Nonlinear Flutter Studies on Control Surface Freeplay

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Abstract: The frequent occurrence of control surface vibration has become one of the key problems affecting aircraft safety. The source of the freeplay of the control surface is studied, and a measurement device is developed. A nonlinear flutter analysis method under trimmed flight condition is proposed based on the discrete state-space method. Consequently, the effects of center-type freeplay and the freeplay with preload on flutter characteristics are analyzed, and the effects of preload on nonlinear flutter are verified by wind tunnel tests of a single wing model.

Key words: freeplay; nonlinearity; flutter; preload; wind tunnel test

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0 Introduction

The vibration response tends to diverge as the aircraft approaches its critical flutter speed[1]. The real physical phenomena are not entirely linear and the limit-cycle oscillation (LCO) usually occurs at speeds below the linear flutter speed when the aeroelastic system contains the freeplay nonlinearity. This issue is commonly seen in aircraft design. Usually, the freeplay nonlinearity results in a steady vibration response with finite amplitude. This will lead to structural damage when the vibration amplitude exceeds the capacity of the structure, but more typically leads to degradation of flight performance and fatigue of the airframe structure[2]. In addition, the freeplay nonlinearity will affect the closed-loop aeroservoelastic stability and active flutter suppression system[3]. Some LCO problems are solved by eliminating the control system freeplay, while others are tackled by conservative measures such as limiting flight speed. The specifications for the freeplay of control surface are clearly stated in GJB 67.7A—2008[4], while the Federal Aviation Administration (FAA) considers the current specifications to be too stringent to be met during manufacturing and requires verification through analysis and flight tests[5]. Therefore, in order to ensure the flight safety, it is essential to carry out nonlinear flutter analysis of freeplay in the design phase.

Nonlinear aeroelasticity research mainly includes theoretical analysis, wind tunnel tests and flight tests. In recent years, the analytical methods based on the nonlinear dynamics theory have been gradually applied to the nonlinear aeroelastic analysis with effective results[4-6]. The exploration of the basic theories and methods of nonlinear dynamics, on the one hand, is helpful to deeply understand and reveal the rules and mechanisms of nonlinear aeroelasticity of various structures, and provides theoretical basis for aeroelastic design of aircraft in the future. On the other hand, it also provides necessary means for preventing and eliminating aeroelastic instability. It is of great theoretical and engineering significance. The mathematical model of nonlinear aeroelastic system is a nonlinear differential equation, and it is difficult to obtain accurate analytical solutions as there is no general and effective method to solve the equation. Based on the discrete state-

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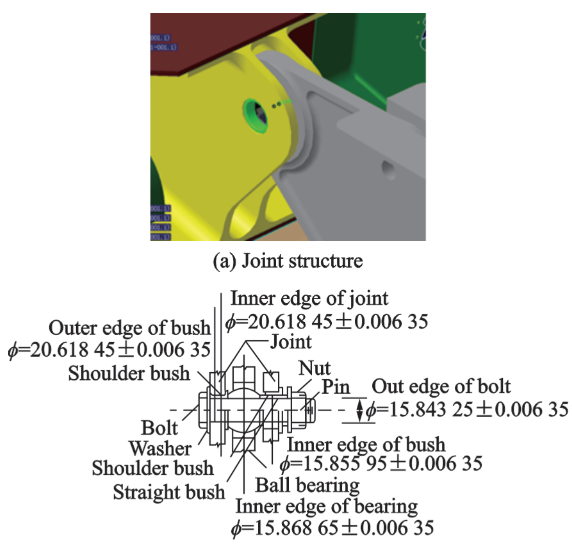
space method, a nonlinear flutter analysis method is proposed under trimmed flight condition in this paper.

1 Design Requirements

1.1 Sources of freeplay

The freeplay mainly comes from some structural links, such as the pivot of the all-moving surface, the rotation of the control surface, nacelle pylon, and the wing folding mechanism. Besides the freeplay incurred in design, manufacturing and assembly, it will also be enlarged due to wear during in-service.

The elevator of a certain aircraft is a point-to-point control. The control joint adopts the structure of two ears, while the bushing is pressed into the ear hole. There is the interference fit between the bushing and the bearing, while the freeplay fit between the bushing and the bolt and between the bolt and the bearing. The structure is shown in Fig.1, where the freeplay value between the bushing and the bolt is (0.001 27±0.001 27) cm, and the value between the bolt and the bearing is (0.002 54±0.001 27) cm. Therefore, the maximum freeplay that may exist after assembling is 0.006 35 cm. Considering the potential wear of the bearing, an additional freeplay of 0.002 54 cm will be generated. The most severe case (freeplay with 0.008 89 cm) will be used for calculation and analysis in this paper.



(a) Joint structure

(b) Size of freeplay

Fig.1 Schematic diagram of freeplay of joint

1.2 Design specifications

The freeplay design specifications are derived from Joint Service Specification Guides (JSSG), which is based on a series of wind tunnel flutter model tests carried out by the Wright-Patterson Air Force Base in the mid-to-late 1950s[7]. The test results show that if these freeplay requirements are applied in use, there will be no significant reduction in the flutter speed margin. These freeplay values can also be found in MIL-A-8870 (ASG)[8]. However, as these requirements are too severe, even F-22 cannot meet the specifications[9]. For most of the control surfaces the values of freeplay of the life cycle exceeded the specifications in the JSSG. In 2000, the Federal Aviation Administration (FAA) stated that these requirements were considered too conservative and too small to be practically controlled in service life[5]. In such cases, the manufacturers have provided analyses and/or flight tests to confirm the adequacy of the freeplay. In 2014, AC25.629-1B added the adequate requirements for wear of components such as control surface actuators, hinge bearings, and engine mounts in order to maintain aeroelastic stability margins[10]. Freeplay requirements can also be found in the British Air Force and Navy Aircraft Design Requirement AP 970 (Aeroelastic Part), with a simpler version (a. Normal control surface 0.1°. b. Full control surface 0.05°)[11].

Domestic aircraft design requirements of freeplay are based on the requirements of U.S. military specifications, which are quite identical to the requirements of MIL-A-8870 (ASG)[8], see Section 3.2.1.8.4. in GJB 67.7A—2008[4]. However, due to the limitation of technology development, there is a lack of freeplay nonlinear flutter analysis and freeplay measurement methods. The freeplay requirements have rarely been considered in previous aircraft design, or a rough evaluation method has been adopted. At present, with frequent occurrence of freeplay problems, more and more companies begin to pay attention to the issues with focus not only on the freeplay control of the structure in the development process, but also on a series of freeplay tests and evaluations during in-service life.

1.3 Measurement requirements

In order to ensure the freeplay of control surface meets the design requirements, it is necessary to obtain the freeplay through reliable measurement. Some simple measurement methods were used in the early stage, such as the marking, splint-holding shaking and so on[12]. Today, sensors, micrometers, image measurement and more accurate and advanced methods are gradually adopted[13-16]. In this paper, a direct freeplay detection device driven by servo-motor is designed, as shown in Fig.2, which is fixed on the stabilizer and the control surface through the clamping device respectively. The force and deflection angle curves are recorded in real time by the sensor and the measuring instrument, and the angle of the freeplay will be read directly by the intersection point of the measured curves and the coordinate axis with an accuracy of 0.002°. In addition to the direct measurement method described above, some indirect measurement methods have been developed, such as frequency response measurement method[17], preload measurement method[18], phase lag measurement method and so on[19]. The frequency response measurement method is based on the principle that the rotation frequency of control surface is directly related to its freeplay size. The phase lag measurement method is based on the description function method of nonlinear system as the fundamental component of the output signal is constant in any frequency range. The phase-frequency characteristic curve is a flat line, and the lag angle φ can be obtained as[19]

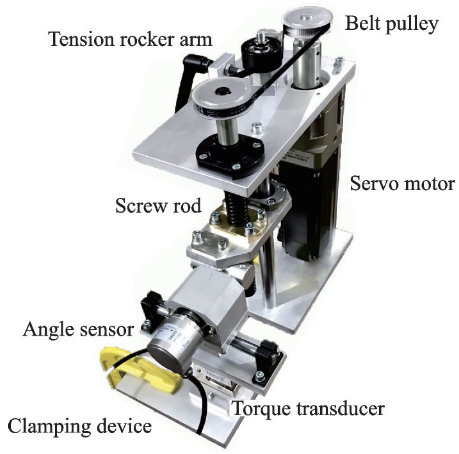


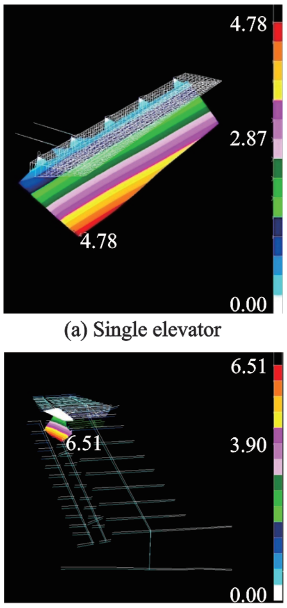
Fig.2 High-precision measurement

$$\varphi=\arctan\frac{A_1}{B_1}=\arctan\frac{c(c/A-1)}{A\left[\pi/2+\arcsin(1-c/A)+2(1-c/A)\sqrt{\frac{c}{2A}(1-c/2A)}\right]} \tag{1}$$

where A and c are amplitude of the input signal and the freeplay of control surface, respectively.

The analysis shows that the input amplitude cannot be too small or too large, otherwise the measurement error of freeplay is large. The recommended value of A is 2 times that of c, and the lag angle is about 6°.

As the freeplay measurement is a highly accurate ground test, it is necessary to consider the influencing factors. The loading force is used in most of the freeplay measurement methods. Therefore, it is important to eliminate the influence of elastic deformation in measurement, or to select a suitable loading force, which can measure the freeplay value but will not cause large elastic deformation. In the case of an aircraft with T-tail, the loading force will cause large elastic deformation of the stabilizer if it is too high when used to measure the freeplay of the elevator. This paper calculates and compares the different displacement of the trailing edge of the elevator under different loading forces, and shows that the deformation of the trailing edge of the whole aircraft is larger than that of the single elevator. As shown in Figs.3, 4, if the loading force is too large and the displacement of the trailing edge is L_1 and L_2, the freeplay value calculated according to the slope of the curve is B, which will be smaller than the actual freeplay value. Therefore, the influence of loading force and other factors should be taken into account in the measurement of the freeplay of control surface.



(a) Single elevator

(b) Whole aircraft

Fig.3 Deformation morphologies of elevator

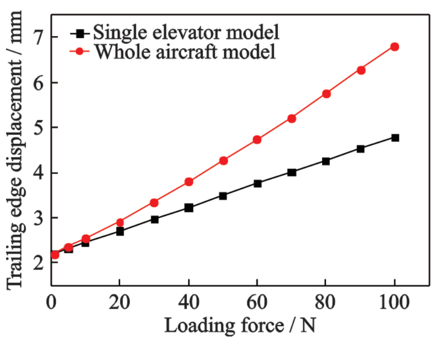


Fig.4 Displacement curves of elevator

2 Nonlinear System Formulations

At present, the main quantitative analyses of the freeplay nonlinear flutter are semi-analytical and numerical integration methods[20]. The descriptive function method is a commonly used semi-analytical method. When the system satisfies certain hypothetical conditions, the output of the nonlinearity in the system under the action of sinusoidal signal is approximated by the first harmonic component. Thus, the approximate linear characteristic of the nonlinear characteristic is obtained. The descriptive function method is therefore an equivalent linearization method. Since the flutter system has good filtering characteristics, the deflection angle $\alpha(t)$ can be obtained by

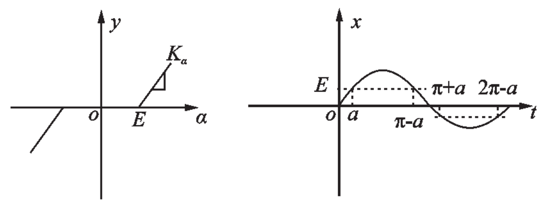
$$\alpha(t)=\alpha_f \sin(\omega_f t) \tag{2}$$

where ω_f is the flutter frequency, and α_f the amplitude of the deflection angle.

As shown in Fig.5, assuming a sinusoidal input $x=A\sin\omega t$, when $\omega t=a$, the excitation amplitude is equal to the freeplay size. In the case of sinusoidal input, the restoring force y is written as

$$y=\begin{cases}0 & \omega t<a,\pi-a<\omega t<\pi+a,\omega t>2\pi-a\\ K(A\sin(\omega t)-E) & a\leqslant\omega t\leqslant\pi-a\\ K(A\sin(\omega t)-E) & \pi+a\leqslant\omega t\leqslant 2\pi-a\end{cases} \tag{3}$$

where K is the normal stiffness, and K becomes the constant K_a when $\alpha>E$. a is the freeplay and E the input corresponding freeplay.



(a) Deflection angle free-play (b) Sinusoidal input-deflection angle

Fig.5 Input-output relationship with freeplay

For periodic output signals, y can be expanded into a Fourier series

$$y=A_0+\sum_{n=1}^{\infty}(A_n\cos(n\omega t)+B_n\sin(n\omega t)) \tag{4}$$

where $A_n=\dfrac{1}{\pi}\int_0^{2\pi}Y(t)\cos(n\omega t)\mathrm{d}(\omega t)$, $B_n=\dfrac{1}{\pi}\int_0^{2\pi}Y(t)\sin(\omega t)\mathrm{d}(\omega t)$. A_0, A_n, B_n are the Fourier coefficients.

By approximating Eq.(4) to the first harmonic component, the following equations can be obtained

$$y=\frac{2K}{\pi}\left[\frac{\pi}{2}-\operatorname{acrsin}\frac{E}{A}-\frac{E}{A}\sqrt{1-\left(\frac{E}{A}\right)^2}\right]A\sin(\omega t) \tag{5}$$

where $K_{eq}=\dfrac{2K}{\pi}\left[\dfrac{\pi}{2}-\operatorname{acrsin}\dfrac{E}{A}-\dfrac{E}{A}\sqrt{1-\left(\dfrac{E}{A}\right)^2}\right]$ is the equivalent stiffness of the control surface with freeplay.

The descriptive function method generally considers first-order harmonics, and only gives a rough approximation of flutter, whose accuracy decreases with the increase of nonlinear stiffness, LCO amplitude, and sometimes even fails. The numerical integration method will solve the problem that the semi-analytical method cannot solve. The current research focuses on the time-domain simulation based on CFD/ CSD coupling[21], which improves the calculation accuracy, but is time-consuming and inefficient.

The discrete state-space method is different from the general time-domain simulation method[22]. As shown in Fig.6, the nonlinear system is divided into subsystems by means of nonlinear parameter configuration. These subsystems can form a set of piecewise discrete time-domain state-space equations. However, the discrete gust or the control input can be designated as the external disturbance of the nonlinear system, and the stability of the system can be judged by the response analysis. The basic assumption of the discrete state-space method is that the nonlinear characteristics of an aeroelastic system can be represented by a set of system parameters. The equations of nonlinear aeroelastic systems can be expressed as function with various discrete values[22]

$$\boldsymbol{M}_{llij}\bar{\boldsymbol{V}}_{ij}\{\ddot{\boldsymbol{\varepsilon}}\}+\boldsymbol{B}_{llij}\bar{\boldsymbol{V}}_{ij}\{\dot{\boldsymbol{\varepsilon}}\}+\boldsymbol{K}_{llij}\bar{\boldsymbol{V}}_{ij}\{\boldsymbol{\varepsilon}\}=\boldsymbol{P}_{lljj}\bar{\boldsymbol{V}}_{ij}+\boldsymbol{P}_{0ij} \tag{6}$$

where $\bar{\boldsymbol{V}}_{ij}$ are the nonlinear parameters; $\boldsymbol{M}_{llij}$, $\boldsymbol{B}_{llij}$ and $\boldsymbol{K}_{llij}$ the generalized mass, damping and stiffness matrices, respectively; $\boldsymbol{P}_{lljj}$ the unsteady aerodynamic force; $\boldsymbol{P}_{0ij}$ the gravitation and the trim force, and $\{\boldsymbol{\varepsilon}\}$ the generalized coordinate.

Eq.(6) is similar to the equation of motion of a linear aeroelastic system, except that the system matrix is a function of nonlinear parameters. When the nonlinear parameters are timed, these system matrices can be obtained at various discrete values. At each value, it is assumed that the aeroelastic system is locally linear. In this way, the time-domain state-space equation of the open-loop aeroelastic system is obtained

$$\dot{\boldsymbol{X}}_{ae}=(\boldsymbol{A}_{ae})_{ij}\boldsymbol{X}_{ae}+(\boldsymbol{B}_{ae})_{ij}\boldsymbol{u}_{ae} \tag{7}$$

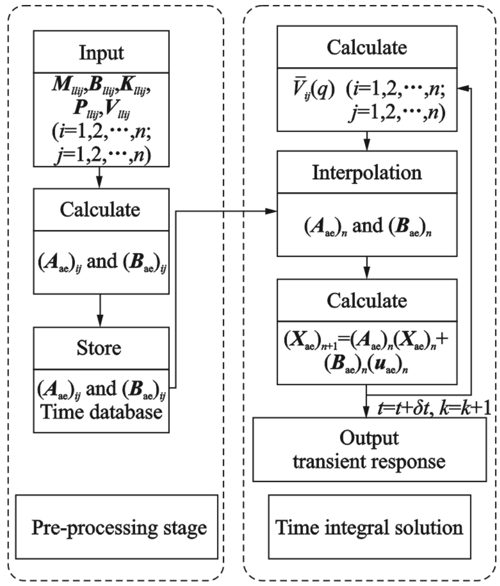


Fig.6 Calculation flow of discrete state-space method

where $\dot{\boldsymbol{X}}_{ae}$ contains the structural and aerodynamic states; $\boldsymbol{u}_{ae}$ contains the deflection, rate and acceleration vectors of the control surface; and $(\boldsymbol{A}_{ae})_{ij}$ and $(\boldsymbol{B}_{ae})_{ij}$ are the state space matrices.

The research on nonlinear flutter mainly focused on the verification of freeplay, but the actual flight will be affected by the aerodynamic loads that cause the equilibrium position of center-type freeplay had shifted to freeplay with preload, as shown in Fig.7. E_p-E is the freeplay with preload.

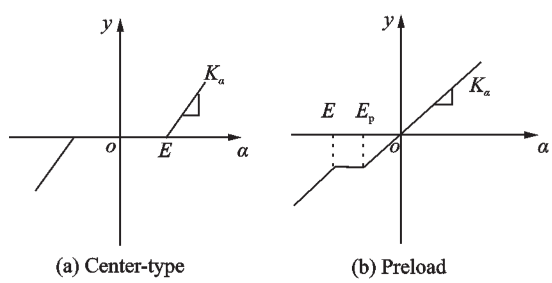


Fig.7 Freeplay type

Before the nonlinear flutter analysis of the freeplay with preload is carried out, an aircraft trim calculation is required. The equation of trim system is written as

$$\bar{\boldsymbol{K}}\{\boldsymbol{x}\}+\bar{\boldsymbol{M}}\boldsymbol{D}\ddot{\boldsymbol{u}}_r-q_\infty\overline{\mathrm{AIC}}\{\boldsymbol{x}\}=\frac{\partial\bar{f}}{\partial\boldsymbol{a}}\{\boldsymbol{a}\} \tag{8}$$

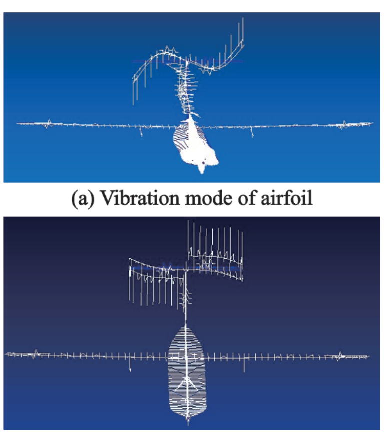
where $\bar{\boldsymbol{K}}$, $\bar{\boldsymbol{M}}$ and $\overline{\mathrm{AIC}}$ are the stiffness, mass and aerodynamic influence coefficient matrices. $\boldsymbol{D}$ is the rigid body model matrix, $\ddot{\boldsymbol{u}}_r$ the acceleration of rigid body, and $\boldsymbol{x}$ the elastic displacement. $\{\boldsymbol{a}\}$ contains the trim parameters of the angle of attack, sideslip angle, roll rate, pitch rate, yaw rate, and deflection angle of control surface. $\frac{\partial \bar{f}}{\partial \boldsymbol{a}}$ is the derivative of aerodynamic force corresponding to the rigid body with respect to trimmed parameters, and q_∞ the dynamic pressure.

After the parameters are obtained, the freeplay nonlinear flutter analysis can be carried out according to the discrete state-space method described above.

3 Numerical Results

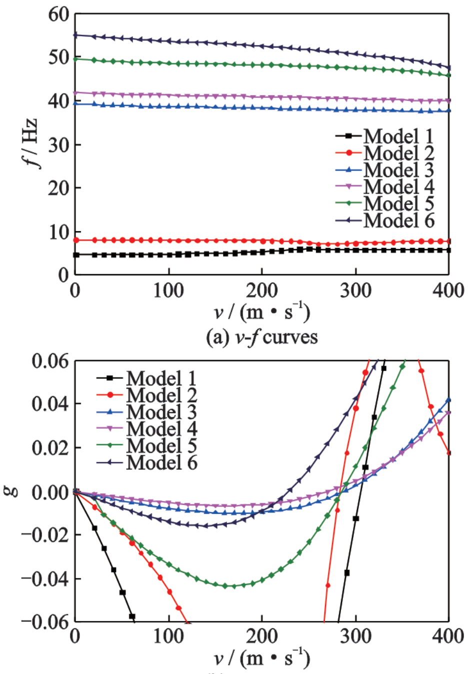
3.1 Linear flutter analysis

In order to ensure the flight safety, the nonlinear flutter analysis of the freeplay of control surface is required. The vibration modes of airfoil and control surface are shown in Fig.8. The accuracy of nonlinear modeling is first verified by the results of frequency-domain flutter analysis. The v-g-f curves are shown in Fig.9. The critical flutter speed is 228.0 m/s and the flutter frequency is 53.1 Hz. Then the structural response without freeplay is calculated by the nonlinear discrete state-space method. 1-cos discrete gust is employed as the external excitation and the response curves are shown in Figs.10, 11. The horizontal tail diverges with a frequency of 52.0 Hz when the flight speed is 228.0 m/s, which is consistent with the results in frequency-domain flutter analysis.


(a) Vibration mode of airfoil

(b) Vibration mode of control surface

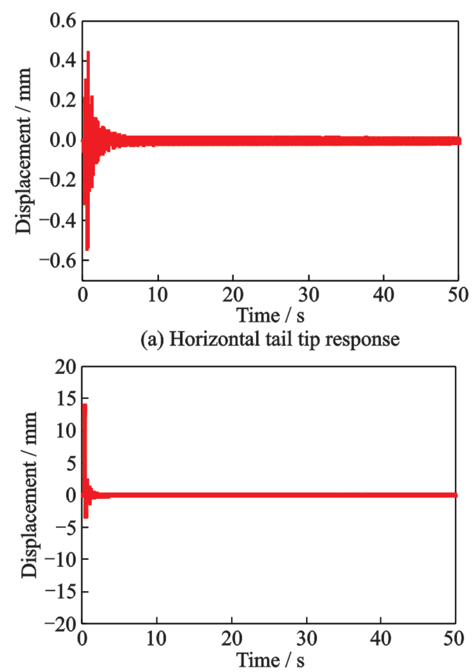
Fig.8 Vibration modes of airfoil and control surface



(a) v-f curves

(b) v-g curves

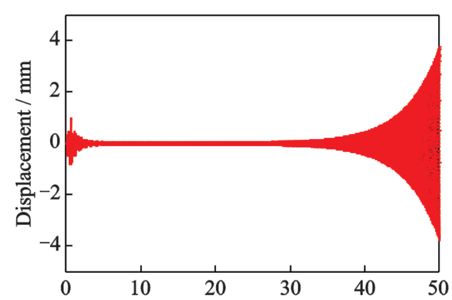
Fig.9 v-g-f curves of flutter in frequency domain



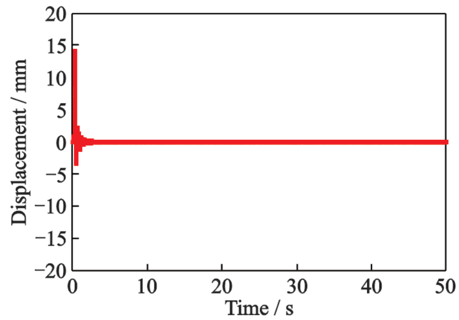
(a) Horizontal tail tip response

(b) Wing tip response

Fig.10 Response curves at 227 m/s without freeplay



(a) Horizontal tail tip response

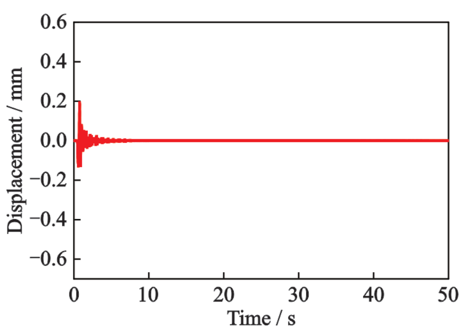


(b) Wing tip response

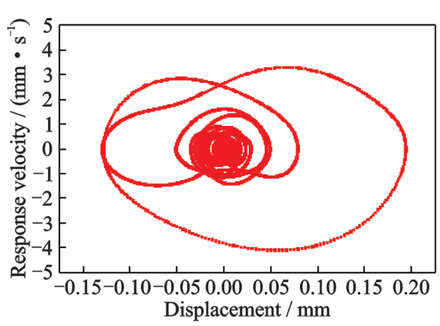
Fig.11 Response curves at 228 m/s without freeplay

3.2 Nonlinear flutter analysis of center-type freeplay

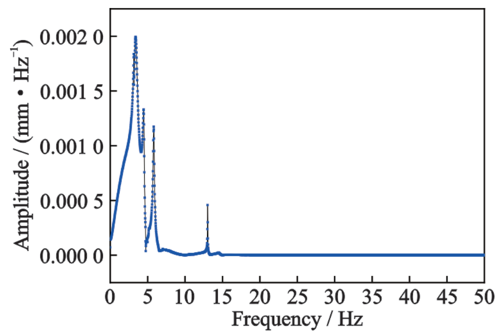
Considering the freeplay of 0.2°(corresponding to the height of the rocker arm of 2.5 cm, the largest freeplay of 0.008 89 cm, see Section 1.1), the structural responses of the center-type freeplay at different speeds are calculated by the discrete state-space method and results are shown in Figs.12—15. The curves show that: The tip response of horizontal tail is attenuation motion when the flow speed is 60 m/s; the response is LCO when the flow speed is 70 m/s, with a frequency of 15.6 Hz; the response is also LCO when the flow speed is 240 m/s, with a frequency of 17.2 Hz; and the response is divergent motion when the flow speed is



(a) Displacement diagram

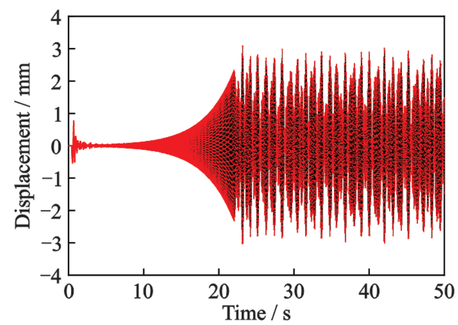


(b) Phase diagram

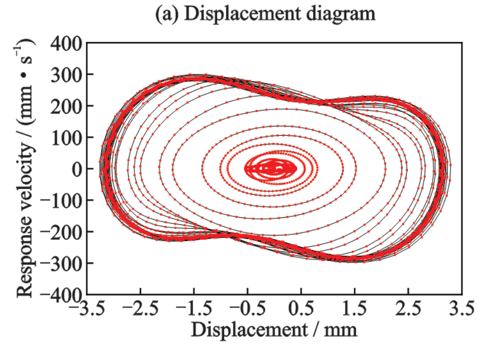


(c) FFT plot

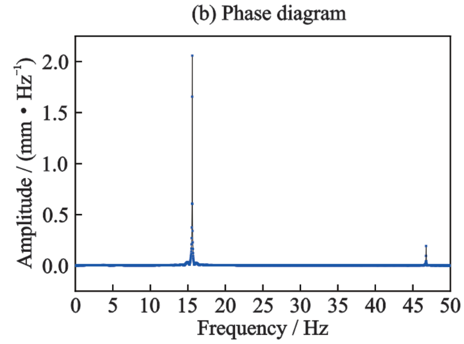
Fig.12 Response curves at 60 m/s in center-type freeplay



(a) Displacement diagram

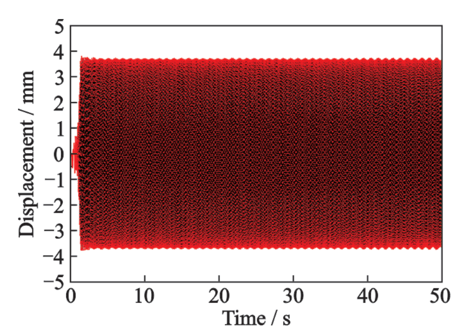


(b) Phase diagram



(c) FFT plot

Fig.13 Response curves at 70 m/s in center-type freeplay



(a) Displacement diagram

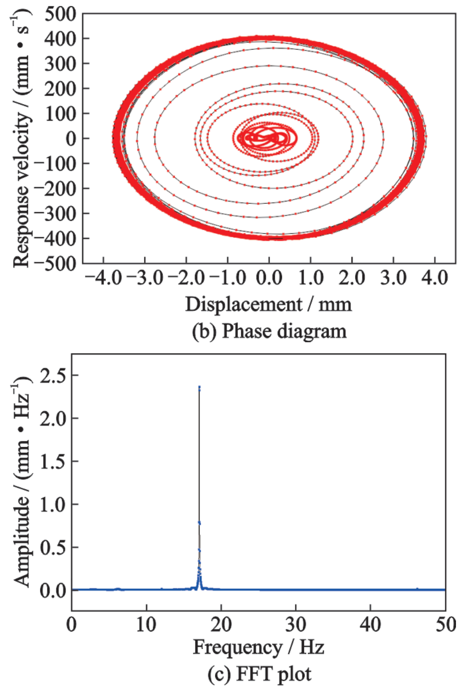


Fig.14 Response curves at 240 m/s in center-type freeplay

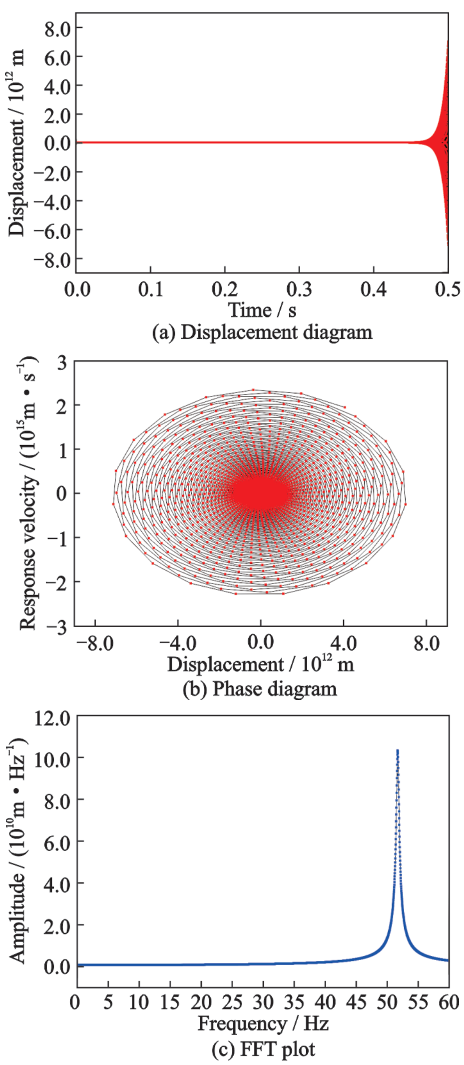


Fig.15 Response curves at 243 m/s in center-type freeplay

243 m/s, with a frequency of 52.1 Hz. Different from the linear flutter case, the center-type freeplay causes an earlier occurrence of LCO before the frequency-domain flutter speed but the divergence speed is higher than that calculated in linear flutter analysis.

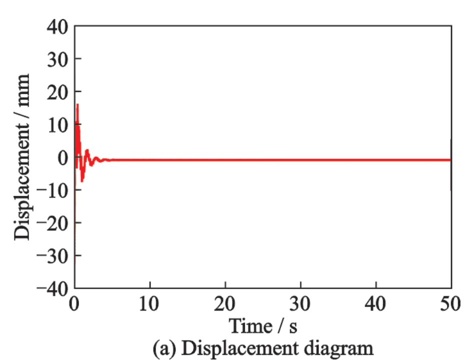
3.3 Nonlinear flutter analysis of freeplay with preload

Different from the center-type freeplay, an aircraft trim is required to calculate the deflection angle at different speeds before implementing the freeplay with preload flutter analysis. Taking the longitudinal trim as an example, this paper investigates the effects of preload on the freeplay of the elevator by adjusting the pitch angle and the deflection angle of the elevator. The results are shown in Table 1.

Table 1 Trim angle and deflection angle of elevator

Speed/(m•s^{-1})	Pitch angle/(°)	Elevator deflection angle/(°)
200	1.16	2.49
210	1.05	2.37
220	0.96	2.27
225	0.92	2.23

The nonlinear model is established according to the deflection angle and freeplay of the elevator, and the structural responses are calculated by the discrete state-space method. The results are shown in Figs.16, 17. The response curves show that the tip response of the horizontal tail is attenuation motion when the flight speed is 220 m/s, and the tip re-



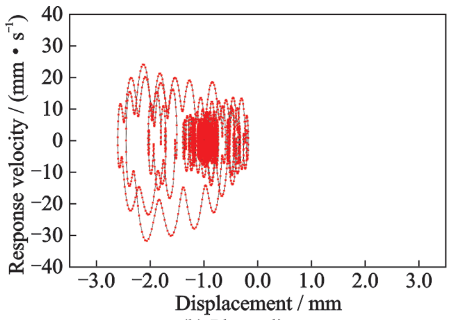


Fig.16 Response curves at 220 m/s in freeplay with preload

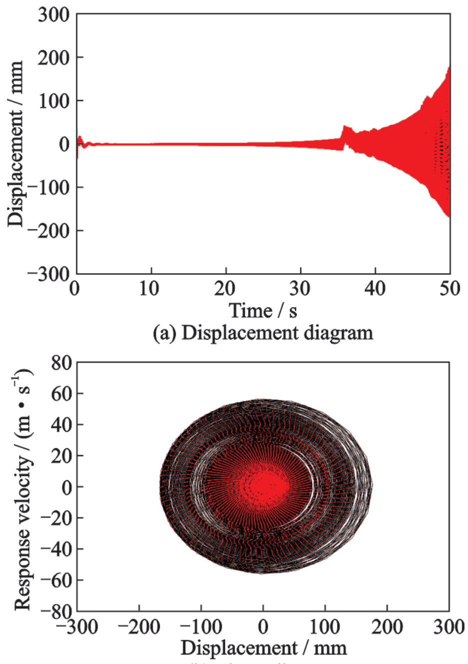


Fig.17 Response curves at 225 m/s in freeplay with preload

sponse is divergent motion when the flight speed is 225 m/s with the frequency of 52.1 Hz. Unlike the central-type freeplay, there is no LCO in the freeplay with preload, and the divergence speed is close to the linear flutter speed.

4 Test Results

In order to verify the effect of preload on the flutter of nonlinear freeplay, a single wing model with freeplay of control surface is selected for the wind tunnel flutter test. A 1/6-scale test model is designed as wind tunnel flutter tests are normally performed at speeds no more than 40 m/s. The freeplay is achieved through a control mechanism, as shown in Fig.18. The force and deflection angle

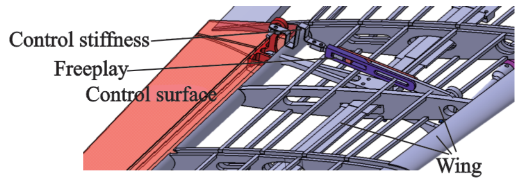


Fig.18 Freeplay control structure

curve obtained by the high-precision measurement are shown in Fig.19, and the measured value of freeplay is twice of 0.7°. The model is connected vertically to the wind tunnel floor to eliminate gravity effects, and the angle of attack can be adjusted as shown in Fig.20. In wind tunnel tests, the signal-to-noise ratio is poor and presents a certain degree of nonlinearity as the model is influenced by loads, damping and noise. The original acceleration signal is converted by FFT after the DC component and the trend are removed, and the frequency domain speed signal is obtained by integral method. Then, the time-domain speed signal is obtained by IFFT. Next, the displacement signal is obtained by frequency domain speed integral, and lastly the time-domain displacement signal is obtained by IFFT.

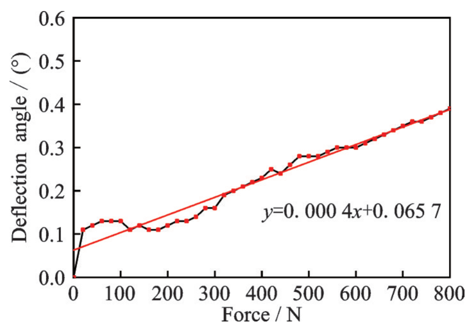


Fig.19 Curves of values of freeplay

Fig.20 Wind tunnel test of single wing model

Figs.21—23 are the results of wind tunnel tests. The results show that: The model starts an approximation of LCO with constant amplitude from the speed of 30 m/s, which continues as the flow speed increases. Meanwhile, it can be seen that the oscillation is accompanied by the low frequency movement, which is caused by the constant change of the equilibrium position of the freeplay under static aerodynamic loads. When the flow speed reaches 40 m/s the oscillation disappears, and the flutter divergence appears. Although the vertically mounted model is used to eliminate the effects of preload, the static load on the wing of asymmetric airfoil increases with the increase of flow speed, and the nonlinear effect caused by the freeplay is eliminated under the preload.

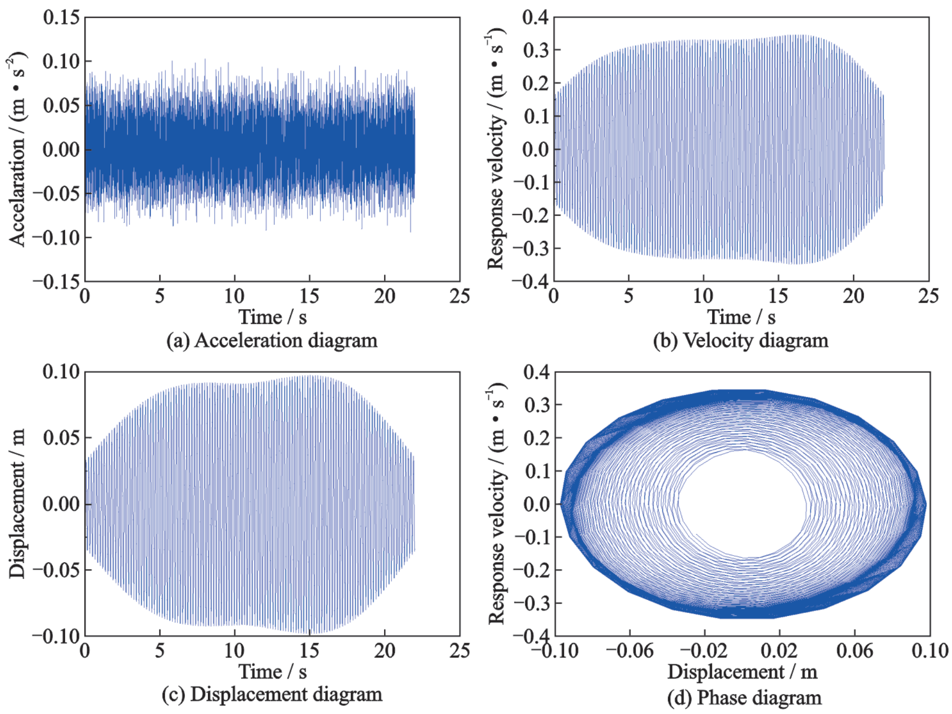


Fig.21 Results of wind tunnel test with flow speed of 30 m/s

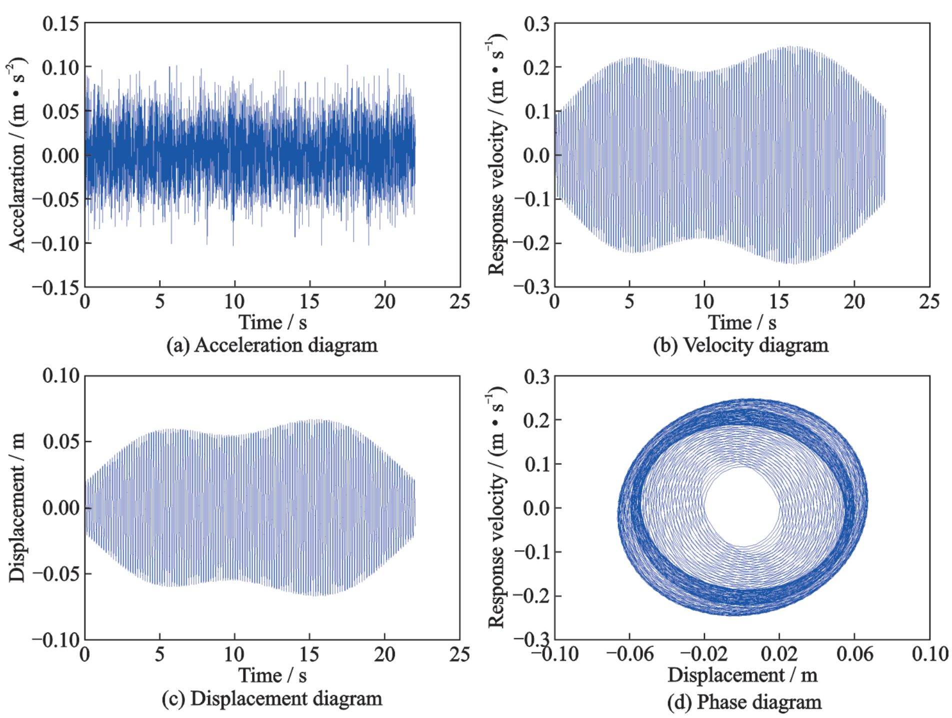


Fig.22 Results of wind tunnel test with flow speed of 37 m/s

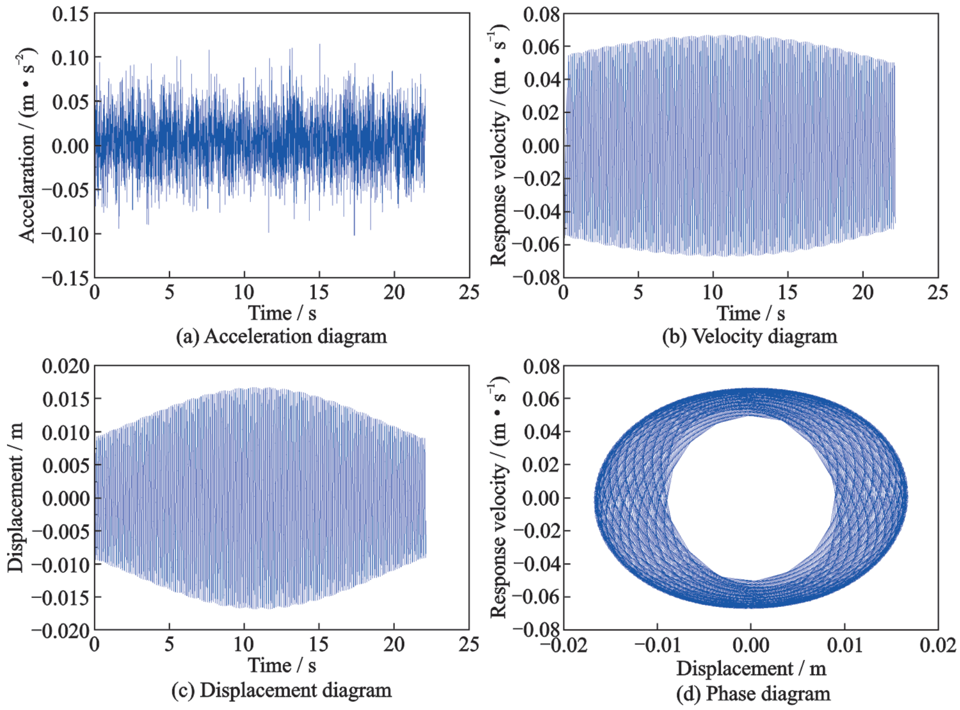


Fig.23 Results of wind tunnel test with flow speed of 40 m/s

According to the curves of the main vibration frequencies (n_z-01—n_z-05) with different flow speeds in Fig.24, the main frequency of the wing vibration signal is about 6 Hz with the speed of 30 m/s, and the frequency fluctuates within a small range as the flow speed increases. The main frequency will produce a step when the flow speed reaches 40 m/s, roughly reaching 8.0 Hz. The divergence speed of the model is close to the result of critical speed of linear flutter, which further proves that the effects of nonlinear freeplay on flutter can be eliminated with preload.

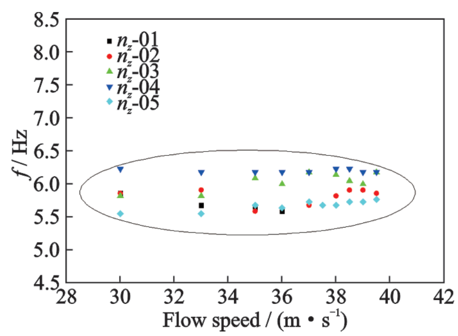


Fig.24 Vibration frequencies with different flow speeds

5 Conclusions

Based on numerical results of the discrete state-space method and results of the wind tunnel tests, this paper investigates the influence of the freeplay on nonlinear flutter as well as the effects of the preload on the nonlinear flutter of freeplay by the wind tunnel tests of a single wing model. The main conclusions are as follows:

(1) LCO occurs prior to the linear flutter speed when the center-type freeplay is considered. When the freeplay with preload is considered, the calculation results differ significantly from the center-type freeplay and the divergence speed is close to that of linear flutter.

(2) In the wind tunnel tests, there is LCO in the wing with center-type freeplay when the flow speed is small. When the flow speed is large, it leads to the freeplay with preload, and the experimental divergence speed is close to the linear flutter speed.

(3) The aircraft is always subjected to loads in the course of flight, therefore, the deflection of the control surface only passing through the freeplay section causes the transient oscillation and then leads to the bearing wear and other fatigue problems.

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Author contributions Mr. ZHAO Dongqiang analyzed the freeplay source, designed the measuring equipment, put forward the analysis method, interpreted the results and wrote the manuscript. Prof. YANG Zhichun put forward the plan and reviewed the method. Mr. HUANG Guoning constructed the analytical model and completed the wind tunnel test. Mr. CHEN Hai designed the structural model. Mr. MA Xiang completed the wind tunnel test. All authors commented on the manuscript draft and approved the submission.

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操纵面间隙非线性颤振研究

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摘要:操纵面振动问题的频繁发生是影响飞机飞行安全的一个关键因素。为此,本文研究了操纵面间隙的来源,研制了一种间隙测量装置。提出了一种基于离散状态空间法的配平飞行条件下的非线性颤振分析方法。分析了中心型间隙和预载间隙对颤振特性的影响,并通过单机翼模型风洞试验验证了预载对非线性颤振的影响。

关键词:间隙;非线性;颤振;预载;风洞试验