

MECHANISM OF ALL-MOVABLE RUDDER NONLINEAR AEROELASTIC BEHAVIOR INDUCED BY BENDING FREEPLAY

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Abstract

Modern high-speed aircraft increasingly employ all movable rudders to improve control authority, maneuverability, and aeroelastic efficiency. However, freeplay existing in the all movable rudder system, resulting from manufacturing tolerances, assembly errors, bearing clearance, gear backlash, and structural wear during service, can significantly reduce structural stiffness and induce limit cycle oscillation (LCO). Such nonlinear aeroelastic phenomena may lead to degraded flight control performance, accelerated structural fatigue, shortened service life, and even catastrophic structural failure. Previous studies have primarily focused on the torsional freeplay of all movable rudder systems, while paying less attention to the mechanism and characteristics of nonlinear aeroelastic behavior caused by bending freeplay. To address this issue, the present study investigates the nonlinear aeroelastic behavior of an all movable rudder with bending freeplay by combining theoretical analysis, numerical simulation, and wind tunnel test. A novel mechanism for LCO induced by bending freeplay is proposed, and the characteristics of LCO caused by bending freeplay are summarized. The results reveal a distinct mechanism for bending-freeplay-induced LCO: when the bending angular displacement remains within the freeplay region, the system behaves as a zero-bending-stiffness configuration and is therefore prone to premature static divergence; once the bending response exceeds the freeplay boundary, the bending spring is re-engaged, providing restoring stiffness and suppressing further divergence. This repeated divergence–suppression process leads to a stable single degree of freedom LCO whose amplitude remains slightly larger than the prescribed bending freeplay angle. Wind tunnel tests with bending freeplay further confirm the theoretical and numerical predictions, showing that the resulting oscillation is dominated by bending motion with negligible torsional participation. These findings demonstrate that bending-freeplay-induced LCO differs fundamentally from torsional-freeplay-induced LCO, which is commonly associated with subcritical Hopf bifurcation and coupled bending–torsional vibration. The study provides new physical insight into bending-freeplay nonlinear aeroelasticity and offers a theoretical and experimental basis for the stability assessment, structural design, and safety evaluation of all movable rudder systems in high-speed aircraft.

Keywords: all movable rudder, freeplay, nonlinear aeroelasticity, limit cycle oscillation

1. Introduction

All movable rudders are widely employed in modern high-speed aircraft because of their high control efficiency, compact structural configuration, and strong maneuvering capability under complex flight conditions. Compared with conventional hinged control surfaces, an all movable rudder can generate larger aerodynamic control moments. However, all movable rudder inevitably exhibits freeplay nonlinearity during design, manufacturing, assembly, and service due to factors such as gear backlash, bearing looseness, and hinge wear. The existence of freeplay introduces a piecewise stiffness characteristic into the supporting structure and may significantly reduce the equivalent stiffness of the system within the free-play region. As a result, the aeroelastic stability boundary of the all movable rudder can be substantially altered, and nonlinear dynamic responses may occur at flow velocities far below the linear flutter speed [1-4].

Among the nonlinear aeroelastic phenomena induced by all movable rudder freeplay, limit cycle oscillation is of particular concern. Unlike linear flutter, which is generally characterized by divergent oscillation beyond a critical speed, limit cycle oscillation is a self-sustained periodic vibration with finite amplitude caused by the interaction between aerodynamic forces, structural dynamics, and nonlinear restoring characteristics. Once limit cycle oscillation occurs in an all movable rudder system, it may lead to degraded control accuracy, reduced flight quality, increased actuator load, accelerated structural fatigue, and shortened service life of key mechanical components. In severe cases, the repeated oscillatory loads may further induce local damage, or even catastrophic structural failure [5-8]. Therefore, the aeroelastic issues of all movable rudder often directly determine the stability and controllability of the entire aircraft, accurate identification of the mechanism and characteristics of freeplay-induced nonlinear aeroelastic responses is essential for the design, analysis, testing, and safety assessment of high-speed aircraft with all movable rudder.

Over the past decades, scholars have conducted extensive research on the aeroelastic behavior caused by all movable rudder freeplay. Chen et al. [9] analyzed the limit cycle oscillation response induced by torsional freeplay in an all movable rudder system using the fictitious mass method, providing an effective approach for predicting nonlinear aeroelastic response. Ai et al. [10] proposed a piecewise optimization describing function method to investigate nonlinear aeroelastic responses caused by torsional freeplay in an all movable rudde. Tian et al. [11] proposed the PadéPIM method and applied it to the aeroelastic analysis of an all movable rudder freeplay nonlinear system. Ai et al. [12] studied the aeroelastic behavior of multiple freeplays nonlinear system through wind tunnel tests. Tang and Dowell [13-15] investigated the influence of torsional freeplay on the aeroelastic response of all movable rudder through theoretical analysis and wind tunnel test. These studies have greatly improved the understanding of freeplay-induced nonlinear aeroelasticity and have provided important guidance for the stability prediction of all movable rudder.

Nevertheless, most existing studies have focused primarily on torsional freeplay, because torsional motion is usually considered to play a dominant role in control-surface flutter and limit cycle oscillation. In contrast, the influence of bending freeplay has received relatively limited attention, although bending free-play may also be introduced by structural connections, elastic support components, and assembly imperfections in practical all movable rudder systems. The dynamic effect of bending freeplay is not necessarily equivalent to that of torsional freeplay. In particular, bending freeplay may directly change the bending stiffness of the supporting structure, modify the static divergence boundary, and trigger nonlinear aeroelastic responses through a mechanism different from the commonly recognized torsional-freeplay-induced subcritical Hopf bifurcation. If the effect of bending freeplay is neglected during design, analysis, or wind tunnel testing, potential nonlinear instability risks may be underestimated, which could compromise the aeroelastic safety margin of the aircraft.

Motivated by this issue, the present paper investigates the mechanism and characteristics of nonlinear aeroelastic behavior induced by bending freeplay in an all movable rudder system. A three-dimensional finite element model of the all movable rudder is established, and the critical conditions for limit cycle oscillation and static divergence under different parameters are analyzed using the describing function method and frequency-domain aeroelastic analysis. Based on the numerical results, a distinct physical mechanism of bending-freeplay-induced limit cycle oscillation is proposed. Theoretical predictions are further validated through wind tunnel tests on an all movable rudder model with bending freeplay. By comparing the response characteristics of bending-freeplay-induced limit cycle oscillation and torsional-freeplay-induced limit cycle oscillation, this study clarifies the fundamental differences between these two types of nonlinear aeroelastic behavior and provides useful insight for the design, evaluation, and safety assessment of all movable rudder systems.

2. Theoretical Analysis

The bending angular displacement–restoring moment relationship in the presence of bending freeplay is illustrated in Figure 1. In this figure, F denotes the restoring moment, A represents the amplitude of the bending angle, θ represents the bending angular displacement, and δ denotes the bending freeplay angle. $\theta=\pm\delta$ denotes the upper and lower limits of the freeplay region, respectively,

thereby dividing the nonlinear freeplay system into three piecewise-linear subsystems, namely two stiffness regions and one freeplay region. *k* denotes the stiffness of the bending spring in stiffness regions.

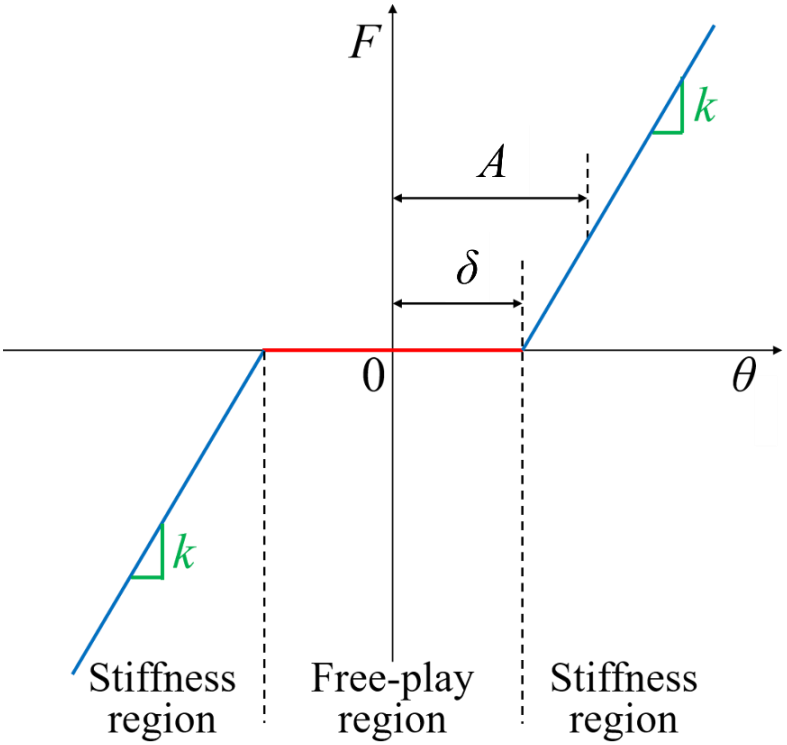


Figure 1 – The stiffness curve for the centrosymmetric free-play nonlinearity.

The relationship between the bending angular displacement and the restoring moment in Figure 1 can be expressed by the following piecewise function:

$$M(\theta)=\begin{cases}k(\theta+\delta) & \theta<-\delta\\ 0 & -\delta\le\theta\le\delta\\ k(\theta-\delta) & \theta>\delta\end{cases} \tag{1}$$

For a given bending angular amplitude, the equivalent linearized stiffness of the bending spring can be calculated using the describing function method [10] and expressed as follows:

$$k^{eq}=\begin{cases}0 & A\le\delta\\ k\left[\frac{2}{\pi}(\varphi-\sin\varphi\cos\varphi)\right] & A>\delta\end{cases} \tag{2}$$

where k^{eq} is the equivalent linearized stiffness, and φ is a function of the bending freeplay angle and the bending angular amplitude, and can be expressed as follows:

$$\varphi=\cos^{-1}\frac{\delta}{A} \tag{3}$$

As can be seen from Eq. (2), when bending freeplay nonlinearity exists in the system and the bending angular displacement lies within the freeplay region, the equivalent linearized stiffness of the spring becomes zero. Since the critical speed for static divergence is positively correlated with structural stiffness, the static divergence speed of an all movable rudder system with bending freeplay may be much lower than that of the corresponding linear system. When static divergence causes the bending angular displacement to increase into the stiffness region, namely when the bending angular displacement exceeds the bending freeplay angle, the bending spring is “activated” and provides a restoring moment, thereby suppressing the divergence of the bending angular displacement. Consequently, an all movable rudder system with bending freeplay may repeatedly undergo a single degree of freedom vibration process characterized by “divergence–suppression”, eventually forming a limit cycle oscillation with an amplitude slightly larger than the bending freeplay angle.

3. Simulation Calculations

In this study, a finite element model of the all movable rudder is established, and nonlinear dynamics analysis and aeroelastic analysis are performed by considering the presence of bending freeplay.

In this paper, A/δ is used to denote the ratio of the bending angular amplitude to the bending freeplay angle. Based on the describing function method [10], the first two natural frequencies of the nonlinear system with bending freeplay under different A/δ conditions are obtained, as shown in Figure 2. The results indicate that the frequency separation between the first torsional mode and the first bending mode gradually increases as A/δ decreases. When A/δ decreases to 1, the equivalent stiffness coefficient is reduced to zero. In this case, the bending spring no longer provides bending stiffness. Only a small amount of bending stiffness is supplied by the supporting device connected to the torsional spring. Consequently, the bending frequency approaches zero.

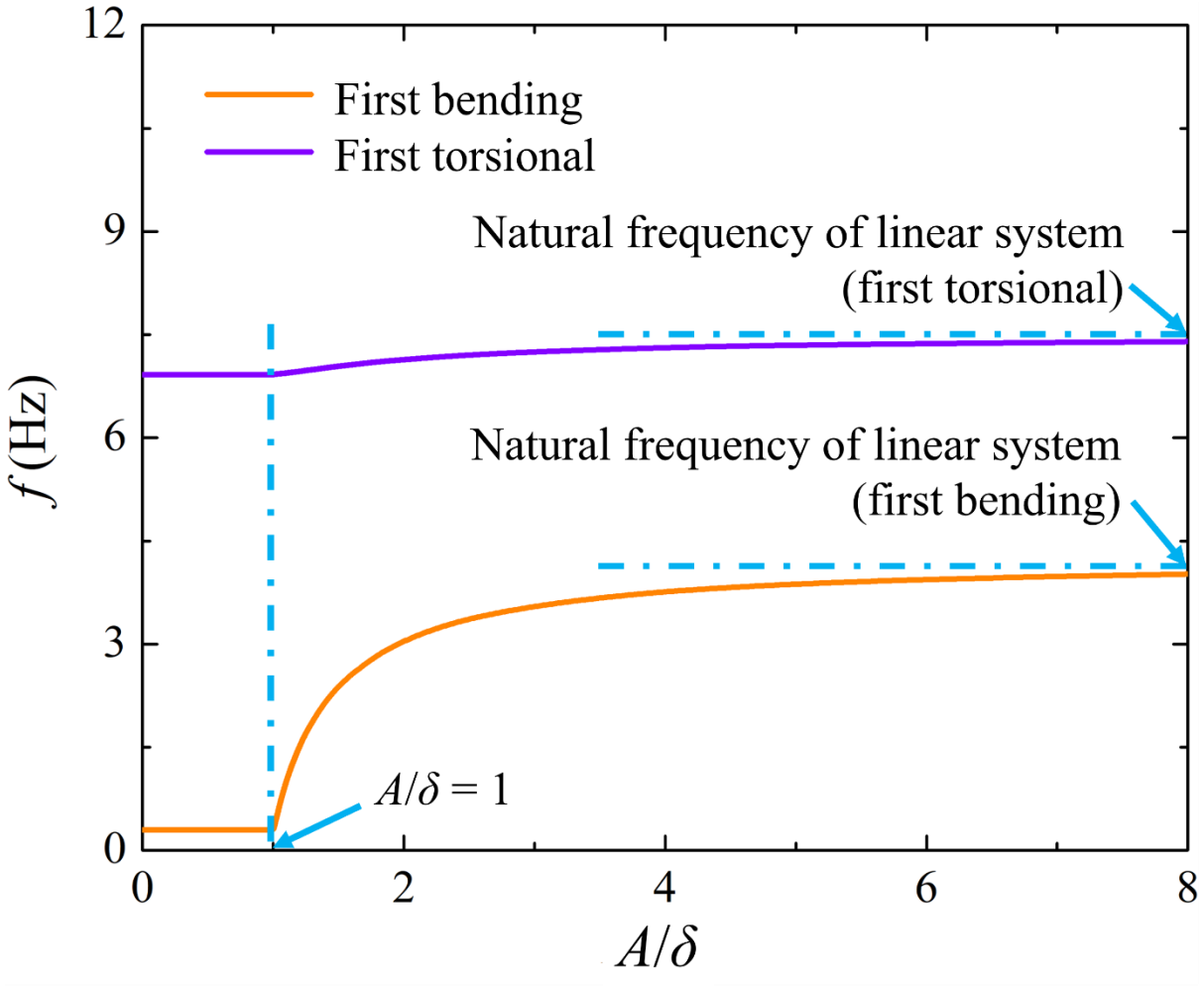


Figure 2 – The first two orders natural frequencies of all movable rudder at different A/δ [16].

Based on the description function method [10] and frequency-domain aeroelastic analysis, the critical speed for limit cycle oscillation and static divergence speed of the all movable rudder model can be obtained under different bending angular amplitude and bending freeplay angle ratios (A/δ), as illustrated in Figure 3.

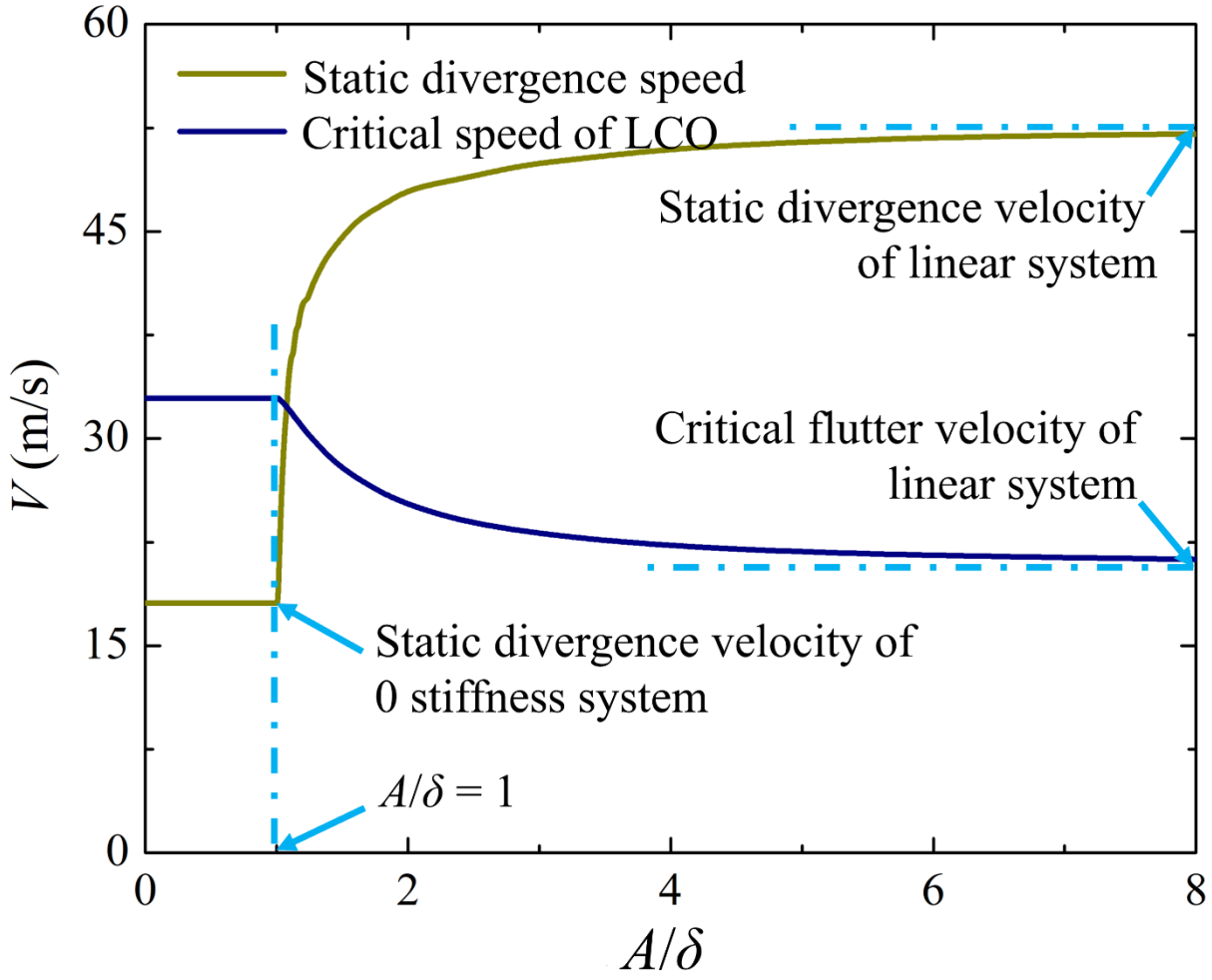


Figure 3 – The critical speeds for limit cycle oscillation and static divergence at different A/δ [16].

As shown in Figure 3, when the bending angular displacement remains within the bending freeplay region (A/δ<1), the bending spring stiffness is zero, allowing the all movable rudder to rotate freely in the bending direction. When the flow velocity reaches the static divergence speed of the zero-stiffness syste, the all movable rudder system will experience static divergence. However, once static divergence causes the bending angular amplitude to exceed the bending free freeplay angle, the bending spring is “activated” to provide bending stiffness, thereby suppressing further divergence of the bending angular amplitude. Consequently, the all movable rudder system undergoes a repetitive “divergence–suppression” bending vibration process [16], ultimately forming a single degree of freedom limit cycle oscillation with an amplitude slightly exceeding the bending freeplay angle.

4. Experimental Validation

To validate the theoretical analysis and numerical predictions, and to further investigate the nonlinear aeroelastic response characteristics induced by bending freeplay, an all movable rudder wind tunnel test model was designed and fabricated. The test model was developed to reproduce the primary structural dynamic features of the all movable rudder while allowing a prescribed bending freeplay to be introduced into the support mechanism. Through this experimental configuration, the bending and torsional responses of the all movable rudder model could be measured under different flow conditions, thereby enabling direct observation of the onset and evolution of bending-freeplay-induced limit cycle oscillation.

A bending freeplay angle of 0.03° was introduced into the all movable rudder test model to experimentally examine the nonlinear aeroelastic response induced by bending freeplay. During the wind tunnel test, a pronounced limit cycle oscillation phenomenon was observed when the flow

velocity reached 20 m/s. The corresponding phase portraits of bending angular displacement versus bending angular velocity are presented in Figure 4.

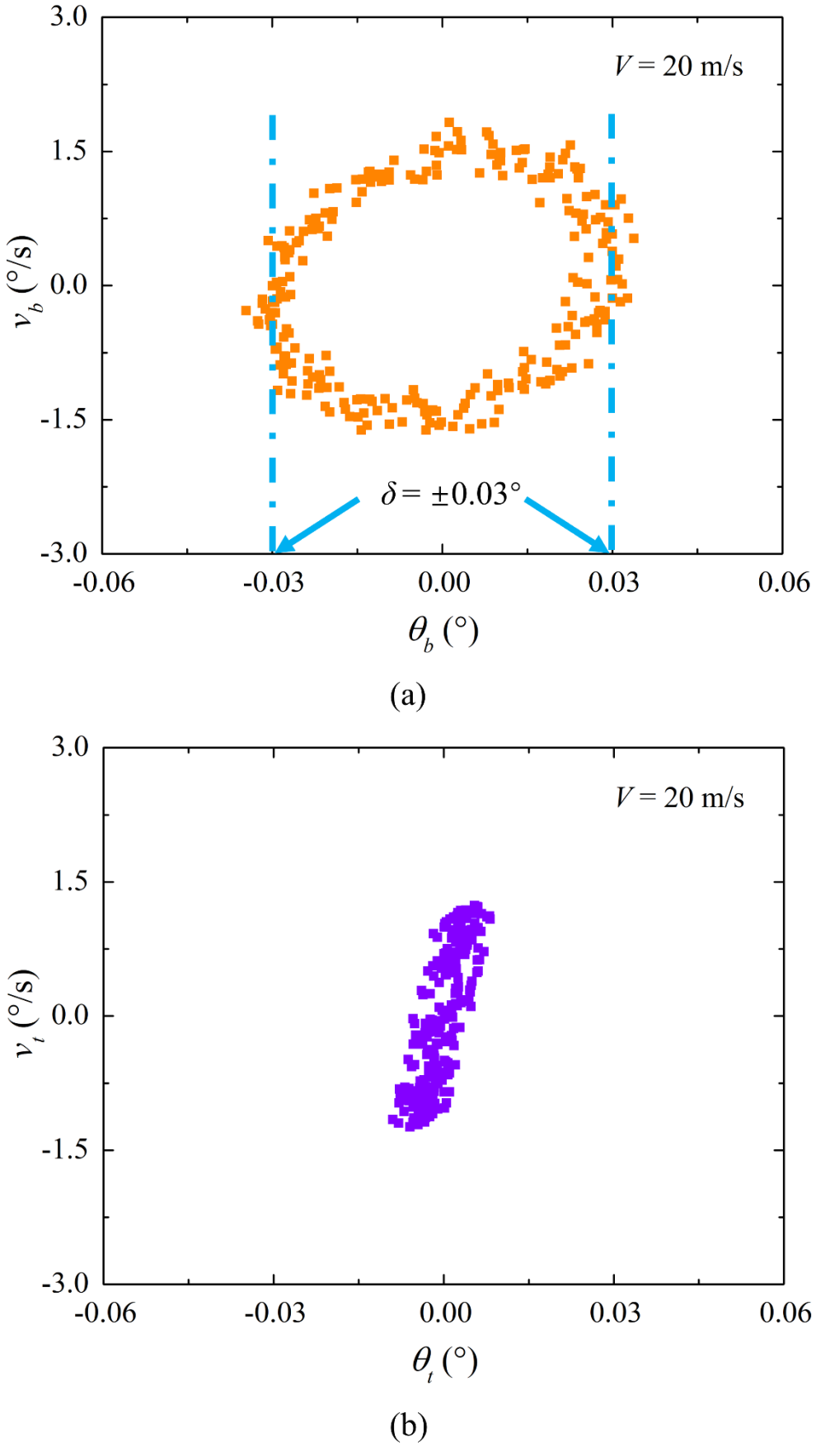


Figure 4 – Phase portraits at V = 20 m/s: (a) bending response; (b) torsional response [16].

The experimental results show that the response trajectory forms a closed and stable limit cycle in the bending phase plane, while no evident oscillatory motion is observed in the torsional degree of freedom. This confirms that the limit cycle oscillation induced by bending freeplay is essentially a single degree of freedom vibration dominated by bending motion, rather than a coupled bending–torsional oscillation. Moreover, as shown in Figure 4a, the steady-state oscillation amplitude is only slightly larger than the prescribed bending freeplay angle of 0.03°, which is consistent with the theoretical prediction that the bending spring is repeatedly activated once the bending displacement exceeds the freeplay boundary [16]. Therefore, the wind tunnel test results provide direct experimental evidence for the proposed “divergence–suppression” mechanism and validate the theoretical analysis and numerical simulation of bending-freeplay-induced nonlinear aeroelastic behavior.

To investigate the influence of the initial angle of attack on the nonlinear aeroelastic behavior of the all movable rudder system with bending freeplay, an initial angle of attack simulation device was also designed in this study. An initial angle of attack of 0.15° was applied to the aforementioned wind tunnel test model, and wind tunnel tests considering both bending freeplay and the initial angle of attack were conducted. The bending angular amplitude and torsional angular amplitude of the all movable rudder model with the initial angle of attack under different flow velocities are shown in Figure 5. It can be seen that the limit cycle oscillation induced by bending freeplay also occurs at V = 20 m/s. However, as the flow velocity increases to 21 m/s, the limit cycle oscillation disappears, indicating that the initial angle of attack has a certain suppressing effect on the limit cycle oscillation caused by bending freeplay. In addition, when the flow velocity is lower than the critical flutter speed, the bending angular amplitude is consistently larger than the torsional angular amplitude. The bending angular amplitude reaches its maximum when limit cycle oscillation occurs, whereas the torsional angular amplitude is almost proportional to the flow velocity and shows no significant variation even during the occurrence of limit cycle oscillation.

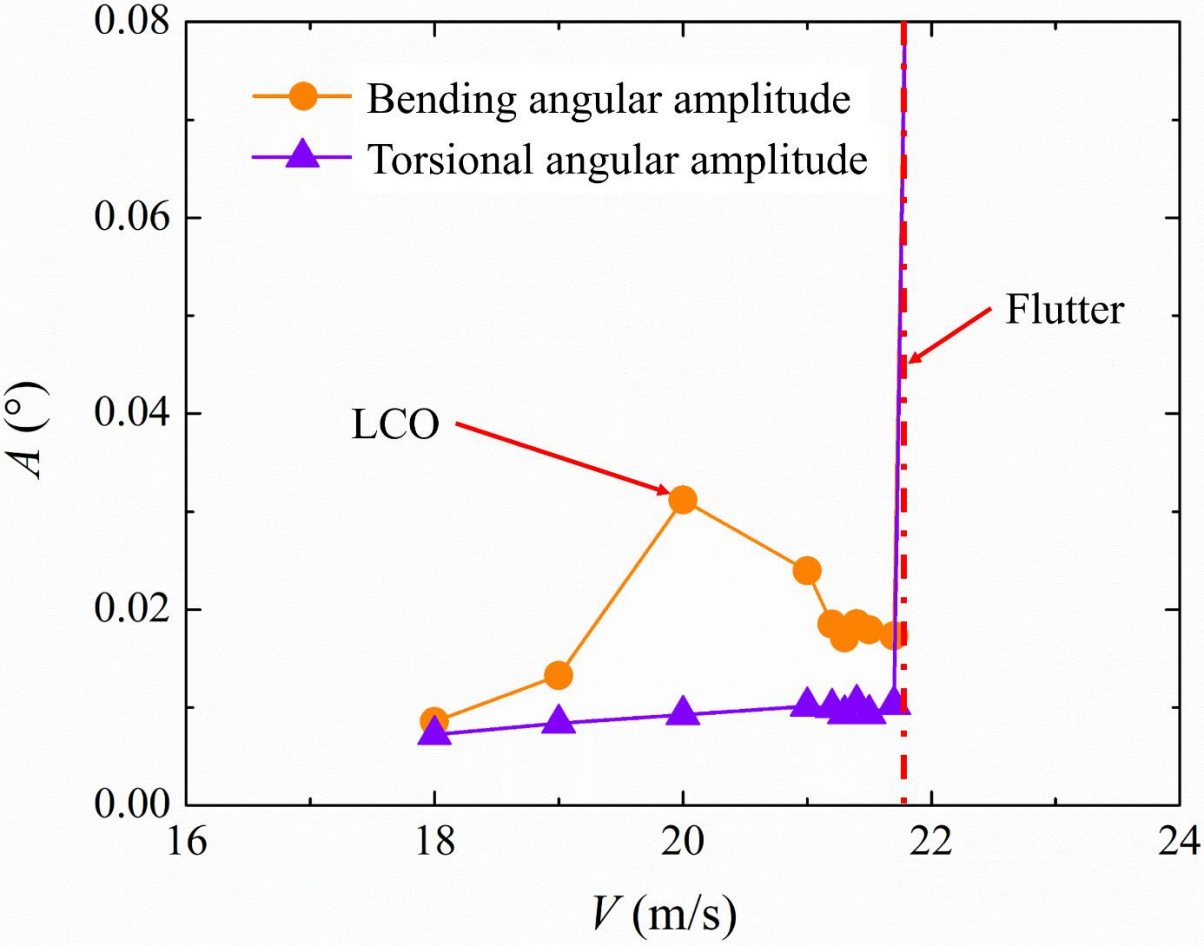


Figure 5 – Angular amplitudes of all movable rudder model with bending freeplay and the initial angle of attack at different flow velocities.

The bending frequency and torsional frequency of the all movable rudder model with the initial angle of attack under different flow velocities are shown in Figure 6. It can be observed that the dominant frequencies of the bending and torsional responses are identical, and both exhibit frequency bifurcation accompanied by a sudden decrease at the critical flutter speed. When the flow velocity is lower than the critical flutter speed, the dominant frequency is almost proportional to the flow velocity and shows no significant variation even during the occurrence of limit cycle oscillation. When the flow velocity exceeds the critical flutter speed, the dominant frequency also remains positively correlated with the flow velocity. In addition, higher-order harmonics appear only when limit cycle oscillation occurs, and they are observed exclusively in the bending response.

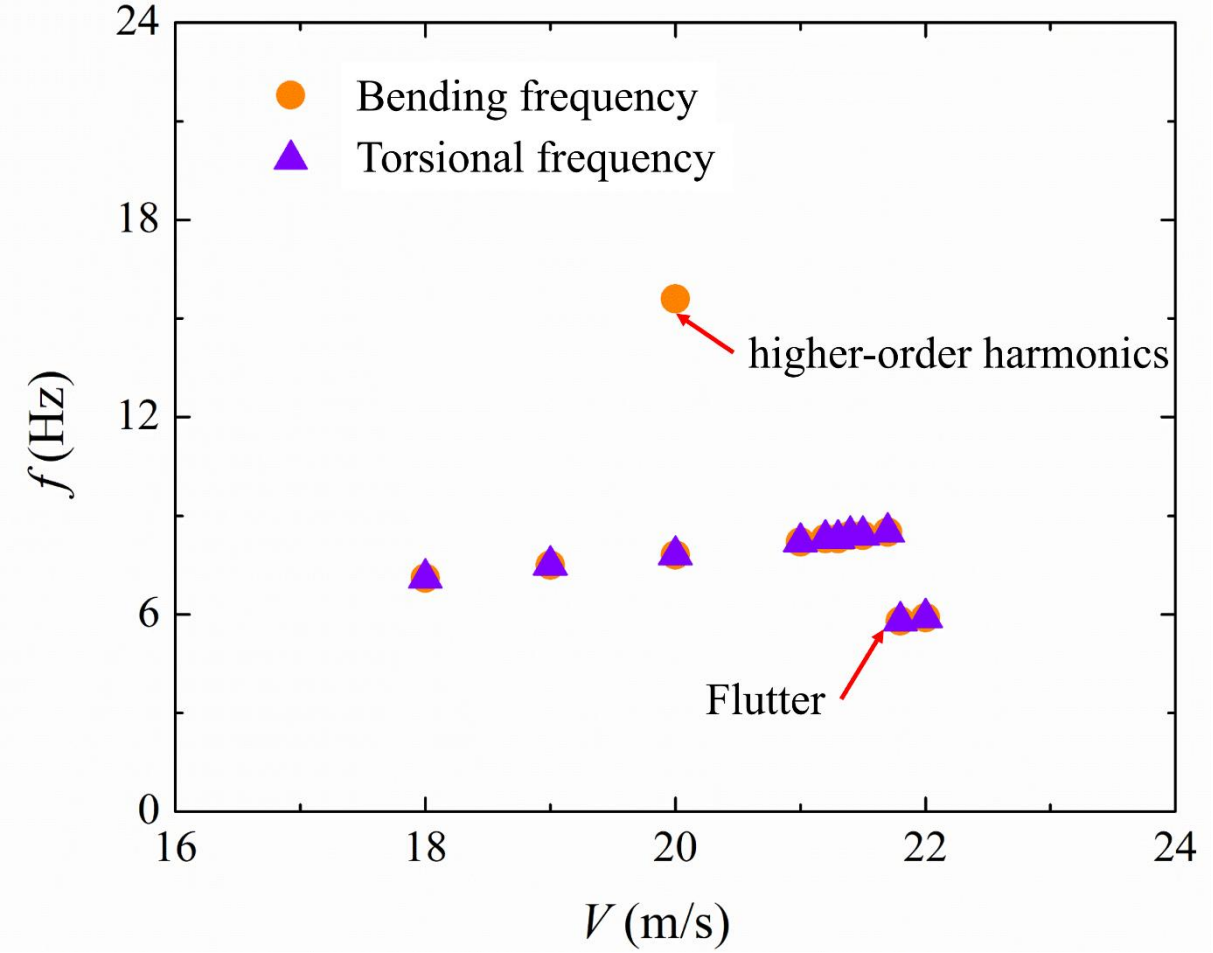


Figure 6 – Frequencies of all movable rudder model with bending freeplay and the initial angle of attack at different flow velocities.

In summary, the limit cycle oscillation induced by bending freeplay has a significant influence only on the bending vibration, leading to an abrupt change in the bending angular amplitude and the emergence of higher-order harmonics in the bending response, whereas it has no significant effect on either the amplitude or the frequency of the torsional vibration.

5. Conclusions

(1) Bending freeplay causes a decrease in the stiffness of the nonlinear system, which in turn causes static divergence at lower flow velocities. When static divergence causes the bending angular displacement to increase to within the stiffness region (greater than the bending freeplay angle), the bending spring will be "activated", while suppressing the divergence of the bending angular displacement. Therefore, the all movable rudder with bending freeplay may repeatedly experience "divergence-suppression" single degree of freedom vibration and form a limit cycle oscillation. It can be seen that the mechanism by which bending freeplay causes limit cycle oscillation in all movable

rudder differs significantly from the mechanism by which torsional freeplay causes limit cycle oscillation through subcritical Hopf bifurcation.

(2) The limit cycle oscillation caused by torsional freeplay simultaneously involves both bending and torsional vibrations. In contrast, the limit cycle oscillation caused by bending freeplay involves only bending vibration.

(3) The amplitude of limit cycle oscillation induced by torsional freeplay is positively correlated with flow velocity. However, the amplitude of limit cycle oscillation induced by bending freeplay is always slightly greater than the bending freeplay angle.

(4) In the limit cycle oscillation induced by torsional freeplay, higher-order harmonics appear in both the bending and torsional responses; in contrast, when the limit cycle oscillation is induced by bending freeplay, higher-order harmonics are observed only in the bending response.

(5) During torsional-freeplay-induced limit cycle oscillation, both the bending and torsional angular amplitudes and the dominant frequencies undergo abrupt changes, whereas bending-freeplay-induced limit cycle oscillation is characterized only by an abrupt change in bending angular amplitude, with no sudden variation in the torsional angular amplitude and dominant frequency.

(6) The initial angle of attack has a certain suppressing effect on the limit cycle oscillation induced by bending freeplay.

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