1] W. Guo, W. Cui, Y. Shi, J. Liu, B. Song, Function failure and failure boundary analysis for an aircraft lock mechanism, *Eng. Fail. Anal.* 70 (2016) 428–442.
- [2] K. Song, Y. Zhang, L. Shen, Reliability assessment and improvement for aircraft lock mechanism with multiple failure modes, *J. Fail. Anal. Prev.* 21 (2021) 640–648.
- [3] X.-Y. Li, W.-B. Chen, R. Kang, Performance margin-based reliability analysis for aircraft lock mechanism considering multi-source uncertainties and wear, *Reliab. Eng. Syst. Saf.* 205 (2021) 107234.
- [4] D.-Y. Jiang, Z.-X. Chen, K.-K. Wang, S.-K. Jiang, W.-M. Cui, B.-F. Song, A reliability analysis method for evaluating performance degradation considering the coupling of multiple progressive damage factors and multiple stochastic factors, *Reliab. Eng. Syst. Saf.* 254 (2025) 110584.
- [5] W. Shu, X.-C. Zhuang, T.-X. Yu, Reliability assessment of an aircraft locking mechanism considering tribocorrosion and correlated failure modes in a marine environment, *Eng. Fail. Anal.* 166 (2024) 108840.
- [6] L. Wang, X. Zhang, Y. Zhou, An effective approach for kinematic reliability analysis of steering mechanisms, *Reliab. Eng. Syst. Saf.* 180 (2018) 62–76.
- [7] Q. Zhang, N. Pan, M. Meloni, D. Lu, J.-G. Cai, J. Feng, Reliability analysis of radially retractable roofs with revolute joint clearances, *Reliab. Eng. Syst. Saf.* 208 (2021) 107401.
- [8] S. Gao, S.-W. Fan, Y.-F. Yang, Non-probabilistic reliability analysis of landing gear retraction and extension system with interval parameters, *Aero Sci Technol* 164 (2025) 110469.
- [9] Z. Sun, T. Yu, H. Pang, B. Song, Failure mechanism and reliability analysis of the rear cargo door lock of transport aircraft, *Eng. Fail. Anal.* 122 (2021) 105182.
- [10] S. Jiang, Y.-P. Lin, S.-T. Zhou, J.-C. Wang, Y.-Z. Li, L.-J. Xiao, F.-Q. Yao, Nonlinear dynamic analysis of multilink mechanism considering the wear effect of kinematic pair, *Nonlinear Dyn.* 112 (2024) 865–885.
- [11] Q. Zhao, J. Guo, J. Hong, Z. Liu, Analysis of angular errors of the planar multi-closed-loop deployable mechanism with link deviations and revolute joint clearances, *Aero Sci Technol* 87 (2019) 25–36.
- [12] Z.-F. Bai, Y. Sun, A study on dynamics of planar multibody mechanical systems with multiple revolute clearance joints, *Eur. J. Mech. A Solids* 60 (2016) 95–111.
- [13] D. Liang, T. Lv, Z. Wang, Research on reliability and dynamic characteristics of planar complex multi-bar mechanism considering clearance and irregular wear effect, *Commun. Nonlinear Sci. Numer. Simul.* 145 (2025) 108708.
- [14] X. Xue, Y. Li, L. Sui, W. Yu, K. Lin, J. Liu, Mechanism and prediction method of fretting damage in involute spline couplings of aero-engine, *Eng. Fail. Anal.* 148 (2023) 107200.
- [15] J. Ren, J. Cao, P. Tang, P. Yang, M. Li, Z. Li, J. Peng, H. Shen, X. Fan, M. Zhu, Probing fretting wear behavior of gauge-changeable spline axle under rotational bending loads, *Eng. Fail. Anal.* 166 (2024) 108846.
- [16] S.M. Varedi, H.M. Daniali, M. Dardel, A. Fathi, Optimal dynamic design of a planar slider-crank mechanism with a joint clearance, *Mech. Mach. Theory* 86 (2015) 191–200.
- [17] R. Basan, M. Franulović, I. Prebil, R. Kunc, Study on Ramberg-Osgood and Chaboche models for 42CrMo4 steel and some approximations, *J. Constr. Steel Res.* 136 (2017) 65–74.
- [18] D. Agius, M. Kajtar, K.I. Kourousis, C. Wallbrink, C.H. Wang, W. Hu, J. Silva, Sensitivity and optimisation of the Chaboche plasticity model parameters in strain-life fatigue predictions, *Mater. Des.* 118 (2017) 107–121.
- [19] M. Subasic, A. Ireland, R. Mansour, P. Enblom, P. Krakhmalev, M. Åsberg, A. Fazi, J. Gårdstam, J. Shipley, P. Waernqvist, B. Forssgren, P. Efsing, Experimental investigation and numerical modelling of the cyclic plasticity and fatigue behavior of additively manufactured 316 L stainless steel, *Int. J. Plast* 176 (2024) 103966.
- [20] D. Agius, K.I. Kourousis, C. Wallbrink, A modification of the multicomponent Armstrong–Frederick model with multiplier for the enhanced simulation of aerospace aluminium elastoplasticity, *Int. J. Mech. Sci.* 144 (2018) 118–133.
- [21] K.I. Kourousis, Y.F. Dafalias, Constitutive modeling of Aluminum Alloy 7050 cyclic mean stress relaxation and ratcheting, *Mech. Res. Commun.* 53 (2013) 53–56.
- [22] S. Das, N. Khutia, P.P. Dey, P. Arora, S.K. Gupta, Multi-objective cyclic plastic modelling of cyclic hardening and softening characteristics of nuclear piping SA333 gr. 6 carbon steel, *Int. J. Fatigue* 180 (2024) 108082.
- [23] P.-F. Wei, J.-W. Song, Z.-Z. Lu, Z.-F. Yue, Time-dependent reliability sensitivity analysis of motion mechanisms, *Reliab. Eng. Syst. Saf.* 149 (2016) 107–120.
- [24] C.-W. Fei, Y.-J. Han, J.-R. Wen, C. Li, L. Han, Y.-S. Choy, Deep learning-based modeling method for probabilistic LCF life prediction of turbine blisk, *Propuls. Power Res* 13 (1) (2024) 12–25.
- [25] C.-X. Su, B. Li, W. Zhang, W. Tian, W.-H. Liao, An analysis and reliability-based optimization design method of trajectory accuracy for industrial robots considering parametric uncertainties, *Reliab. Eng. Syst. Saf.* 254 (2025) 110626.
- [26] C.-D. Zeng, Z.-C. Qiu, F.-H. Zhang, X.-M. Zhang, Error modelling and motion reliability analysis of a multi-DOF redundant parallel mechanism with hybrid uncertainties, *Reliab. Eng. Syst. Saf.* 235 (2023) 109259.
- [27] W.-X. Wang, H.-S. Gao, C.-C. Zhou, Z.-Z. Zhang, Reliability analysis of motion mechanism under three types of hybrid uncertainties, *Mech. Mach. Theory* 121 (2018) 769–784.
- [28] C.-W. Fei, H. Li, H.-T. Liu, C. Lu, L.-Q. An, L. Han, Y.-J. Zhao, Enhanced network learning model with intelligent operator for the motion reliability evaluation of flexible mechanism, *Aero Sci Technol* 107 (2020) 106342.
- [29] D. Jiang, Y. Han, K. Wang, S. Jiang, W. Cui, B. Song, Functional degradation reliability analysis for non-uniform wear of multi-rotating joints of mechanical structures, *Eng. Fail. Anal.* 157 (2024) 107934.
- [30] J. Wen, C. Liang, Y. Choy, C. Fei, J. Li, Explainable spatiotemporal graph neural network with dynamic SHAP enhancement for aeroengine RUL prediction, *Aero Sci Technol* 168 (2026) 110875.
- [31] G. Li, Y. Teng, S. Ding, Complex physical-model based dynamic system safety analysis of aviation piston engine considering hybrid uncertainty of fault, *Eng. Fail. Anal.* 152 (2023) 107515.

- [32] J. Wen, B. Zheng, C. Fei, Prioritized experience replay-based adaptive hybrid method for aerospace structural reliability analysis, *Aero Sci Technol* 163 (2025) 110257.
- [33] J. Lin, C. Li, A. Chao, C. Fei, Q. Ren, Design and performance evaluation of novel wing-shaped fin radiators for advanced aeroengines, *Prop Power Res* 14 (3) (2025) 1–12.
- [34] B. Zheng, J. Wen, Y. Choy, C. Fei, Physics-constrained EBSD image inpainting via adversarial graph learning: Bridging crystallographic rules and multimodal deep learning, *Expert Syst. Appl.* 298 (2026) 129667.
- [35] W. Wang, Y. Ma, B. Liu, G. Cai, P. Jin, Reliability analysis of reusable turbine rotor blisk: an application of parametric modelling method under multi-field coupling, *Eng. Fail. Anal.* 152 (2023) 107511.
- [36] J. Zhang, Q. Zhang, R. Kang, Reliability Is a Science: A Philosophical Analysis of Its Validity. 35 (2019) 275–277.
- [37] M. Aristizabal, J.L. Hernández-Estrada, M. Garcia, H. Millwater, Solution and sensitivity analysis of nonlinear equations using a hypercomplex-variable Newton-Raphson method, *Appl. Math Comput.* 451 (2023) 127981.
- [38] Q. Tian, P. Flores, H.M. Lankarani, A comprehensive survey of the analytical, numerical and experimental methodologies for dynamics of multibody mechanical systems with clearance or imperfect joints, *Mech. Mach. Theory* 122 (2018) 1–57.
- [39] J. Zhang, X. Du, Time-dependent reliability analysis for function generation mechanisms with random joint clearances, *Mech. Mach. Theory* 92 (2015) 184–199.