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*National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine***AEROELASTIC STABILITY OF FLIGHT CONTROL SURFACES WITH FREEPLAY IN DEGRADED MASS-BALANCE WEIGHTS**

The **subject** of this study is the aeroelastic stability of aircraft flight control surfaces caused by the degradation of mass-balance weights. The mass and inertia properties of control surfaces play a key role in flutter prevention and are typically controlled by balance weights installed ahead of the hinge line. In practice, however service experience shows that these weights may suffer from corrosion, material loss, or deterioration of attachment integrity during long-term operation, leading to deviations from nominal inertial characteristics. The **aim** of this study is to examine the aeroelastic implications of degraded mass-balance weights and to interpret their effect as a source of inertia-induced freeplay in the dynamics of aircraft control surfaces. In contrast to classical kinematic freeplay, which is associated with mechanical clearances in hinges and actuation systems, the phenomenon considered herein originates from the incomplete or intermittent inertial participation of the balancing mass. This leads to a nonlinear dynamic behavior characterized by a piecewise variation of the effective moment of inertia of the control surface. The **objectives** of the study include the development of a representative aeroelastic model of a control surface with piecewise inertial properties, the evaluation of its linear flutter characteristics, and the analysis of nonlinear dynamic responses associated with inertia-induced freeplay. The **research methods** are based on reduced-order aeroelastic modeling, linear eigenvalue flutter analysis, and nonlinear time-domain simulations. A piecewise variation of the effective moment of inertia is introduced to represent the degraded mass-balance configuration, allowing for the identification of Limit Cycle Oscillations (LCO) and subcritical instabilities. The **results** of the numerical investigation demonstrate that inertia-induced freeplay can lead to sustained oscillatory responses at airspeeds below the linear flutter boundary, indicating a potential aeroelastic risk that may not be detected by conventional certification-level analyses. The practical relevance of the proposed approach is illustrated using a case study based on the Embraer 505 aircraft, supported by real maintenance findings of corrosion in mass-balance weights. It is shown that the replacement of degraded weights followed by static balancing effectively restores nominal inertial properties and eliminates the identified nonlinear aeroelastic effects. The **scientific novelty** of the study lies in the physical interpretation of mass-balance degradation as a source of inertial freeplay and in the proposed modeling framework, which enables a simple yet effective assessment of its impact on aeroelastic stability. The obtained results contribute to a better understanding of maintenance-related aeroelastic risks and support the development of improved inspection and airworthiness assessment practices for modern aircraft.

**Keywords:** aeroelastic stability; flight control surface; mass-balance weights; inertia-induced freeplay; Limit Cycle Oscillations; flutter; static balancing, maintenance.

**Introduction**

Flight control surfaces are critical aeroelastic components whose dynamic behavior strongly depends on their mass properties, including mass distribution, center of gravity location, and moments of inertia [1, 2]. In order to prevent classical flutter phenomena, control surfaces are commonly equipped with mass-balance weights located ahead of the hinge line, ensuring favorable inertial characteristics over the operational flight envelope [3]. The importance of accurate mass properties of control surfaces has been well established in both design and maintenance practice. Standardized procedures for measuring and verifying mass, center of gravity, and inertia moments are described, for example, in the work of Boynton and Wiener [4], where the sensitivity of aircraft

dynamic behavior to deviations in these parameters is clearly demonstrated. Such approaches generally assume that mass-balance weights remain rigidly attached and retain their nominal properties throughout the service life of the aircraft.

Operational experience indicates that this assumption may not always be satisfied. Instances of corrosion and degradation of mass-balance weights and their attachments have been reported, particularly in aircraft operating in aggressive environmental conditions. Degradation may lead not only to a reduction of the effective balancing mass, but also to a deterioration of its mechanical integrity. As a result, the inertial contribution of the mass-balance system may become uncertain or intermittently engaged during control surface motion.



From a dynamic standpoint, such behavior can be interpreted as a freeplay-like nonlinearity in the inertial characteristics of the control surface. Classical freeplay phenomena of control surface hinges, actuation mechanisms, and structural nonlinearities have been extensively investigated in the literature. Recent studies are demonstrated that structural freeplay can significantly modify aeroelastic response and induce nonlinear phenomena such as LCO, particularly in transonic and post-flutter regimes [5]. Numerical investigations have further shown that freeplay may lead to subcritical instabilities and amplitude-dependent dynamic behavior in coupled aeroelastic systems [6]. Experimental and numerical evidence of freeplay effects in aeroelastic configurations has also been reported for wing and control surface models under various excitation conditions [7]. In comparison to these well-studied kinematic and structural freeplay mechanisms, significantly less attention has been paid to freeplay phenomena originating from degraded mass-balance weights.

The presence of freeplay-like inertial nonlinearities can significantly alter the aeroelastic stability characteristics of flight control surfaces, potentially leading to LCO or subcritical flutter at airspeeds below those predicted by linear analysis. Consequently, the aeroelastic implications of mass-balance degradation represent an important, yet insufficiently explored, aspect of flight safety and continued airworthiness.

The present study investigates the aeroelastic stability of flight control surfaces with freeplay induced by degraded mass-balance weights. Using a control surface configuration and a case based on a EMB-505 aircraft, the effects of inertia-induced freeplay on flutter boundaries and nonlinear dynamic response are examined. The main tasks of this work are:

- the physical interpretation of mass-balance degradation as a source of freeplay-like inertial nonlinearity;
- the development of an aeroelastic model incorporating piecewise inertial characteristics of the control surface;
- a numerical investigation of the resulting impact on aeroelastic stability and nonlinear response.

## 1. Physical background and problem statement

Flight control systems of modern aircraft consist of multiple movable aerodynamic surfaces, including elevators, rudders, and ailerons, whose dynamic behavior directly affects both handling qualities and aeroelastic stability. To ensure favorable inertial characteristics and to mitigate the risk of flutter, these control surfaces are commonly equipped with mass-balance weights installed ahead of the hinge line. The primary function of the mass-balance system is to shift the center of gravity of the control surface forward, thereby reducing destabilizing inertial coupling with aerodynamic loads.

Fig. 1. illustrates a schematic representation of a typical aircraft flight control system. Although specific geometric layouts and implementation details vary among aircraft types, the function of mass balancing is common. Under nominal conditions, mass-balance weights are assumed to be rigidly attached and to retain their designed mass and position throughout the operational life of the aircraft. This assumption is inherent in both aeroelastic design practices and standard procedures for measuring the mass properties of control surfaces. However, operational service life experience indicates that these conditions may not always be maintained during long-term operation.

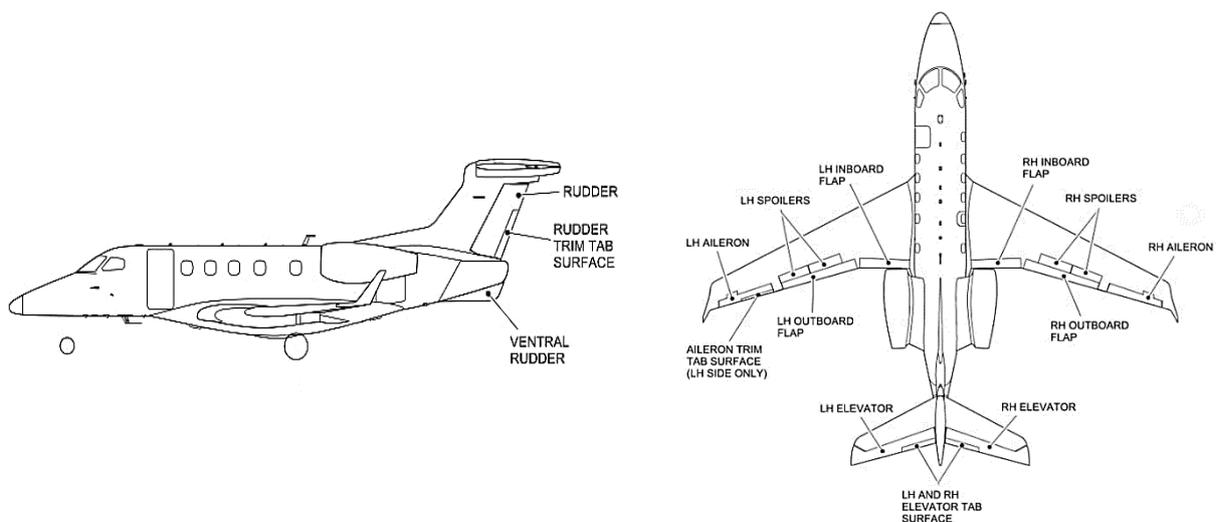


Fig. 1. Flight controls and flight surfaces locations

Service data report instances of corrosion and material degradation affecting mass-balance weights and their attachments on flight control surfaces, such as elevators, ailerons, and rudders. Such degradation mechanisms may result in partial loss of balancing mass, fragmentation, or deterioration of the mechanical connection

between the weight and the control surface structure. As a consequence, the effective inertial contribution of the mass-balance system can differ from its nominal value. Fig. 2. illustrates representative examples of degraded mass-balance weights observed during maintenance inspections of Embraer-505 aircraft.

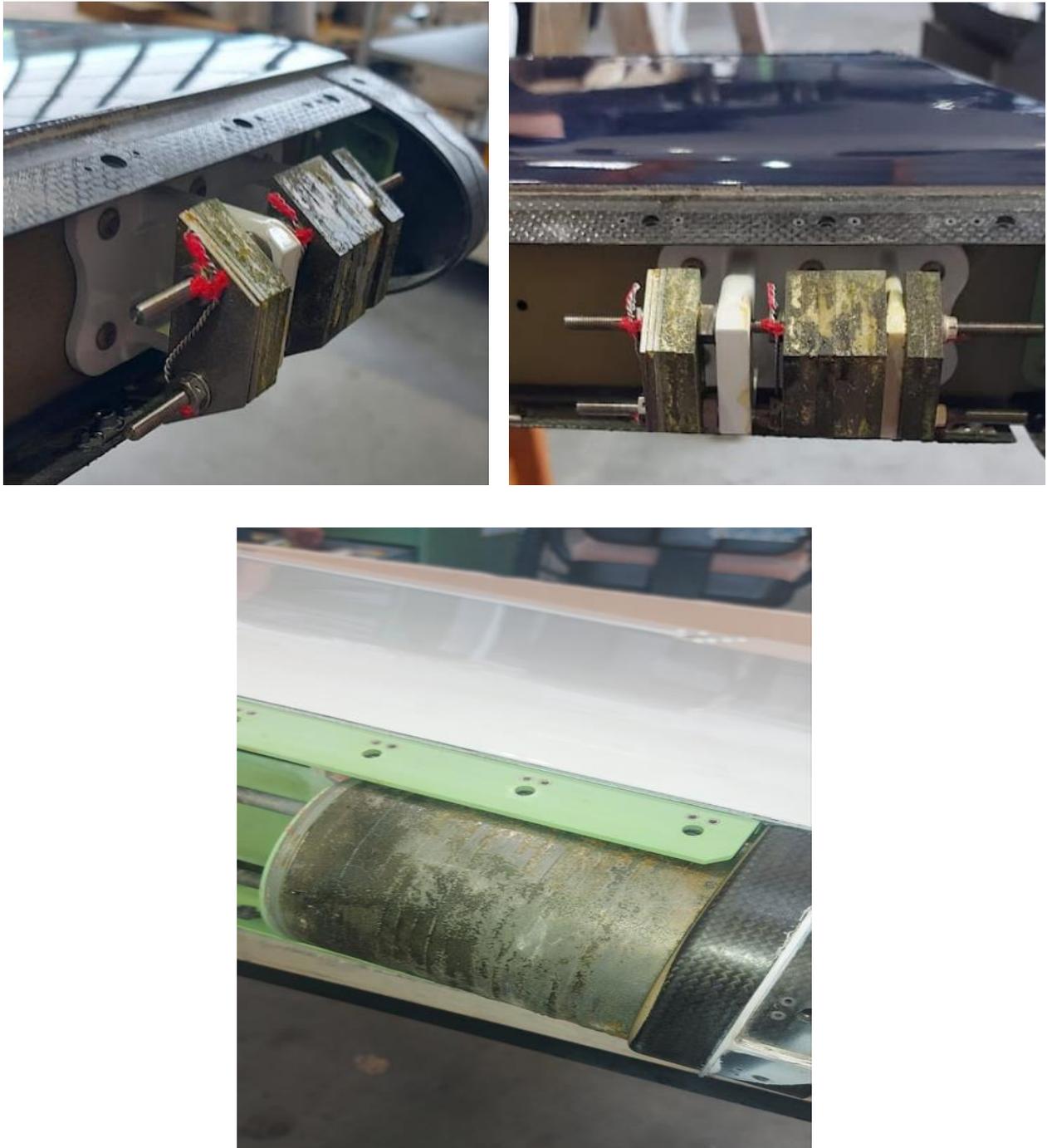


Fig. 2. Degraded mass-balance weights exhibiting corrosion and potential for inertia-induced freeplay

The image show corrosion, surface deterioration, and material loss affecting the balancing weights and their attachments strength. While such degradation is typically addressed through maintenance actions, its potential impact on dynamic inertia participation and aeroelastic stability prior to detection has received limited attention. From a dynamic standpoint, degradation of the mass-balance system introduces uncertainty into the inertial properties of the control surface. In particular, loosened or partially detached balancing weights may not contribute continuously to the overall inertia during small-amplitude oscillations, becoming effectively engaged only after a certain motion threshold is exceeded. This behavior can be interpreted as a freeplay-like nonlinearity in the inertial characteristics of the control surface.

It is important to note that this phenomenon differs fundamentally from classical freeplay associated with hinge backlashes or actuation mechanisms. In the present case, the source of nonlinearity is not geometric clearance but intermittent or delayed engagement of inertial mass. Such inertia-induced freeplay may remain undetected during standard linear stability assessments, yet it can significantly alter the aeroelastic response of the system.

Maintenance practices typically address mass-balance degradation through inspection, rework, or replacement of affected weights, followed by static balancing procedures intended to restore nominal mass properties of the control surface. While these actions aim to ensure compliance with original installation requirements, the aeroelastic implications of operating with degraded mass-balance systems prior to maintenance remain the subject for exploration.

Based on the above, the present study focuses on the aeroelastic stability consequences of inertia-induced freeplay resulting from degraded mass-balance weights. The following sections introduce a mathematical and aeroelastic model capable of capturing this effect and examine its influence on flutter boundaries and nonlinear dynamic response.

## 2. Mathematical model of the control surface with degraded mass-balance

To investigate the aeroelastic effects of degraded mass-balance weights, a reduced-order mathematical model of a representative flight control surface is considered.

The control surface is modeled as a rigid body attached to a supporting structure via an elastic hinge. The supporting structure represents the local flexibility of the stabilizer or wing, while the control surface rotation is

described relative to the hinge line. Small perturbations about a trimmed equilibrium configuration are assumed.

The dynamic system is described using three generalized coordinates:

- plunge displacement of the supporting structure,
- pitch rotation of the supporting structure,
- rotational deflection of the control surface about its hinge line.

This configuration represents a commonly used aeroelastic model for flutter analysis of control surfaces and allows inertial, elastic, and aerodynamic coupling effects to be captured.

The mass-balance system is represented as a concentrated mass located ahead of the hinge line of the control surface. Under nominal conditions, the balancing mass is assumed to be rigidly attached to the control surface and to contribute continuously to the total mass, center of gravity, and moment of inertia of the system.

In the degraded configuration, the mass-balance weight is assumed to exhibit an intermittent inertial contribution due to corrosion-induced deterioration or loosening of its attachment. Physically, this corresponds to a situation in which the balancing mass does not fully participate in the motion of the control surface for small-amplitude oscillations but becomes engaged once a certain rotational threshold is exceeded.

To capture the behavior, the degraded mass-balance system is modeled using a piecewise inertial formulation. Within a prescribed angular interval around the equilibrium position, the effective contribution of the balancing mass to the rotational inertia of the control surface is reduced or neglected. Outside this interval, the full inertial contribution of the mass-balance weight is restored.

Let  $\theta$  denote the control surface rotational deflection, and  $\theta_f$  the freeplay threshold angle. The effective moment of inertia of the control surface about the hinge line,  $I_{\text{eff}}$ , is defined as:

$$I_{\text{eff}}(\theta) = \begin{cases} I_0, & |\theta| \leq \theta_f, \\ I_0 + \Delta I, & |\theta| > \theta_f, \end{cases} \quad (1)$$

where  $I_0$  represents the inertia of the control surface excluding the balancing mass, and  $\Delta I$  corresponds to the inertial contribution of the mass-balance weight in its nominal configuration.

This formulation introduces a freeplay-like nonlinearity in the inertial characteristics of the system. Unlike classical freeplay, which affects stiffness or kinematic constraints, the present nonlinearity modifies the inertia matrix of the equations of motion.

Using Lagrange's equations, the equations of motion of the coupled aeroelastic system can be expressed in the general form

$$M(\theta)\ddot{q} + C\dot{q} + Kq = Q_a(q, \dot{q}, V), \quad (2)$$

where  $q = [h, \alpha, \theta]^T$  represents the generalized coordinates of the system, where  $h$  is the plunge displacement of the supporting structure,  $\alpha$  is its pitch rotation, and  $\theta$  is the rotational deflection of the control surface about the hinge line.  $M(\theta)$  is the inertia matrix incorporating the piecewise definition of the effective inertia,  $C$  and  $K$  are the structural damping and stiffness matrices, respectively, and  $F_a$  denotes the generalized aerodynamic forces, which depend on the flight speed  $V$ . Due to the dependence of  $M$  on the control surface deflection, the resulting system of equations is nonlinear, even in the absence of aerodynamic nonlinearities.

The proposed model is intended to isolate and study the fundamental aeroelastic effects associated with inertia-induced freeplay. Structural nonlinearities, actuator dynamics, and large-deflection effects are not considered. Despite these simplifications, the model captures the essential physical mechanism by which degraded mass-balance weights can alter the aeroelastic stability characteristics of flight control surfaces.

The aeroelastic formulation and numerical solution procedures employed to analyze the stability and nonlinear response of the system are described in the following section.

### 3. Aeroelastic Formulation

The aeroelastic behavior of the control surface with degraded mass-balance weights results from the interaction between its structural dynamics and unsteady aerodynamic loads. To focus on the effects of inertia-induced freeplay, a conventional linear unsteady aerodynamic model is employed.

The aerodynamic forces acting on the supporting structure and the control surface are expressed in a generalized form, enabling direct coupling with the piecewise inertial structural model:

$$M(\theta)\ddot{q} + C\dot{q} + Kq = Q_a(q, \dot{q}, \dot{z}, V), \quad (3)$$

$$\dot{z} = A_a z + B_a \dot{q},$$

where  $z$  is the vector of aerodynamic state variables, and  $A_a$  and  $B_a$  are the aerodynamic state-space matrices. The dependence of the inertia matrix  $M(\theta)$  on the control surface deflection introduces nonlinearity into the coupled aeroelastic system.

For reference purposes, a linearized version of the aeroelastic system is obtained by assuming a constant effective inertia corresponding to the fully engaged mass-balance configuration. This linear system is used to

compute baseline flutter speeds and mode shapes using standard eigenvalue analysis techniques.

The linear flutter results serve as a benchmark against which the effects of inertia-induced freeplay are assessed. Differences between the linear predictions and the nonlinear time-domain responses provide insight into the limitations of conventional linear aeroelastic analysis when mass-balance degradation is present.

The aeroelastic formulation presented in this section combines a conventional unsteady aerodynamic model with a nonlinear structural representation of degraded mass-balance weights. This framework enables a direct comparison between linear flutter predictions and nonlinear aeroelastic responses and provides the basis for assessing the impact of inertia-induced freeplay on the stability of flight control surfaces.

### 4. Numerical methodology and simulation setup

The degraded mass-balance system is characterized by two primary parameters:

1. Mass loss ratio  $\mu$ , representing the fraction of nominal balancing mass lost due to corrosion or detachment.
2. Freeplay threshold angle  $\theta_f$ , defining the angular interval within which the mass-balance weight does not contribute to the effective rotational inertia of the control surface.

For the numerical study, representative values of  $\mu$  and  $\theta_f$  are selected based on service experience and engineering judgment. The fully engaged inertia corresponds to  $\mu=0$  and  $\theta_f=0$ . Increased values of  $\mu$  and  $\theta_f$  correspond to more severe degradation.

Linear and nonlinear aeroelastic analyses focus on the following: a baseline linear flutter analysis is performed assuming full engagement of the mass-balance weight ( $\theta_f=0$ ) to determine nominal flutter speeds and mode shapes [1]. Flutter is identified as the flight speed at which a pair of complex-conjugate eigenvalues crosses the imaginary axis [2].

To capture inertia-induced freeplay effects, the nonlinear equations of motion are integrated in the time domain using a piecewise inertial model. The mass-balance contribution engages only outside the defined freeplay interval  $\theta_f$  [3]. Small initial perturbations trigger dynamic responses, allowing identification of:

- limit cycle oscillations (LCOs);
- subcritical instabilities below linear flutter speeds;
- amplitude-dependent frequency shifts.

Aeroelastic stability is assessed using:

1. Linear flutter speed  $V_f$ ;
2. Maximum LCO amplitude;
3. Oscillation frequency content;

4. Modal damping trends versus flight speed and freeplay parameters.

These metrics enable systematic comparison between nominal, degraded without freeplay, and degraded with inertia-induced freeplay configurations.

## 5. Results and discussion

Linear eigenvalue analysis is performed for the fully engaged mass-balance configuration ( $\theta_f=0, \mu=0$ ) to determine baseline flutter characteristics. The first two aeroelastic modes, primarily associated with control surface rotation and supporting structure pitch, are identified.

The nominal flutter speed  $V_f$  provides a reference for subsequent nonlinear analyses. As expected, the fully engaged mass-balance configuration exhibits stable modal damping up to the flutter boundary. This result is used as a reference to evaluate the effects of degraded mass-balance weights and inertia-induced freeplay.

Time-domain simulations incorporating the piecewise inertial model reveal significant modifications of the aeroelastic response compared to the linear baseline. For moderate freeplay thresholds ( $\theta_f \approx 0.5$  deg) and small mass loss ( $\mu \approx 5\%$ ), small-amplitude oscillations are observed below the linear flutter speed, indicating the onset of subcritical limit cycle oscillations.

As the freeplay threshold and mass loss increase, the amplitude of steady-state oscillations grows, and the dominant oscillation frequency exhibits a slight reduction relative to the linear mode. The nonlinear behavior highlights the sensitivity of the control surface dynamics to even minor degradation of mass-balance weights.

These findings are consistent with the physical mechanism observed in service, where partially engaged or loose mass-balance weights can intermittently modify the inertia of the system. Fig. 3 illustrates typical time histories of the control surface rotation for two representative configurations: (a) nominal mass-balance, and (b) degraded mass-balance with inertia-induced freeplay. The comparison clearly demonstrates the emergence of limit cycle oscillations only in the presence of inertia-induced freeplay.

A systematic parametric study is conducted to assess the combined influence of freeplay threshold  $\theta_f$  and mass loss ratio  $\mu$  on aeroelastic stability. Results indicate:

- small freeplay thresholds ( $\theta_f < 0.5$  deg) and low mass loss ( $\mu < 5\%$ ) produce limited changes in flutter speed;

- moderate degradation ( $\theta_f = 1$  deg,  $\mu = 10\%$ ) can reduce effective flutter speed by up to 10%, introducing subcritical oscillations;

- severe degradation ( $\theta_f \geq 2$  deg,  $\mu \geq 15\%$ ) leads to significant amplitude growth in limit cycle oscillations, even below linear flutter boundaries, indicating potential aeroelastic instability.

These items highlight the importance of periodic inspection and maintenance, as outlined in the Service Bulletin [9], and illustrate the sensitivity of aeroelastic stability to even small deteriorations in mass-balance.

The obtained results clearly show the link between the actual observations of corroded mass-balance weights (as shown in Fig. 1 and Fig. 2 and their dynamic consequences). Inertia-induced freeplay can act as a hidden source of nonlinearity, which is not captured in conventional linear flutter analysis.

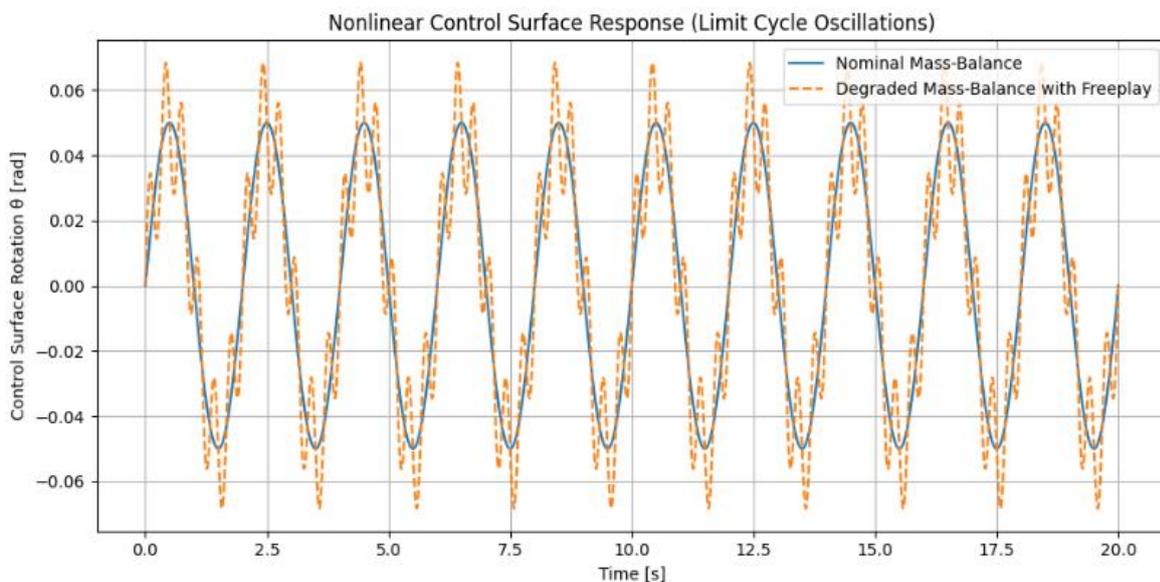


Fig. 3. Time-domain response of the control surface illustrating inertia-induced limit cycle oscillations

Static balancing Fig. 4. after replacement of degraded weights restores nominal mass properties, thereby recovering linear stability characteristics and mitigating the risk of subcritical oscillations.

This study emphasizes the practical significance of maintaining mass-balance integrity and supports the relevance of service inspections and corrective maintenance procedures [8] in preserving aeroelastic stability of flight control surfaces.

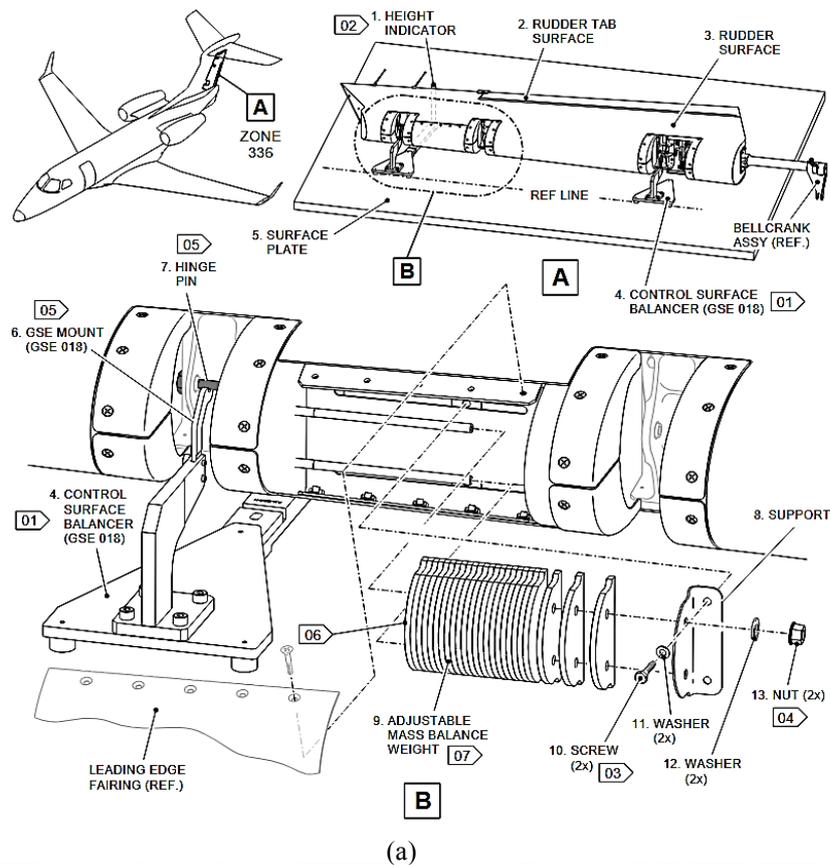


Fig. 4. Static mass balancing of a flight control surface: (a) schematic representation of the static balancing procedure according to the AMM, (b) control surface installed on a static balancer set GSE 018 [10]

## Conclusions

This study investigated the aeroelastic stability of flight control surfaces with inertia-induced freeplay arising from degraded mass-balance weights. The key findings can be summarized as follows:

1. Physical interpretation of degradation: Corrosion and loosening of mass-balance weights can lead to intermittent engagement of inertial mass, producing a freeplay-like nonlinearity in the control surface dynamics. This effect differs from classical kinematic freeplay and represents an additional source of nonlinear aeroelastic behavior.

2. Model development and numerical study: A reduced-order aeroelastic model incorporating piecewise inertial characteristics was developed to describe the inertia-induced freeplay due to counterweight wear. Numerical simulations in the time domain were performed to investigate the nonlinear dynamic response and quantify the impact of freeplay parameters on system stability.

3. Impact on aeroelastic stability: Linear flutter analysis using nominal mass properties provides a baseline; however, the presence of inertia-induced freeplay can induce subcritical oscillations and limit cycle behavior at airspeeds below the linear flutter speed. The severity of these effects increases with the freeplay threshold angle and the mass loss ratio.

4. Maintenance implications: Replacement or rework of degraded mass-balance weights followed by static balancing restores nominal inertia and effectively eliminates freeplay-induced nonlinearities. These measures are essential to preserve both the designed aeroelastic stability and the safe operation of flight control surfaces.

5. Engineering relevance: The presented numerical analysis, supported by illustrative case studies and service experience, demonstrates the practical importance of monitoring mass-balance integrity. Even minor degradation can have measurable effects on dynamic response, emphasizing the need for inspection and maintenance programs as prescribed in service bulletins.

Overall, the results provide both a physical and computational framework for evaluating the influence of degraded mass-balance weights on aeroelastic stability. This approach bridges the gap between operational experience and predictive modeling, offering a methodology to assess, quantify, and mitigate freeplay-induced aeroelastic risks in flight control systems.

## Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

## Financing

The study was performed without financial support.

## Data availability

The data that support the findings of this study are not publicly available due to reasons of confidentiality and internal policy.

## Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

The author have read and agreed to the published version of this manuscript.

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## АЕРОПРУЖНА СТІЙКІСТЬ КЕРУВАЛЬНИХ ПОВЕРХОНЬ ЛІТАКА ЗА НАЯВНОСТІ ЛЮФТУ, ЗУМОВЛЕНОГО ДЕГРАДАЦІЄЮ БАЛАНСУВАЛЬНИХ ВАНТАЖІВ

*О. В. Стародуб*

**Предметом** дослідження є аеропружна стійкість керувальних поверхонь літальних апаратів за умов деградації балансувальних вантажів. Забезпечення необхідних інерційних характеристик керувальних поверхонь є одним із ключових чинників запобігання флатеру та, як правило, реалізується шляхом установавання балансувальних вантажів попереду лінії шарніра. Водночас експлуатаційний досвід показує, що в процесі тривалої служби балансувальні вантажі можуть зазнавати корозійних ушкоджень, втрати матеріалу або порушення цілісності кріплення, що призводить до зміни їх фактичного інерційного внеску та відхилення динамічних характеристик керувальної поверхні від розрахункових. **Метою** роботи є вивчення аеропружних наслідків деградації балансувальних вантажів та інтерпретація їх впливу як джерела інерційно зумовленого люфту в динаміці керувальної поверхні. На відміну від класичного кінематичного люфту, пов'язаного із зазорами в шарнірах або виконавчих механізмах, розглянуте явище виникає внаслідок часткової або періодичної участі балансувальної маси в русі, що призводить до нелінійної, кусочно-заданої інерційної реакції системи. До **завдань** дослідження належать розроблення репрезентативної аеропружної моделі керувальної поверхні з поетапно змінними інерційними характеристиками, оцінювання її лінійних флатерних властивостей, а також аналіз нелінійних динамічних відгуків, зумовлених інерційно індуктованим люфтом. **Методи дослідження** базуються на аеропружному моделюванні зменшеного порядку, аналізі лінійного флатеру власних значень та нелінійному моделюванні в часовій області. Кусочно-варіаційний аналіз ефективного моменту інерції вводиться для представлення деградованої конфігурації балансу маси, що дозволяє ідентифікувати коливання граничного циклу та субкритичні нестійкості. **Результати та висновки** дослідження демонструють, що вільний хід, викликаний інерцією, може призвести до стійких коливальних реакцій на швидкостях нижче лінійної межі флаттера, що вказує на потенційний аеропружний ризик, який може бути не виявлений за допомогою звичайних аналізів сертифікаційного рівня. Практичну актуальність запропонованого підходу ілюструють на прикладі літака Embraer 505, що підтверджується реальними результатами технічного обслуговування щодо корозії вантажів балансування. Показано, що заміна деградованих вантажів з подальшим статичним балансуванням ефективно відновлює номінальні інерційні властивості та усуває виявлені нелінійні аеропружні ефекти. **Наукова новизна** дослідження полягає у фізичній інтерпретації деградації балансу маси як джерела інерційного вільного ходу та у запропонованій моделі моделювання, яка дозволяє провести просту, але ефективну оцінку її впливу на аеропружну стійкість. Отримані результати сприяють кращому розумінню аеропружних ризиків, пов'язаних з технічним обслуговуванням, та підтримують розробку вдосконалених практик інспекції та оцінки льотної придатності сучасних літаків.

**Ключові слова:** аеропружна стійкість; керувальна поверхня; балансувальний вантаж; інерційно зумовлений люфт; коливання граничного циклу; флатер; статичне балансування, технічне обслуговування.

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