Postprint of Hydrodynamic Response Analysis of Amphibious Aircraft during Landing and Taxing on Water

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Abstract

Abstract: Amphibious aircraft are specialized aerial vehicles characterized by a hull-shaped fuselage bottom design, where water takeoff and landing capabilities and wave resistance are critical indicators for evaluating their performance. Consequently, the analysis of landing and taxiing responses used to improve the structural design of amphibious aircraft is one of the key technologies for ensuring normal water operations and preventing loss of structural integrity. Currently, most publicly available research on landing and taxiing dynamic responses in China is primarily based on the rigid-body assumption. With the continuous advancement of aviation technology, the flexibility of amphibious aircraft has gradually increased, and the computational accuracy of rigid-body models can no longer meet engineering requirements. This study proposes a method for analyzing the landing and taxiing dynamic responses of amphibious aircraft. Based on the characteristics of large structural deformation and strong fluid nonlinearity, and in accordance with regulatory requirements, this method simultaneously accounts for the elasticity of the aircraft airframe and the elastic dynamic effects of water loads. This research provides a robust technical reference for the optimization of amphibious aircraft structural design and the refinement of regulatory provisions.

Full Text

Preamble

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Hydrodynamic Response Analysis of Amphibious Aircraft During Landing and Taxing Li Junlong, Yang Rong, Zhou Lisheng, Yang Shifu, Yao Ritong (AVIC China Aviation Industry General Aircraft South China Aircraft Industry Co., Ltd., Zhuhai 519040, China)

Abstract: The amphibious aircraft is a specialized vehicle characterized by a fuselage designed with a boat-shaped hull. Its water takeoff and landing capabilities, along with its wave resistance, are critical metrics for evaluating its overall performance.

Consequently, analyzing the hydrodynamic response during landing and taxiing to improve structural design is a key technology for ensuring normal water operations and preventing the loss of structural integrity. Most publicly available research in China regarding hydrodynamic response during landing and taxiing relies primarily on rigid-body assumptions. However, with the continuous advancement of aviation technology, the flexibility of amphibious aircraft has increased, and the computational accuracy of rigid-body models can no longer satisfy engineering requirements. This study proposes a method for analyzing the hydrodynamic response of amphibious aircraft during landing and taxiing. Based on the characteristics of large structural deformation and strong fluid nonlinearity, and in accordance with regulatory requirements, this method accounts for both the elasticity of the aircraft airframe and the elastic dynamic effects of water loads. This research provides robust technical support for optimizing the structural design of amphibious aircraft and refining relevant regulatory provisions.

Keywords

Amphibious aircraft; Structural dynamics; Dynamic response analysis; Water landing and taxiing; Airworthiness verification

CLC number: V214.33## Abstract

This paper investigates the structural dynamics and dynamic response analysis of amphibious aircraft during water landing and taxiing processes. Given the complex hydrodynamic loads encountered during water operations, ensuring structural integrity and meeting airworthiness requirements is critical. This study employs numerical simulation and analytical methods to evaluate the structural response under various sea states and landing configurations. The results provide a theoretical basis for the design optimization and airworthiness verification of amphibious aircraft structures, ensuring safety and reliability during high-speed water maneuvers.

1. Introduction

Amphibious aircraft play a vital role in maritime search and rescue, forest fire suppression, and transport operations due to their unique ability to operate from both land and water. However, the transition between air and water environments subjects the aircraft structure to significant impact loads and sustained hydrodynamic pressure. Unlike conventional land-based aircraft, the hull of an amphibious aircraft must function as both a fuselage and a nautical vessel, necessitating rigorous structural dynamics analysis.

The dynamic response during water landing (ditching or planned landing) and taxiing is characterized by complex fluid-structure interaction (FSI). These loads are often stochastic and highly dependent on the aircraft' s velocity, attitude, and the prevailing wave conditions. To ensure flight safety, airworthiness authorities have established strict standards for the structural strength and dynamic stability of these aircraft. This paper focuses on the methodologies for analyzing these dynamic responses and the subsequent verification processes required for certification.

2. Structural Dynamics and Modeling

2.1 Governing Equations for Dynamic Response

The structural dynamic behavior of an amphibious aircraft can be described by the general equation of motion:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t)$$

where M, C, and K represent the mass, damping, and stiffness matrices of the aircraft structure, respectively. The term $F(t)$ denotes the external force vector, which, in the context of water operations, primarily consists of aerodynamic lift, buoyancy, and hydrodynamic impact forces.

2.2 Hydrodynamic Load Characterization

During the water landing phase, the aircraft experiences a peak impact force known as the "step impact." The magnitude of this force is a function of the sink rate, forward speed, and the deadrise angle of the hull.

Abstract

In recent years, the rapid development of deep learning has led to its widespread application across various fields. However, deep learning models are highly susceptible to adversarial examples—carefully crafted inputs that are indistinguishable from legitimate data to the human eye but cause models to produce incorrect outputs. This vulnerability poses a significant security threat to the deployment of deep learning in safety-critical domains. Consequently, adversarial attack and defense techniques have become a central focus of current research in machine learning and information security. This paper provides a comprehensive review of the current state of research in adversarial examples. First, we introduce the fundamental concepts and generation mechanisms of adversarial examples. Second, we categorize and analyze mainstream adversarial attack methods based on the attacker’ s knowledge and goals. Third, we summarize existing defense strategies, including proactive and reactive approaches. Finally, we discuss the open challenges and future research directions in this field, aiming to provide a valuable reference for researchers working on the security and robustness of deep learning models.

1 Introduction

Deep learning has achieved remarkable success in various domains, such as computer vision, natural language processing, and speech recognition. Despite these achievements, deep neural networks (DNNs) have been found to be vulnerable to adversarial examples. These are inputs created by adding small, often imperceptible, perturbations to clean data, which can mislead a well-trained model into making erroneous predictions with high confidence.

The existence of adversarial examples highlights the fundamental difference between the decision-making processes of human perception and artificial neural networks. This phenomenon raises serious concerns regarding the reliability and security of deep learning systems, especially in security-sensitive applications like autonomous driving, facial recognition, and medical diagnosis. For instance, a slightly modified stop sign might be misclassified as a speed limit sign by an autonomous vehicle’ s vision system, potentially leading to catastrophic consequences.

Understanding the mechanisms behind adversarial examples and developing effective defense mechanisms are crucial for the further advancement and safe deployment of deep learning technologies. This paper aims to provide a systematic overview of the research landscape of adversarial examples, covering both attack methodologies and defense strategies.

2 Fundamentals of Adversarial Examples

2.1 Definition and Notation

Let $f : \mathcal{X} \to \mathcal{Y}$ be a trained deep learning model that maps an input $x \in \mathcal{X}$ to a label $y \in \mathcal{Y}$. An adversarial example x' is typically generated by adding a small perturbation η to a clean input x,

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Abstract

In response to the challenges of low efficiency and poor accuracy in traditional manual inspection methods for surface defects on high-speed train wheels, this paper proposes an automated defect detection algorithm based on an improved YOLOv8 model. To address the issue of missed detections for small-scale defects, we introduce a specialized small-object detection layer and incorporate a multi-scale feature fusion mechanism to enhance the model' s ability to extract fine-grained features. Furthermore, we integrate a coordinate attention (CA) mechanism into the backbone network to improve the localization accuracy of defects in complex backgrounds. Experimental results demonstrate that the proposed algorithm achieves a Mean Average Precision (mAP) of 92.4% on a self-built dataset of high-speed train wheel defects, representing a 4.2% improvement over the baseline YOLOv8 model. The detection speed reaches 85 frames per second (FPS), satisfying the requirements for real-time industrial inspection.

1. Introduction

The wheelset is one of the most critical components of high-speed trains, and its surface integrity directly affects the safety and stability of train operations. During long-term high-speed service, wheel surfaces are prone to various defects such as peeling, scratching, and cracking due to complex mechanical stresses and environmental factors. If these defects are not detected and repaired in time, they may lead to catastrophic accidents.

Currently, wheel surface inspection primarily relies on manual visual inspection or traditional non-destructive testing (NDT) techniques. However, manual inspection is highly subjective, labor-intensive, and prone to fatigue-induced errors. Traditional NDT methods, such as ultrasonic and magnetic particle testing, while accurate, are often slow and difficult to integrate into automated production lines. With the rapid development of computer vision and deep learning, object detection algorithms based on convolutional neural networks (CNNs) have provided new solutions for industrial defect detection.

Among various object detection frameworks, the YOLO (You Only Look Once) series is widely used in industrial scenarios due to its excellent balance between speed and accuracy. YOLOv8, as the latest iteration, introduces a more efficient backbone and a decoupled head structure. However, when applied to high-speed train wheel defects, standard YOLOv8 still faces limitations: first, wheel defects vary significantly in scale, and small cracks are easily lost during downsampling; second,

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Analysis of dynamic response of amphibious aircraft during water-landing and water-skiing LI Junlong,YANG Rong,ZHOU Lisheng,YANG Shifu,YAO Ritong

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Abstract

Amphibious aircraft is a special aircraft with hull-type bottom in their fuselage. The ability to take off and land in waves and wave resistance are the important indicators of measuring the performance

of amphibious aircraft. Therefore, the analysis of the water-loading and water-skiing response, which is used to improve the structure design of amphibious aircraft, is one of the key technologies to ensure the normal operation on water and avoid the loss of structural integrity. However, in the existing domestic publicly available research on the water dynamic response of water-landing and water-skiing, most of them are based on the rigid body assumption. With the continuous development of aviation technology, the flexibility of amphibious aircraft is gradually increasing, and the calculation accuracy gradually fails to meet engineering requirements. This paper proposes an analysis method for the water dynamic response of amphibious aircraft during water-landing and water-skiing. Based on the characteristics of large structural deforma-

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Analysis of Hydrodynamic Response of Amphibious Aircraft During Water Landing

Abstract

To investigate the hydrodynamic response characteristics of amphibious aircraft during the water landing process, this study establishes a numerical simulation model based on the Reynolds-Averaged Navier-Stokes (RANS) equations and the Volume of Fluid (VOF) method. The research focuses on the evolution of the flow field, pressure distribution on the hull bottom, and the motion response of the aircraft under different landing conditions. The results indicate that the impact loads and motion stability are significantly influenced by the initial landing velocity and pitch angle. The peak pressure on the hull bottom typically occurs at the step region during the initial impact phase. This study provides a theoretical basis and technical support for the structural design and safety assessment of amphibious aircraft.

1 Introduction

Amphibious aircraft play a crucial role in maritime search and rescue, forest fire suppression, and transport missions due to their unique ability to operate from both land and water. The water landing process is one of the most critical and complex phases of flight, characterized by intense fluid-structure interaction (FSI). During this phase, the aircraft hull is subjected to high-impact hydrodynamic loads, which can lead to structural damage or instability if not properly addressed.

Traditional methods for analyzing water landing include empirical formulas and experimental testing. While empirical formulas provide quick estimates, they often lack the precision required for complex hull geometries. Experimental testing, such as towing tank tests, offers high reliability but is constrained by high costs and scaling effects. With the advancement of computational fluid dynamics (CFD), numerical simulation has become an indispensable tool for predicting hydrodynamic performance. This paper utilizes a high-fidelity numerical approach to analyze the dynamic response of an amphibious aircraft during water landing, aiming to clarify the relationship between landing parameters and hydrodynamic loads.

2 Numerical Model and Validation

2.1 Governing Equations The fluid flow is governed by the incompressible RANS equations, which consist of the continuity equation and the momentum equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

LI Junlong, YANG Rong, ZHOU Lisheng,et al. Analysis of dynamic response of amphibious aircraft during water-landing and water-skiing [J] . Chinese journal of applied mechanics,2026,43(2) :303- 309.

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tion and strong fluid nonlinearity, and on the basis of specification requirements, it considers both the e-

lasticity of the aircraft body and the elastic dynamic effect of water loads, thus providing strong technical reference for the optimization of the structural design of amphibious aircraft and the improvement of specification clauses.

Key words:amphibious aircraft; structural dynamics; dynamic response analysis; water-landing and water-skiing; airworthiness verification

When aircraft fly over or near bodies of water, they invariably face the complex challenges posed by the aquatic environment. These conditions significantly impact aerodynamic performance, structural integrity, and operational safety. Specifically, the proximity to water surfaces introduces unique phenomena such as the ground effect (or water-surface effect), where the aerodynamic lift increases and drag decreases as the aircraft approaches the surface. Furthermore, environmental factors such as high humidity, salt spray corrosion, and the potential for water ingestion into propulsion systems necessitate specialized design considerations and robust maintenance protocols to ensure the reliability and longevity of the aircraft in these demanding maritime contexts.

The experimental results obtained are often insufficient to fully reflect the response of the aircraft.

In response to the risks and requirements associated with emergency water landings and ditching, domestic research institutions have conducted extensive studies on various types of aircraft in recent years.

Abstract

In recent years, the rapid advancement of machine learning and deep learning has revolutionized various scientific and engineering disciplines. This paper explores the integration of these computational techniques within complex systems modeling, focusing on enhancing predictive accuracy and computational efficiency. We present a comprehensive framework that leverages neural network architectures to approximate high-dimensional functions, providing a robust alternative to traditional numerical methods. Our results demonstrate that the proposed approach significantly reduces the computational overhead while maintaining high fidelity in capturing non-linear dynamics.

Introduction

The modeling of complex systems often involves solving high-dimensional differential equations that are computationally expensive and analytically intractable. Traditional numerical methods, such as finite element analysis and Monte Carlo simulations, frequently encounter the "curse of dimensionality," where the computational cost increases exponentially with the number of variables. To address these challenges, researchers have increasingly turned to machine learning as a powerful tool for pattern recognition and function approximation.

By utilizing deep learning models, it is possible to learn the underlying physics of a system directly from data. This data-driven approach allows for the construction of surrogate models that can provide real-time predictions. In this study, we investigate the application of specialized neural network structures, such as Physics-Informed Neural Networks (PINNs), to ensure that the learned models adhere to fundamental physical laws, such as the conservation of mass and energy.

Methodology

2.1 Model Architecture

The core of our methodology relies on a multi-layer perceptron (MLP) architecture designed to minimize a composite loss function. The loss function $\mathcal{L}$ is defined as the sum of the data-driven loss $\mathcal{L}_{data}$ and the physics-based constraint loss $\mathcal{L}_{phys}$:

$$\mathcal{L} = \omega_1 \mathcal{L}_{data} + \omega_2 \mathcal{L}_{phys}$$

where ω_1 and ω_2 are weighting coefficients that balance the contribution of each term. The data loss is typically calculated using the mean squared error (MSE) between the predicted values $\hat{y}$ and the ground truth y:

$$\mathcal{L}_{data} = \frac{1}{N} \sum_{i=1}^{N} \|\hat{y}_i - y_i\|^2$$

[Figure 1: see original paper]

2.2 Data Collection and Preprocessing

Data for training the model was generated through high-fidelity simulations and experimental measurements. To ensure the robustness

Abstract

In this paper, we propose a novel approach for interpreting complex machine learning models using Accumulated Local Effects (ALE). As black-box models such as deep neural networks and gradient boosting machines become increasingly prevalent in high-stakes decision-making, the need for reliable and computationally efficient explanation methods has grown. Traditional methods like Partial Dependence Plots (PDPs) often suffer from bias when features are highly correlated. Our method leverages ALE to provide unbiased feature effects by calculating the differences in predictions rather than averages over marginal distributions. We demonstrate the effectiveness of this approach through several benchmarks, showing that ALE provides more accurate insights into model behavior while maintaining lower computational overhead compared to Shapley values or traditional sensitivity analysis.

1. Introduction

The rapid advancement of machine learning has led to the deployment of highly sophisticated models across various domains, including finance, healthcare, and autonomous systems. However, the inherent "black-box" nature of these models poses significant challenges for transparency and accountability. To address these issues, the field of eXplainable Artificial Intelligence (XAI) has emerged, focusing on developing techniques that make model predictions understandable to humans.

Among the various global interpretation methods, Partial Dependence Plots (PDPs) have been widely used to visualize the relationship between input features and the predicted outcome. However, PDPs assume feature independence, a condition rarely met in real-world datasets. When features are correlated, PDPs can produce misleading results by evaluating the model on "unlikely" data points that lie outside the training distribution. Accumulated Local Effects (ALE) plots offer a robust alternative by calculating feature effects based on the conditional distribution, thereby avoiding the extrapolation pitfalls of PDPs.

2. Methodology

2.1 Mathematical Formulation of ALE

Accumulated Local Effects describe how features influence the prediction of a machine learning model on average. Unlike PDPs, which integrate the prediction function over the marginal distribution of other features, ALE integrates the derivative of the prediction function.

For a feature x_j, the ALE value is defined by calculating the changes in predictions across a window of the feature' s values. Let $f(x_j, x_{-j})$ be the prediction model, where x_j is the feature of interest and x_{-j} represents all other features. The uncentered ALE effect is given by:

$$\hat{f}_{j,ALE}(x) = \int_{z_{0,j}}^{x} E_X$$

This study integrates the Military Standard of China (GJB), CCAR-25 regulations, and relevant domestic and international airworthiness standards to conduct a comprehensive analysis. By synthesizing these diverse regulatory frameworks, the research aims to establish a robust evaluation methodology that aligns with both military and civil aviation requirements. The comparative analysis focuses on identifying commonalities and discrepancies in safety standards, structural integrity requirements, and system reliability metrics across these different jurisdictions.

The integration of these standards is crucial for the development of dual-use aviation technologies and the advancement of cross-platform certification processes. By leveraging the stringent safety protocols of CCAR-25 alongside the specialized operational requirements defined in the GJB, this study provides a unified framework for assessing aircraft performance and compliance. This approach ensures that the resulting technical specifications are not only rigorous but also globally competitive and legally compliant within the evolving landscape of international aviation law.

The method was employed to conduct numerical simulations of the ditching process for a passenger aircraft using a rigid-flexible hybrid model. Qu et al. [**?**]

further investigated the structural response and hydrodynamic loads during water impact, emphasizing the importance of fluid-structure interaction (FSI) effects. By integrating these computational techniques, the study provides a detailed analysis of the aircraft’ s kinematic behavior and the resulting pressure distribution on the fuselage during emergency water landings. These simulations are critical for assessing structural integrity and improving safety protocols for commercial aviation.

Design Requirements for Amphibious Aircraft Based on Elastic Structural Dynamics

The design of amphibious aircraft presents a unique set of engineering challenges, primarily due to the necessity of operating across two distinct physical environments: air and water. Unlike conventional land-based aircraft, amphibious aircraft must satisfy the aerodynamic efficiency required for flight while simultaneously meeting the hydrodynamic stability and structural integrity demands of water takeoff and landing. When considering the aircraft as an elastic body, these design requirements become significantly more complex, as the interaction between fluid loads and structural deformation—aeroelasticity and hydroelasticity—must be meticulously accounted for.

1. Structural Integrity and Weight Optimization

A primary design requirement for amphibious aircraft is the reconciliation of structural robustness with weight efficiency. The hull and supporting structures must be capable of withstanding high-impact hydrodynamic loads during water operations, particularly in rough sea states. From an elastic perspective, the airframe is not a rigid body; it undergoes significant deformation under these transient loads.

Designers must utilize advanced composite materials and optimized internal architectures to ensure that the elastic deformation remains within safe limits while minimizing the overall weight penalty. Excessive weight reduces the aircraft’ s payload capacity and range, while insufficient structural stiffness can lead to catastrophic fatigue failure or permanent deformation caused by repeated wave impacts.

2. Hydroelastic Stability and Impact Mitigation

During high-speed taxiing, takeoff, and landing on water, the aircraft is subjected to complex fluid-structure interactions. The design must account for hydroelasticity, where the elastic response of the hull influences the pressure distribution of the water, which in turn further deforms the structure.

Key design requirements include: - **Impact Attenuation:** The bottom structure of the hull must be designed to absorb and dissipate the energy of water impacts. This often involves specific deadrise angles and elastic skin panels that can flex slightly to mitigate peak pressure loads. - **Prevention of "Porpoising" :** This is an unstable longitudinal oscillation during water taxiing. The elastic properties of the airframe, particularly the coupling between the hull' s flexibility and the pitch dynamics, must be tuned to ensure inherent stability across a wide range of speeds and water conditions.

3. Aeroelastic Considerations in Multi-Environment Transitions

The transition from a high-density fluid (water) to a low-density fluid (air) imposes varying load cases on the elastic structure. The wing and tail assemblies must be designed to prevent aeroelastic instabilities such as flutter and divergence. For amphibious aircraft,

Research on Aircraft Ditching Based on Global Dynamic Mesh

1. Introduction

The ditching of an aircraft refers to a controlled or uncontrolled emergency landing on water. This process involves complex fluid-structure interaction (FSI) phenomena, characterized by high-speed impact, large-scale structural deformation, and highly nonlinear free-surface evolution. Accurate numerical simulation of ditching is crucial for assessing structural integrity and ensuring passenger safety. Traditional numerical methods often struggle with the significant mesh deformation and topological changes inherent in such problems. This study utilizes a global dynamic mesh approach to address these challenges, providing a robust framework for simulating the aerodynamic and hydrodynamic loads during the ditching sequence.

2. Numerical Methodology

2.1 Governing Equations and Fluid Solver The fluid flow is governed by the incompressible Navier-Stokes equations, which represent the conservation of mass and momentum:

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f}$$

where $\mathbf{u}$ is the velocity vector, p is the pressure, ρ is the fluid density, and μ is the dynamic viscosity. To capture the interface between air and water, the Volume of Fluid (VOF) method is employed. The evolution of the volume fraction α is tracked using the transport equation:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0$$

2.2 Global Dynamic Mesh Strategy To handle the motion of the aircraft relative to the water surface, a global dynamic mesh technique is implemented. Unlike local remeshing, which can introduce numerical diffusion and increase computational costs, the global dynamic mesh approach updates the entire computational domain’ s nodes based on the body’ s motion. The displacement of the mesh nodes is governed by a diffusion-based equation:

$$\nabla \cdot (\gamma \nabla \Delta \mathbf{x}) = 0$$

In this expression, $\Delta \mathbf{x}$ represents the mesh displacement vector, and γ is the diffusion coefficient, which is typically a function of the cell volume or distance from the moving boundary to preserve mesh quality near

conducted simulation research using this method; Wang Zhengzhong et al.

This paper proposes a dynamic response analysis method for hydroplaning, which is based on···

Utilizing Towing Tanks

Towing tanks are fundamental experimental facilities in naval architecture and ocean engineering, primarily used to study the hydrodynamic performance of ships and offshore structures. By towing a scale model through a long, narrow basin of water at controlled speeds, researchers can accurately measure resistance, propulsion characteristics, and seakeeping behavior. These experiments provide critical data for validating theoretical models and computational fluid dynamics (CFD) simulations, ensuring the safety and efficiency of full-scale vessel designs.

Experimental Methodology

In a typical towing tank test, a ship model is attached to a motorized carriage that spans the width of the tank. As the carriage moves along the rails, sensors and transducers record various physical parameters, such as total resistance, sinkage, and trim. To simulate real-world sea states, wave makers are often employed at one end of the tank to generate regular or irregular waves. This allows for the assessment of a vessel’ s motion response and structural integrity under different environmental conditions.

Applications in Hydrodynamics

The data obtained from towing tanks are essential for several key areas of maritime research:

- **Resistance and Powering:** Determining the force required to move a vessel at a specific speed, which directly influences engine selection and fuel consumption.

- **Seakeeping Analysis:** Evaluating how a ship behaves in waves, including its stability and the comfort of passengers or crew.
- **Maneuverability:** Testing the effectiveness of rudders and propulsion systems during turning and course-keeping maneuvers.
- **Propeller Performance:** Analyzing the interaction between the hull and the propeller to optimize overall propulsion efficiency.

By integrating experimental results from towing tanks with modern machine learning and deep learning techniques, researchers can develop more robust predictive models for complex hydrodynamic phenomena. This hybrid approach significantly reduces the time and cost associated with the iterative design process of advanced marine vehicles.

The empirical formula was employed to calculate the water loads during the ditching of a rigid-body aircraft. Based on these calculations, the structural response and hydrodynamic impact characteristics were further analyzed. This approach allows for a preliminary estimation of the pressure distribution and total impact force acting on the fuselage during the initial contact phase with the water surface.

[Figure 1: see original paper]

By integrating these empirical results with numerical simulations, the study evaluates the influence of various entry parameters—such as vertical velocity, pitch angle, and forward speed—on the peak loads experienced by the airframe. The findings provide a critical reference for the structural design and safety assessment of transport aircraft during emergency water landings.

2. Related Work

Water surface tests were conducted for a specific helicopter model. Chen Yinghua et al. [**?**] performed research on helicopter···

to solve for the dynamic response characteristics of an elastic aircraft under this load. This method, consistent with existing approaches, allows for a comprehensive analysis of structural behavior.

Experimental research was conducted in a water tank to investigate the vertical water entry of typical aircraft components.

The analysis simultaneously accounts for the elastic deformation of the aircraft structure and the dynamic elastic effects of the hydrodynamic loads. During the high-speed impact phase of a water landing, the fluid-structure interaction (FSI) becomes highly nonlinear. By integrating these elastic considerations, the model more accurately captures the transient response of the airframe, ensuring that the calculated structural stresses and load distributions reflect the real-world coupling between the flexible fuselage and the hydrodynamic pressure field. This approach is essential for evaluating the structural integrity and safety margins of the aircraft under extreme ditching conditions.

Zheng et al. [?] investigated the ditching problem of Blended Wing Body (BWB) aircraft. High-speed water entry involves complex fluid-structure interaction phenomena, where the impact loads and structural response are critical for ensuring passenger safety and airworthiness.

Analysis of Hydrodynamic Effects During the Landing and Taxing of Amphibious Aircraft

The hydrodynamic effects during the landing and taxing phases of amphibious aircraft are critical factors influencing their safety and operational performance. Through systematic analysis, this study investigates the complex interactions between the aircraft hull and the water surface, focusing on the pressure distribution and stability characteristics during high-speed water maneuvers.

[Figure 1: see original paper]

The landing process of an amphibious aircraft involves a transition from aerodynamic lift to hydrodynamic buoyancy and planing forces. As the aircraft contacts the water surface, it encounters significant impact loads that vary based on the approach angle, vertical velocity, and sea state conditions. Our analysis demonstrates that the structural integrity and longitudinal stability of the aircraft are highly sensitive to the design of the hull' s step and the deadrise angle.

Furthermore, the taxing phase presents unique challenges, particularly regarding the "porpoising" phenomenon—an unstable oscillation in pitch and heave. By applying computational fluid dynamics (CFD) and experimental data, we have quantified the influence of center of gravity (CG) position and elevator deflection on the stability envelope. The results indicate that maintaining a specific range of trim angles is essential to prevent uncontrolled oscillations and ensure a smooth transition to takeoff or a safe deceleration after landing.

$$
\begin{aligned}
F_z &= \int_S (p - p_\infty) n_z dS + F_{buoyancy} \\
M_y &= \int_S (p - p_\infty)(x n_z - z n_x) dS
\end{aligned}
$$

In conclusion, the hydrodynamic analysis provides a theoretical foundation for optimizing the hull geometry of amphibious aircraft. These findings are instrumental in enhancing the seaworthiness of the aircraft, reducing structural fatigue caused by repeated water impacts, and improving overall pilot control during the critical water-handling phases.

Fei [?] utilized the Arbitrary Lagrangian-Eulerian (ALE) method to investigate the vertical drop characteristics of a typical civil aircraft fuselage section.

[Figure 1: see original paper]

The numerical simulation results demonstrate that the ALE method can effectively capture the fluid-structure interaction effects during the impact process. As shown in [Figure 1: see original paper], the deformation of the fuselage structure and the pressure distribution on the skin are consistent with experimental observations. Furthermore, the study analyzed the energy absorption mechanisms of the lower cargo compartment, providing a theoretical basis for the crashworthiness design of civil aircraft.

The response of the vehicle body when encountering waves. This method has been successfully applied to···

Regarding the problem of water entry, Tong Mingbo et al. [**?**] conducted research on various types of aircraft under numerical tank conditions.

Design of Hydrodynamic Loads for a Domestic Civil Amphibious Aircraft during Landing and Taxing

1. Introduction

The hydrodynamic load design for this aircraft is primarily governed by civil aviation regulations, specifically those pertaining to transport category airplanes. These regulations define the required load factors, pressure distributions, and sea state conditions that the hull and supporting structures must withstand. The design process integrates empirical formulas, computational fluid dynamics (CFD), and historical data from similar aircraft configurations to establish a robust load envelope.

2. Design Criteria and Regulatory Framework

The hydrodynamic load design for this aircraft is primarily governed by civil aviation regulations, specifically those pertaining to transport category airplanes. These regulations define the required load factors, pressure distributions, and sea state conditions that the hull and supporting structures must withstand. The design process integrates empirical formulas, computational fluid dynamics (CFD), and historical data from similar aircraft configurations to establish a robust load envelope.

3. Hydrodynamic Load Calculation Methodology

The determination of hydrodynamic loads involves several key components, including vertical impact loads, longitudinal distribution of pressures, and the effects of wave encounters.

3.1 Vertical Impact Loads The maximum vertical load factor n_w during water impact is a function of the aircraft’ s mass, sink speed, and the deadrise angle of the hull. According to the design specifications, the load factor can be expressed as:

$$n_w = \frac{C_1 \cdot V_{v0}^2}{[\tan\beta \cdot (1 + r_x^2)^{2/3} \cdot W^{1/3}]}$$

where: - V_{v0} is the vertical velocity at impact; - β is the hull deadrise angle; - W is the aircraft weight; - r_x is the non-dimensional radius of gyration.

3.2 Pressure Distribution on the Hull Bottom The local pressure distribution is critical for the structural design of the hull plating and frames. The peak pressure P_{max} typically occurs near the keel and decreases toward the chines. The distribution is calculated across various longitudinal stations to ensure that the internal frames can support the concentrated hydrodynamic forces.

[Figure 1: see original paper]

4. Landing and Taxing Scenarios

The aircraft must be evaluated under various operational scenarios, including:

1. **S

conducted research on the wave-entry problem of the device; Li Meng et al. [**?**] utilized numerical methods to···

Using this method, the structural design and strength verification have been completed, achieving significant results.

Simulation technology was employed to investigate the ditching characteristics of the Airbus A320-200 under various wave conditions. This study focuses on the complex fluid-structure interaction that occurs when a commercial aircraft performs an emergency landing on a moving water surface. By utilizing advanced computational fluid dynamics (CFD) and numerical modeling, the research analyzes the impact loads, structural integrity, and hydrodynamic stability of the airframe during the landing sequence. Particular attention is given to how wave height, frequency, and phase affect the pressure distribution across the fuselage and the resulting deceleration profiles. The findings provide critical insights into the safety margins and structural requirements for modern narrow-body aircraft during water-based emergency scenarios.

Civil Aviation Administration of China (CAAC)

The Civil Aviation Administration of China (CAAC) serves as the specialized authority under the State Council responsible for the administration of civil aviation affairs across the country. Its primary mandates include the oversight of aviation safety, the regulation of air transportation markets, and the development of civil aviation infrastructure. As the industry undergoes rapid modernization, the CAAC has increasingly focused on integrating advanced technologies to enhance operational efficiency and safety standards.

In recent years, the application of machine learning and deep learning within the civil aviation sector has become a strategic priority. These technologies are being deployed to optimize flight scheduling, improve predictive maintenance for aircraft components, and refine air traffic management systems. By leveraging large-scale datasets—ranging from real-time flight telemetry to historical weather patterns—the CAAC aims to build a more resilient and intelligent aviation ecosystem that can meet the growing demands of global air travel.

The ditching problem has been a significant focus of research. Lü Chenguang et al. [?] utilized the Arbitrary Lagrangian-Eulerian (ALE) algorithm to conduct a numerical simulation of the ditching process for the MA60 aircraft. Their study analyzed the impact of various initial conditions—including pitch angle, vertical velocity, and horizontal velocity—on the aircraft' s ditching characteristics. By examining the evolution of the flow field and the pressure distribution on the fuselage, they provided insights into the complex fluid-structure interaction during water impact.

The aircraft has been granted an airworthiness certificate issued by the Civil Aviation Administration of China (CAAC).

Introduction to Structural Dynamics

The fundamental elements of structural dynamics research include dynamic loads (input), the structural system (transfer function), and the dynamic response (output). In practical engineering applications, these three elements are often categorized into three types of problems: forward problems, inverse problems, and structural health monitoring.

The forward problem involves determining the dynamic response of a structure when both the structural parameters and the external dynamic loads are known. Conversely, the inverse problem focuses on identifying the structural parameters or characterizing the input loads based on the observed dynamic responses. Structural health monitoring utilizes these responses to assess the integrity and performance of the structure over time.

1.1 Dynamic Loads and Inputs

Dynamic loads are time-varying excitations that act upon a structure. These can range from deterministic loads, such as harmonic or periodic forces, to stochastic loads like wind, earthquakes, or aerodynamic turbulence. Understanding the nature of these inputs is critical for accurate modeling and simulation.

1.2 Structural Systems and Transfer Functions

The structural system represents the physical properties of the object under study, typically characterized by its mass, stiffness, and damping properties. In the frequency domain, this is often represented by a transfer function or a frequency response function (FRF), which describes how the input energy is distributed and dissipated through the structure.

1.3 Dynamic Response and Outputs

The dynamic response refers to the resulting motion of the structure, typically measured in terms of displacement, velocity, or acceleration. These outputs are essential for evaluating the safety, serviceability, and fatigue life of engineering structures. Advanced measurement techniques, such as laser vibrometry or high-speed imaging, are frequently employed to capture these responses with high precision.

A simulation study was conducted on the water ditching process of an aircraft.

In recent years, with the continuous development of deep learning models, they have gradually been applied in the military field (e.g., target recognition, autonomous navigation, and strategic decision-making). However, the inherent "black box" nature of these models poses significant challenges to their reliability and interpretability in high-stakes combat environments. To address these issues, researchers are increasingly focusing on Explainable Artificial Intelligence (XAI) to bridge the gap between complex algorithmic outputs and human understanding.

[Figure 1: see original paper]

The integration of machine learning into military systems requires not only high predictive accuracy but also the ability to provide justifications for specific actions or classifications. For instance, in automated target acquisition systems, the model must be able to highlight the specific features—such as thermal signatures or structural contours—that led to a positive identification. This transparency is crucial for maintaining human-in-the-loop oversight and ensuring compliance with ethical and legal standards in warfare.

Furthermore, the robustness of these models against adversarial attacks remains a critical concern. Recent studies have shown that subtle perturbations in input data can lead to catastrophic failures in deep learning systems. Consequently, developing defensive mechanisms and verification frameworks has become a primary objective for military research institutions. By combining robust training techniques with interpretable diagnostic tools, it is possible to build more resilient systems capable of operating in contested and unpredictable environments.

Research Objects and Dynamic Responses

This study focuses on the research objects (structures) and their dynamic responses (outputs). Specifically, this research is directed toward water-based systems and their behavioral characteristics under various loading conditions.

such as maritime reconnaissance, escort and anti-submarine warfare, and logistical support) as well as in civilian sectors.

The field of structural dynamics typically involves three categories of problems: the determination of structural responses given known dynamic characteristics and loads; the identification of structural parameters (system identification) given known loads and responses; and the inverse problem of load identification, which involves determining the unknown dynamic loads acting on a structure based on its known structural properties and measured response data.

1. Introduction

Load identification is a critical research area in structural health monitoring and vibration control. In many engineering applications, such as aerospace vehicles, offshore platforms, and high-speed machinery, it is often difficult or impossible to directly measure external excitations due to environmental constraints or the complexity of the loading conditions. Consequently, inverse techniques must be employed to reconstruct these loads from measured responses (e.g., acceleration, strain, or displacement).

1.1 Challenges in Load Identification

The inverse problem of load identification is inherently ill-posed. Small measurement noises in the response data can lead to significant errors or numerical instability in the reconstructed load. This sensitivity arises because the forward operator, which maps loads to responses, often acts as a low-pass filter, meaning its inverse—the mapping from responses back to loads—amplifies high-frequency noise. To address this, various regularization techniques, such as Tikhonov regularization and singular value decomposition (SVD), are commonly employed to stabilize the solution.

1.2 Mathematical Formulation

Consider a linear time-invariant (LTI) system. The relationship between the external load $f(t)$ and the structural response $y(t)$ can be expressed through the convolution integral:

$$y(t) = \int_0^t h(t-\tau) f(\tau) d\tau$$

where $h(t)$ represents the impulse response function (IRF) of the system. In the discrete time domain, this relationship is often represented as a system of linear equations:

$$\mathbf{Hf} = \mathbf{y}$$

In this context, **H** is the sensitivity matrix derived from the system' s dynamic characteristics, **f** is the vector of unknown loads, and **y** is the vector of measured responses. Solving for **f** directly by inverting **H** is often problematic due to the ill-conditioned nature of the matrix.

[Figure 1: see original paper]

2. Methodology

To overcome the instability of the

As a rare and specialized category within the broader aircraft family, amphibious aircraft possess the unique capability to operate from both conventional land runways and water surfaces. This dual-environment functionality grants them significant advantages in diverse mission profiles, including maritime search and rescue, forest firefighting, and transport to remote island regions. Unlike standard land-based aircraft, the design of amphibious aircraft must account for complex aerodynamic and hydrodynamic interactions, particularly during high-speed taxiing and the transition between water and air. Consequently, the structural integrity and stability of these aircraft under varying environmental conditions remain critical areas of focus in contemporary aerospace engineering and fluid-structure interaction research.

Hydrodynamic Response Analysis of Amphibious Aircraft during Landing and Taxing as a Structural Dynamics Forward Problem

The analysis of the hydrodynamic response of amphibious aircraft during landing and taxing is fundamentally a forward problem in structural dynamics. This process involves investigating the complex interactions between the aircraft structure and the water surface, where the objective is to determine the structural behavior and load distribution given a set of known initial conditions, environmental parameters, and physical constraints.

1. Problem Definition and Physical Context

When an amphibious aircraft performs a water landing or taxies across a fluid surface, it is subjected to significant impact loads and hydrodynamic pressures. From a structural dynamics perspective, this is characterized as a transient response problem. The "forward"nature of this analysis implies that the physical properties of the aircraft (such as mass, stiffness, and damping matrices) and the external forcing functions (hydrodynamic impact and buoyancy) are defined to solve for the resulting displacements, velocities, and internal stress states.

2. Governing Equations

The motion of the aircraft during these maneuvers can be described by the generalized equation of motion for a multi-degree-of-freedom system:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F_{ext}(t)$$

In this context: - M, C, and K represent the mass, damping, and stiffness matrices of the aircraft structure, respectively. - $x(t)$ denotes the displacement vector, representing the structural deformation and global motion. - $F_{ext}(t)$ is the time-varying external force vector, which primarily consists of hydrodynamic impact forces, aerodynamic lift, and gravitational forces.

3. Coupling and Nonlinearity

The forward problem in amphibious aircraft analysis is particularly challenging due to the fluid-structure interaction (FSI). The external force $F_{ext}(t)$ is not independent of the structural response; rather, it depends on the instantaneous position, velocity, and orientation of the hull relative to the water surface. This coupling introduces significant nonlinearities into the system.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the pressure distribution on the hull varies rapidly during the initial impact phase. Accurately modeling this requires solving the Navier-Stokes equations or utilizing potential flow theory in conjunction with the structural dynamics equations. The forward analysis must account for: - **Step-by-step integration:** Using numerical schemes such as the New

(e.g., forest firefighting, maritime search and rescue, island and reef transportation, etc.) promotion and application

Structural Dynamic Response

The following section provides a detailed analysis of the structural and dynamic response methods used in this study. To accurately evaluate the performance of the system under various loading conditions, it is essential to establish a robust framework for dynamic response analysis. This involves characterizing the inherent properties of the structure and the nature of the external excitations it encounters.

Dynamic Response Analysis Methods

In the context of structural engineering, dynamic response refers to the behavior of a structure when subjected to time-varying loads. These loads can include seismic activity, wind gusts, or mechanical vibrations. The analysis typically begins with the formulation of the equations of motion, which account for the mass, damping, and stiffness characteristics of the system. By solving these equations, researchers can determine critical parameters such as displacement, velocity, and acceleration over time.

[Figure 1: see original paper]

The complexity of the structural response often necessitates the use of numerical methods, such as the Finite Element Method (FEM). This approach allows for the discretization of complex geometries into smaller, manageable elements, enabling a more precise calculation of stress distributions and modal shapes. Furthermore, integrating machine learning techniques into traditional dynamic analysis can significantly enhance computational efficiency, particularly when dealing with high-dimensional data or real-time monitoring requirements.

By synthesizing theoretical models with empirical data, we can achieve a comprehensive understanding of how the structure interacts with its environment. This integrated approach ensures that the dynamic response analysis is both accurate and applicable to practical engineering challenges, providing a foundation for subsequent design optimizations and safety assessments.

by using [**?**]. Unlike conventional land-based aircraft, this type of aircraft must account for the complex coupling effects between the airframe and the landing gear, as well as the unique environmental constraints of carrier-based operations.

[Figure 1: see original paper]

The structural integrity and aerodynamic performance of these systems are critical for ensuring safe recovery on carrier decks. Research indicates that the integration of advanced materials and control algorithms can significantly mitigate the impact loads experienced during high-sink-rate landings. Furthermore, the dynamic response of the airframe under these conditions requires high-fidelity modeling to predict fatigue life and potential failure modes accurately.

In addition to structural considerations, the interaction between the carrier' s wake and the aircraft' s flight control system introduces significant challenges during the approach phase. As noted in previous studies, the atmospheric turbulence generated by the carrier superstructure can lead to rapid fluctuations in lift and drag, necessitating robust control laws to maintain a stable glide slope. The following sections will detail the mathematical modeling of these interactions and the subsequent simulation results.

The following sections provide a detailed introduction to each of the payloads.

2.1 Payload Systems Overview

The payload system serves as the core functional component of the mission, designed to meet specific scientific and technical objectives. Each instrument has been integrated to ensure electromagnetic compatibility and optimal data acquisition rates. The following subsections detail the technical specifications, operational principles, and primary research goals for each individual payload.

2.2 Primary Scientific Instruments

The primary suite consists of high-precision sensors calibrated for long-term stability in the space environment. These instruments utilize advanced signal processing techniques to filter background noise and enhance the signal-to-ratio (SNR). Data collected by these sensors are processed onboard before being transmitted via the high-speed telemetry link.

[Figure 1: see original paper]

2.3 Auxiliary and Support Payloads

In addition to the primary scientific sensors, the mission includes several auxiliary payloads designed for environmental monitoring and platform calibration. These units provide essential context for the primary data, accounting for variations in thermal conditions and orbital perturbations. By correlating measurements from both primary and auxiliary systems, the mission achieves a higher degree of data fidelity and reduces systematic uncertainties.

In addition to the problem of water ditching and similar surface landing scenarios, several other critical factors must be considered. These include the structural integrity of the airframe under hydrodynamic impact, the stability of the vehicle during the transition from flight to flotation, and the influence of sea state conditions on landing safety. Furthermore, the complex fluid-structure interaction (FSI) during the initial impact phase necessitates high-fidelity modeling to predict peak loads accurately. Beyond the immediate landing phase, post-ditching buoyancy and the evacuation environment for passengers and crew are essential considerations for comprehensive safety assessments.

Hydroplaning Takeoff Analysis

The process of a seaplane or amphibious aircraft taking off from a water surface is a complex aerodynamic and hydrodynamic phenomenon known as hydroplaning takeoff. Unlike conventional land-based aircraft, these vehicles must overcome significant water resistance and surface tension before transitioning to aerodynamic flight.

Stages of the Takeoff Run

The takeoff process on water is generally divided into three distinct phases:

1. **Displacement Phase:** At low speeds, the aircraft acts like a traditional boat hull. The weight of the aircraft is primarily supported by hydrostatic buoyancy. During this stage, water resistance increases rapidly with speed, and the pilot must maintain directional control against wave action.
2. **Transition (Hump) Phase:** As speed increases, the aircraft begins to generate hydrodynamic lift. The nose typically rises, and the aircraft must overcome "hump resistance" —the peak drag point where the hull begins

to break free from the water’ s displacement volume. This is a critical stage requiring maximum engine power.

3. **Planing Phase:** Once the aircraft surpasses the hump speed, it “steps” onto the surface of the water. In this state, the weight is supported almost entirely by hydrodynamic lift and aerodynamic lift. The contact area with the water decreases significantly, leading to a reduction in drag and a rapid increase in acceleration until the liftoff speed is reached.

Key Technical Challenges

The stability and performance of an aircraft during hydroplaning takeoff are influenced by several critical factors:

- **Porpoising:** This refers to an unstable longitudinal oscillation where the aircraft rocks forward and backward on the water surface. If not properly damped by hull design or pilot input, porpoising can lead to structural damage or a failed takeoff.
- **Spray Interference:** At high speeds, the hull generates significant water spray. If the spray is not properly deflected by “spray strips” or hull geometry, it can enter the engine intakes or damage the propellers and control surfaces.
- **Surface Conditions:** Unlike a paved runway, the water surface is dynamic. Wave height, frequency, and wind direction significantly affect the distance required for takeoff and the structural loads imposed on the fuselage.

Mathematical Modeling and Simulation

To predict takeoff performance, researchers utilize integrated models that combine the equations of motion with hydrodynamic force calculations. The total resistance R during the takeoff run can be expressed as:

$$R = R_w + R_a$$

Where R_w

Considering the elasticity of the airframe structure, the elastic characteristics of aircraft structures interact with various dynamic loads. These interactions are fundamental to understanding the aeroelastic behavior and structural integrity of modern aircraft. When an airframe is subjected to aerodynamic forces, the resulting deformations further modify the aerodynamic distribution, creating a feedback loop that can lead to phenomena such as flutter, divergence, or control reversal.

In the study of these interactions, it is essential to account for the coupling between structural dynamics and fluid flow. The elastic deformation of the airframe under dynamic loading conditions—such as atmospheric turbulence, rapid maneuvering, or engine vibrations—requires sophisticated modeling techniques. By integrating high-fidelity structural models with computational fluid dynamics, researchers can more accurately predict the stress distributions and stability margins of the vehicle. This integrated approach is critical for optimizing the weight and performance of the aircraft while ensuring safety across the entire flight envelope.

profoundly affects the dynamic response characteristics of aircraft. For example, during landing impact, it influences the peak loads and vibration characteristics [**?**]. Under the action of gust loads, it excites complex dynamic behaviors.

Water-Surface Taxiing of Amphibious Aircraft

The water-surface taxiing process of amphibious aircraft involves complex elastic vibration modes [**?**]. During high-speed taxiing and hydroplaning, the interaction between these elastic modes and the wave environment is a critical factor.

Water-skiing of amphibious aircraft

vibration occurs due to coupling with the encounter frequency [**?**].

Starting from the fundamental principles of structural dynamics, the elastic structure of an aircraft

research experience is still relatively lacking. Relevant water load designs are primarily based on engineering

The dynamic equations can be expressed as

algorithms and model basin tests: National Military Standards and the Civil Aviation Regulations of China

Where: M is the generalized mass matrix; C is the generalized damping matrix; K is the

Currently, domestic research on the landing and taxiing problems of amphibious aircraft

Part 25 (CCAR-25-R4) provides rigid-body water loads derived from the assumption of a rigid

generalized stiffness matrix; $q(t)$ is the generalized coordinate vector describing structural deformation;

body aircraft, which fails to account for the elastic dynamic effects of water

$F(t)$ is the dynamic load vector in the time domain. This equation establishes the mathematical relationship between dynamic

loads; model basin tests also consistently utilize

loads and the structural elastic response, serving as the basis for analyzing aircraft dynamic rigid models for

[12-13]

Ignoring the effects of the elastic deformation of the airframe, we obtain

Submission Website: https://cjam.xjtu.edu.cn

This forms the core foundation for response analysis [?]. WeChat Official Account: Journal of Applied Mechanics.

The dynamic response analysis of an aircraft primarily investigates the macroscopic behavior of the airframe structure.

Simplified simulations are performed on the system. The primary dynamic behavior of the aircraft structure is characterized by bending and torsional deformations, with its elastic dynamic response dominated by the first few low-frequency modes [?]. In engineering practice, single-beam models from the field of aeroelasticity are frequently used to simulate the dynamic characteristics of the aircraft and subsequently conduct dynamic response analysis. The parameters of the beam elements can be equivalently calculated using closed-section theory.

Equivalent calculations are performed.

During taxiing takeoff, national military standards assume that the aerodynamic lift of the aircraft is zero [?].

Considering the downward inertial load, the load factor is

Based on the principle of major simplification, the elastic dynamic response problem of complex aircraft structures is simplified into a one-dimensional beam bending-torsion problem; the specific simplification methods can be found in relevant aeroelasticity literature. The single-beam model preserves the mapping relationship between "elastic parameters (E, G) - inherent characteristics (ω_i, ϕ_i) - dynamic response (resonance, transient response, random response)," thereby satisfying the requirements for dynamic response analysis.

where V_{s1} is the stall speed at a given weight; β is the deadrise angle at the step; W is the design takeoff weight of the aircraft; and $n_0 = n$ is the water load factor at the center of gravity during takeoff. 2) Landing conditions.

During water landing, national military standards assume that the aerodynamic lift of the aircraft is 2/3 of the landing weight [?].

The water surface reaction load factor during step impact landing is

The matrix exerts critical influences on the dynamic response, such as frequency shifts, amplitude amplification, and modal coupling. It serves as an efficient theoretical tool for dynamic analysis during the preliminary design phase of the aircraft.

The results of the Ground Vibration Test (GVT) are used to update the model to improve the accuracy of the dynamic simulation. Model updating methods typically include matrix updating methods, parametric updating methods, and neural network updating methods.

C 1 V2S0

(tan 2 / 3 β) · W 1ZS/ 3

The water surface reaction force load coefficients for the bow and stern during water entry are given by:

In engineering practice, the single-beam model should subsequently be validated through full-scale ground tests.

[21- 22]

(tan 2 / 3 β) · W 1 / 3

In the formula: C_{TO} is the aircraft operational experience coefficient, C_{TO} = 0.00307; V_{S1}

meets engineering requirements. This model reveals that structural elasticity, by adjusting stiffness,

C TO V2S1

The flap is set to the corresponding takeoff position, and the takeoff weight is designed for the water surface.

The single-beam model is constructed through stiffness equivalence, mass equivalence, and modal truncation.

[25- 26]

1) Takeoff Conditions

Due to its load-bearing and transmission characteristics, the system can be modeled as a multi-degree-of-freedom structure composed of elastic elements.

Li Junlong, et al. Analysis of Hydrodynamic Response during Water Landing and Taxing for Amphibious Aircraft

C 1 V2S0

(tan β) · W

(1 + r 2x) 2 / 3

In the equation, C_1 represents the aircraft control coefficient, where C_1 = 0.00922 for $h_{1/3} \leq 1.25$ m.

C 1 = 0. 011 68,1. 25 m < h 1 / 3 ≤ 2 m

However, this coefficient must not be less than the value required to obtain the minimum step-break load coefficient.

The numerical values required; V_{S0} represents the stall speed in the landing configuration with flaps extended to the corresponding position.

[Figure 1: see original paper]

In the design of flight control systems, the determination of characteristic speeds is fundamental to ensuring aircraft safety and performance. These parameters are typically derived from aerodynamic modeling and validated through flight testing. When the flaps are deployed, the lift coefficient increases, thereby reducing the stall speed V_{S0} and allowing for lower approach and landing speeds. This transition must be carefully managed within the flight control laws to maintain adequate structural margins and maneuverability.

Water Loads Under the Rigid Body Assumption

In the field of marine engineering and naval architecture, calculating the impact of water loads on structures is a fundamental requirement for ensuring structural integrity and operational safety. When analyzing these interactions, the "rigid body assumption" is frequently employed as a primary simplification. This assumption posits that the structure itself does not undergo any deformation under the influence of external hydrodynamic forces, allowing researchers to focus exclusively on the global motion and the pressure distribution exerted by the fluid.

Theoretical Framework

Under the rigid body assumption, the motion of a vessel or offshore structure is typically defined by six degrees of freedom (6-DOF): translations along the three principal axes (surge, sway, and heave) and rotations about them (roll, pitch, and yaw). The water loads acting on such a body are generally categorized into hydrostatic and hydrodynamic components.

The hydrostatic load is governed by Archimedes' principle and depends solely on the submerged geometry of the rigid body in a state of equilibrium. In contrast, hydrodynamic loads are more complex, arising from the relative motion between the body and the fluid. These are further subdivided into:

- **Radiation Forces:** Loads generated by the body' s own motion in calm water, typically characterized by added mass and damping coefficients.
- **Excitation Forces:** Loads caused by incident waves acting upon the fixed body, including Froude-Krylov forces and diffraction forces.

Governing Equations and Pressure Distribution

To determine the total water load, the fluid is often assumed to be inviscid, incompressible, and irrotational, allowing for the application of potential flow theory. The velocity potential ϕ must satisfy the Laplace equation:

$$\nabla^2\phi = 0$$

Once the velocity potential is solved using appropriate boundary conditions on the hull surface and the free surface, the local fluid pressure p can be derived from the Bernoulli equation:

$$p = -\rho\left(\frac{\partial\phi}{\partial t} + \frac{1}{2}|\nabla\phi|^2 + gz\right)$$

By integrating this pressure over the entire wetted surface area S of the rigid body, the total force $\mathbf{F}$ and moment $\mathbf{M}$ can be calculated:

$$\mathbf{F} = \iint_S p\mathbf{n}dS$$

$$\mathbf{M} = \iint_S p(\mathbf{r}\times\mathbf{n})dS$$

The stall speed at the design landing weight, excluding the effects of slipstream;

Introduction

Water loads represent a unique loading condition for amphibious aircraft. When an aircraft operates on a water surface, the interaction between the hull and the water generates complex hydrodynamic forces that differ significantly from those experienced by land-based aircraft. These loads are critical factors in the structural design, safety evaluation, and aerodynamic performance of amphibious platforms.

1.1 Characteristics of Water Loads

Unlike the relatively predictable impact forces encountered during runway landings, water loads are characterized by high nonlinearity and transient behavior. During takeoff and landing phases, the aircraft’ s hull must withstand intense slamming pressures, which are influenced by the aircraft’ s velocity, attitude, and the prevailing sea state. Understanding these loads is essential for ensuring the structural integrity of the fuselage and the stability of the aircraft during water maneuvers.

1.2 Research Significance

Accurately predicting water loads is a fundamental challenge in the development of advanced amphibious aircraft. Traditional empirical formulas often provide conservative estimates, which can lead to excessive structural weight. By employing modern computational fluid dynamics (CFD) and experimental testing, researchers can better characterize the pressure distribution across the hull. This precision allows for optimized structural design, reducing weight while maintaining the necessary safety margins required for multi-environment operations.

W_{ZS} represents the design landing weight of the aircraft; K_1 is the empirical weighting coefficient for the hull station; r_x denotes the distance from the center of gravity to the hull landing station, measured parallel to the hull reference axis.

The problem of planing on waves is, in a strict sense, a transient impact problem. When a planing craft travels at high speeds, the interaction between the hull and the wave surface generates intense hydrodynamic loads. These loads are characterized by their short duration and high peak values, which significantly influence the vessel’ s motion response and structural integrity.

[Figure 1: see original paper]

1.1 Mathematical Model and Governing Equations

To accurately describe the slamming phenomenon during the planing process, we consider the fluid to be incompressible and inviscid, with the flow being irrotational. Under these assumptions, the velocity potential ϕ satisfies the Laplace equation within the fluid domain:

$$\nabla^2\phi = 0$$

The boundary conditions on the free surface, accounting for both kinematic and dynamic effects, are expressed as:

$$\begin{gathered}\frac{D\eta}{Dt} = \frac{\partial\phi}{\partial z}\\ \frac{D\phi}{Dt} = -gz + \frac{1}{2}|\nabla\phi|^2\end{gathered}$$

where η represents the free surface elevation and g is the acceleration due to gravity. For a planing craft moving at a constant forward velocity V, the body boundary condition on the wetted surface S_B is given by:

$$\frac{\partial\phi}{\partial n} = \mathbf{V}\cdot\mathbf{n}$$

where $\mathbf{n}$ is the unit normal vector pointing into the fluid.

1.2 Hydrodynamic Impact Force

The instantaneous pressure distribution p on the hull can be derived from the Bernoulli equation:

$$p = -\rho \left(\frac{\partial \phi}{\partial t} + \frac{1}{2} |\nabla \phi|^2 + gz \right)$$

In the context of high-speed planing, the slamming force is often dominated by the rate of change of added mass. According to the momentum theory proposed by [?], the vertical impact force F_z can be approximated as:

$$F_z = \frac{d}{dt}(m_a w)$$

where m_a is the 2D added mass of the section and w is the relative vertical velocity between the hull and the wave surface. As shown in , the peak pressures recorded during wave impact are significantly higher than those observed in

the ratio of the distance of the position to the aircraft' s pitch radius of gyration.

Introduction

The impact problem is a critical consideration in the design and operation of marine vessels. In practical scenarios, when an amphibious aircraft moves on the water surface, it is subjected to complex hydrodynamic forces that significantly influence its structural integrity and stability. These interactions are particularly pronounced during takeoff and landing phases, where the high-velocity impact between the aircraft hull and the water surface can lead to substantial impulsive loads. Understanding these phenomena is essential for ensuring the safety and performance of amphibious platforms under varying environmental conditions.

The water load factor at the center of gravity during water landing is given by $n_0 = n_w + 2/3$.

The aquatic environment is considerably complex, making it difficult to accurately calculate the water loads acting on an aircraft during takeoff and landing on water.

As can be observed from the aforementioned content, domestic codes and standards do not currently take into account the effects of touchdown and sliding.

In the absence of more accurate methods, the dynamic response analysis of hydroplaning can be effectively utilized to evaluate the safety performance of aircraft tires during takeoff and landing on contaminated runways. Hydroplaning occurs when a layer of fluid builds up between the tire and the runway surface, leading to a loss of traction and potential loss of directional control. By employing computational fluid dynamics (CFD) coupled with finite element analysis (FEA), researchers can simulate the complex interactions between the tire structure, the fluid film, and the pavement texture. These analyses provide critical insights into the critical hydroplaning speed and the reduction in braking efficiency under various water film thicknesses and tire inflation pressures.

Consequently, such modeling serves as a vital tool for developing safety protocols and improving tire tread designs to mitigate the risks associated with wet runway conditions.

Abstract

This study investigates the dynamic effects of water loads. Based on the requirements of domestic Chinese codes, we analyze the impact of water-structure interaction on structural response.

1. Introduction

The dynamic effect of water load is a critical factor in the safety assessment of hydraulic structures. Traditional static analysis methods often fail to capture the complex behavior of fluid-structure interaction during seismic events or rapid water level fluctuations. This research focuses on the dynamic characteristics of water loads and their influence on structural stability, adhering to the technical standards and design specifications currently mandated within domestic engineering frameworks.

2. Dynamic Effects of Water Loads

When a structure is subjected to dynamic excitation, the surrounding water body exerts additional hydrodynamic pressure. This pressure is not merely a static force but a time-varying load that depends on the acceleration of the structure and the compressibility of the fluid.

2.1 Theoretical Framework

The interaction between the water and the structure can be described by the governing equations of fluid mechanics. For an incompressible fluid, the hydrodynamic pressure P satisfies the Laplace equation:

$$\nabla^2 P = 0$$

In cases where fluid compressibility cannot be ignored, the wave equation is employed:

$$\nabla^2 P = \frac{1}{c^2} \frac{\partial^2 P}{\partial t^2}$$

where c represents the speed of sound in water. The boundary conditions at the fluid-structure interface must ensure that the normal acceleration of the fluid matches the acceleration of the structural boundary.

2.2 Compliance with Domestic Codes

According to the current domestic design specifications for hydraulic structures, the calculation of dynamic water loads must account for added mass effects. These codes provide empirical formulas and numerical guidelines to ensure that the structural design can withstand potential seismic loads. This study evaluates these regulatory requirements by comparing simplified code-based calculations with advanced numerical simulations.

[Figure 1: see original paper]

3. Methodology

To analyze the dynamic effects, a coupled finite element model (FEM) was developed. The structure is represented by solid elements, while the reservoir water is modeled using fluid elements that account for both hydrostatic and hydrodynamic pressures.

3.1 Modeling Fluid-Structure Interaction

The coupling at the interface is handled by enforcing displacement compatibility and force equilibrium. The total load acting on the structure is the sum of the static water pressure and the dynamic increment:

$$F_{total} = F_{static} + F_{dynamic}$$

[TABLE

The process is divided into two steps: first, the flight characteristics are calculated using empirical formulas without considering the elasticity of the airframe; second, these results are refined by incorporating structural flexibility.

1. Calculation of Aerodynamic Coefficients

The calculation of aerodynamic coefficients is a critical component of flight vehicle design. In the initial stage, we assume a rigid body model to simplify the preliminary analysis.

1.1 Empirical Formula Approach

Without considering the elasticity of the airframe, the aerodynamic coefficients are determined using established empirical formulas. These formulas are derived from extensive wind tunnel testing and historical flight data, providing a rapid estimation of lift, drag, and moment coefficients. The lift coefficient C_L is typically expressed as a function of the angle of attack α:

$$C_L = C_{L0} + C_{L\alpha}\alpha$$

where C_{L0} represents the lift coefficient at zero angle of attack and $C_{L\alpha}$ is the lift curve slope. Similarly, the drag coefficient C_D is modeled using the drag polar equation:

$$C_D = C_{D0} + KC_L^2$$

In this expression, C_{D0} is the zero-lift drag coefficient and K is the induced drag factor. These parameters allow for an initial assessment of the vehicle' s performance envelope and stability margins.

[Figure 1: see original paper]

1.2 Limitations of the Rigid Model

While the empirical approach provides a computationally efficient baseline, it neglects the structural deformation that occurs under aerodynamic loading. In high-speed or high-aspect-ratio configurations, the interaction between aerodynamic forces and structural elasticity—known as aeroelasticity—can significantly alter the effective geometry of the vehicle, thereby modifying the pressure distribution and resulting aerodynamic forces.

2. Consideration of Structural Elasticity

To achieve higher fidelity in the flight simulation, the second step involves coupling the aerodynamic model with a structural model. This accounts for the deformation of components such as wings and control surfaces.

2.1 Aeroelastic Coupling

When the airframe is treated as an elastic body, the local angle of attack is modified by the torsional and bending deformations of the structure. The total displacement vector **u** can be represented using a modal superposition approach:

$$\mathbf{u}(t) = \sum_{i=1}^{n} \phi_i q_i(t)$$

Based on this foundation, and incorporating research findings from similar foreign models [**?**], the flight characteristics were considered.

water loads under rigid aircraft conditions; (2) using the rigid aircraft water loads as input

Hydrodynamic Performance of Planing Hulls in Single and Regular Waves

In the field of marine engineering, understanding the hydrodynamic behavior of planing hulls is critical for ensuring operational stability and safety. This study investigates the performance of planing hulls when encountering two distinct wave conditions: single waves and regular waves.

1. Response to Single Waves

When a planing hull encounters a single wave, such as a solitary wave or a transient wake, it undergoes a rapid change in its equilibrium state. The interaction is characterized by a sudden increase in vertical acceleration and a significant shift in the longitudinal trim angle. As the hull strikes the wave crest, the impact force—often referred to as slamming—can lead to high local pressures on the hull' s bottom. The duration of this encounter is brief, yet the peak loads generated are often the limiting factors for structural design. Analyzing the time-history of the heave and pitch motions during a single wave encounter allows for the assessment of the vessel' s dynamic stability and the potential for deck wetting or "stuffing" into the next wave trough.

2. Response to Regular Waves

In contrast to the transient nature of single waves, regular waves (sinusoidal waves with constant frequency and amplitude) induce periodic oscillations in the planing hull. This scenario is essential for determining the vessel' s Transfer Functions or Response Amplitude Operators (RAOs).

[Figure 1: see original paper]

When operating in regular head seas, the planing hull exhibits complex coupling between heave and pitch motions. At specific encounter frequencies, resonance may occur, leading to amplified motions that significantly degrade crew comfort and increase the risk of structural fatigue. The hydrodynamic lift, which is the primary support mechanism for planing hulls, fluctuates as the submerged geometry changes periodically. This fluctuation affects the pressure distribution along the keel and the position of the center of pressure, further influencing the longitudinal stability of the craft.

3. Comparative Analysis

The primary difference between encountering single and regular waves lies in the accumulation of energy and the predictability of the motion. While single wave encounters are stochastic and require time-domain analysis to capture peak impact loads, regular wave studies provide a frequency-domain perspective that is vital for long-term seakeeping predictions. In both cases, the non-linear nature of the planing surface—where the wetted area varies significantly with speed and wave elevation—must be accounted for to achieve accurate numerical simulations or experimental correlations. Understanding these interactions is fundamental to optimizing hull forms for high-speed operations

Introduction

The study of the dynamic response characteristics of elastic aircraft is a critical component of modern aeronautical engineering. As aircraft designs trend toward higher aspect ratios and lighter structures to improve fuel efficiency and performance, the coupling between aerodynamic forces and structural elasticity becomes increasingly significant. This interaction, known as aeroelasticity, can profoundly influence the stability, control, and structural integrity of the vehicle.

To accurately predict these behaviors, it is necessary to develop robust mathematical models that integrate structural dynamics with unsteady aerodynamics. Traditional rigid-body assumptions are often insufficient for modern flexible aircraft, necessitating the inclusion of elastic degrees of freedom in the equations of motion. By solving for the dynamic response, engineers can evaluate how the aircraft reacts to atmospheric turbulence, control surface inputs, and sudden maneuvers.

The formulation typically involves a set of coupled differential equations. Let the generalized coordinates be represented by q, which include both rigid-body motions and elastic modal coordinates. The governing equation can be expressed in a general form as:

$$M\ddot{q} + C\dot{q} + Kq = F_{ext}(t)$$

where M, C, and K represent the generalized mass, damping, and stiffness matrices, respectively, and $F_{ext}(t)$ denotes the time-dependent external aerodynamic forces. Solving these equations requires sophisticated numerical methods and computational fluid dynamics (CFD) or doublet-lattice methods (DLM) to capture the transient nature of the aerodynamic loads. This paper explores the methodologies for solving these dynamic responses and analyzes the impact of structural flexibility on the overall flight characteristics.

[23- 24]

The takeoff and landing of amphibious aircraft on water can be categorized into water takeoff (planing) and water landing (alighting). In the following analysis, the takeoff and landing conditions are evaluated separately.

In practice, triangular waves are commonly used to simplify the simulation of cosine waves.

When an aircraft encounters a single wave, the water load coefficients are determined by Equation (2) and

Equation (3). The load rise time for the overload is typically taken to be between 0.065 and 0.25 s.

Domestic regulatory requirements, including the National Military Standards and CCAR-25-R4, are based on the assumption of a rigid body.

Empirical formulas for calculating water loads during water landing and take-off taxiing are provided. These formulas initially assume that the amphibious aircraft sustains the water loads as a single integrated