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THE NONLINEAR FLUTTER WIND TUNNEL TEST OF A FOLDING FIN WITH FREEPLAY NONLINEARITIES

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Abstract: The flutter characteristics of a folding control fin with freeplay are investigated by the flutter wind tunnel test. Based on the characteristics of the structures, the fins with different freeplay angles are designed. At the situation of 0°angle of attack (AOA), the wind tunnel tests of fins with different freeplay angles are carried out, and the vibration is observed by accelerometers and the high-speed camera. Based on the tests at the case of 0°AOAs, the fins within the same freeplay angle are tested in the wind tunnel under different AOAs. The result showed that the flutter speed increased due to the existence of the freeplay. As long as the increase of the freeplay angle, the flutter speed increases. The aerodynamic load could decrease the influence of the freeplay. Along with the increase of the AOA, the flutter speed decreases untill to the linear flutter speed.

1 INTRODUCTION

Due to the raised of the requirement of the storage space and the firepower, the folding wing structures are widely used in missiles. Although torsion springs and dowels are used to strengthen the structure in the folding axes, nonlinear phenomena of the freeplay and fictions always exist because of the mismachining tolerance and the attrition.

Bacause of the existence of the structural nonlinearities, the characteristics of the vibration and aeroelasticity are changed. The aeroelastic characteristics might not be analyzed precisely by the traditional linear methods in some situations and the design process might be affected. In recent years, many investigations of the nonlinear aeroelastic analysis are performed. A three degree-of-freedoms (DOF) aerofoil with nonlinear torsional spring is investigated by Alighanbari [1,2], and the bifurcations and the limit cycle oscillations(LCO) are observed under the linear flutter boundary by the Fourier transform. The nonlinear flutter characteristics of a two DOFs foils are researched by Price [3]. The LCOs and chaos motions might occur under the linear flutter boundary and the vibration characteristics have relationships with structural parameters and initial conditions. A series of two DOFs foils with freeplay and frictions in the torsion direction are investigatied and wind tunnel tests are carried out by Yang [4]. Similar researchs about the two or three DOFs foils are abundant. In these researchs, the nonlinear aeroelastic phenomena and the nonlinear analysis methods are the emphases. But actual mechanisms are Multi-DOF structures, the establishing and analysis methods are difficult to be applied at actual cases.

The existence of the freeplay makes the relationship between the structural stiffness and the generalized coordinates to be nonlinear. As a consequence, the results calculated by the linear modal method may differ from real phenomena. Kan investigated the impact of freeplay on flutter and LCO of an all-movable horizontal tail by adding a gap element at the root and flutter/LCO characteristics calculated agreed well with experimental data[5]. In order to establish the nonlinear vibration equation, the fictitious mass method is introduced by Karpel [6,7]. In this method, the fictitious modals are obtained by the modal analysis of the structure with fictitious mass in the DOFs where the stiffnesses are changed. The fictitious mass method is widely used in the nonlinear aeroelastic analysis. Lee analyzed an all-movable nonlinear control fin [8], and results showed that the nonlinear parameters and initial conditions had a strong influence on the nonlinear responses. Different velocities and different ratios between the freeplay and the vibration amplitude make vibrational responses to be LCO or chaos motions. Bae established the nonlinear aeroelastic equation of a wing-aileron mode and the nonlinear characteristics were analyzed [9]. The LCOs occur under linear flutter boundary. Kim performed a study on a folding wing with freeplay and friction nonlinearities [10][11], and LCOs were observed. Lee and Tron carried out a study of the aeroelastic characteristics of F-18 by fictitious mass method [12]. Results showed that LCOs occurred within a small range and the angle of attack could suppress vibrations. Although the nonlinear equation could be established by fictitious mass method, the selected parameters of the fictitious masses are a suggested range and the nonlinear stiffness is not expressed in the equation directly.

As previous introduction shows, the researches about the numerical analysis of the nonlinear aeroelastic characteristics are sufficient, but the open literatures of nonlinear flutter wind tunnel tests of missile control fins are few. Although configurations of folding wings are different from the missile control fins, the wind tunnel tests of folding wings could provide references. The test vibration responses in the wind tunnel environment could be used to verify the analysis method. Sebastiano investigated the effect of the control-surface freeplay to the aeroelastic characteristics and a wind-tunnel model of a T-tail with freeplay[13]. A state-space system with nonlinearity represented as a feedback loop and the high-order harmonic balance approach are performed to simulate the experimental results. Comparison with experimental results, the FRF and LCO calculated agreed well. Tang carried out wind tunnel test of the folding wing and results showed that flutter speed had relationship with the folding stiffness and folding angles [14]. But in tang's experiment there is no freeplay in the folding structure and the flutter speed is the linear result. In order to observe the nonlinear flutter and the flutter suppression technique, a three DOFs foil mode with freeplay in the pitching direction was designed and the wind tunnel test was carried out by Texas University [15,16,17]. The results of wind tunnel showed that the LCOs were observed because of the freeplay. Although the wind tunnel test of foils could observe the nonlinear flutter and verify the analyzed method, phenomena between the foils and the folding structures are different and the modeling method of the folding wing is more complex. As a result, the nonlinear flutter wind tunnel test face to the folding fin is necessary.

In present work, a serie of folding fin with different freeplay angles is designed and the nonlinear flutter wind tunnel test is carried out. The fins with freeplay under different angles of attack (AOAs) are test in the wind tunnel. The nonlinear phenomena are observed by accelerometers and the high-speed camera.

2 RESULTS AND DISCUSSION

2.1 The experimental structure

Based on the environment and the dimension of the wind tunnel, the experimental fin is designed as Fig. 1. The structure is consist of the out-boarding wing, the inner wing , the rudder shaft and the folding shaft, in which the rudder shaft and the inner wing are manufactured together, and the bottom of the rudder shaft is fixed on a rigid supported structure by bolts. The experimental fin is manufactured by aluminum. In order to make the flutter speed of the structure to be in the range of the ability of the wind tunnel, the rudder shaft is designed to be an I-beam, which is showed in Fig. 1. The bend and torsional frequencies could be designed. The inner wing and the out-boarding wing are connected by the folding shaft, which is showed in Fig. 1. The bending moment is transferred by contact faces which are showed in Fig. 1. The freeplay is generated by the manufacturing tolerance of the contact face between the inner wing and the out-boarding wing. The angle of the freeplay could be altered and the freeplay makes an influence to the bending modals. The vibrational responses are measured by the accelerometers at the root and top of the trailing edge, which is showed in Fig. 2.

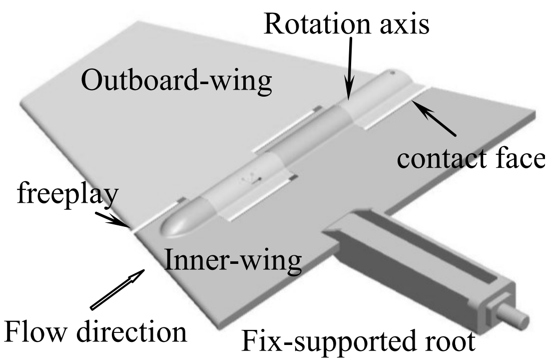

Fig. 1 The sketch map of the experimental fin

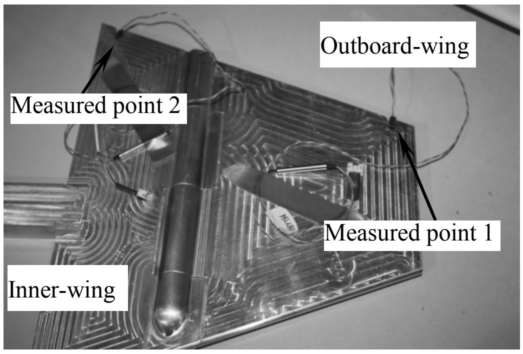

Fig. 2 The structure and the measured points

In actual fight conditions, the control fin is installed on the body of the missile. In order to imitation the actual aerodynamic force, the fin is installed in a rigid missile body which is showed in Fig. 3. The vibration process is recorded by high speed cameras set at the observed window.

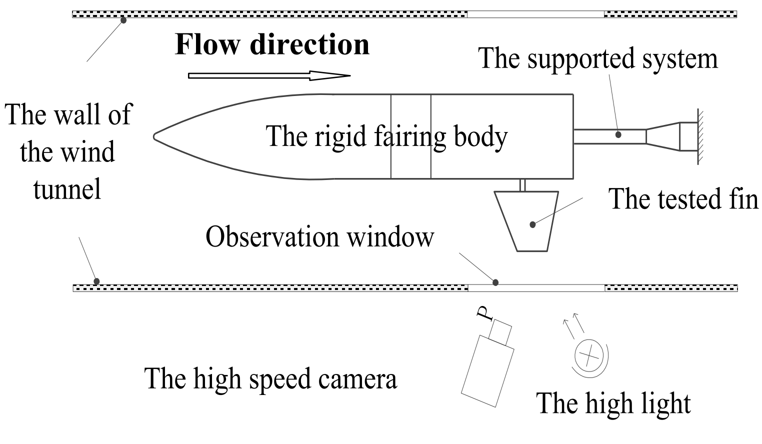

Fig. 3 The sketch of the installation of the structures in the wind tunnel

2.2 The results of nonlinear wind tunnel tests under AOA 0°

Fins under three freeplay conditions which are showed in Table. 1 are tested in the wind tunnel. The connected faces which are showed in Fig. 1 are welded and the structure becomes a linear structure, which is the situation of the number 1 in Table. 1. The tested results of linear structure are the references of nonlinear tests. The distance between connected faces is increased at the No.2 and No.3 cases in Table. 1, and the freeplay angles are increased.

Table. 1 Three freeplay situations

Number	Freeplay
1	No freepay
2	Smaller
3	Larger

The wind tunnel tests of three fins are carried out respectively. The Mach number of the incoming flow of the wind tunnel is kept 0.6Ma. In the test process, the dynamic pressure of the incoming flow is increased gradually until the vibrational broken of the structure, and each value of the dynamic pressure is kept for seconds.

The wind tunnel test of the linear fin No.1 is courried out, and the result is showed in Fig. 4. In the test process, the dynamic pressure is increased gradually by 24kpa-26kpa-28kpa and the vibrational responses are increased correspondingly, which are showed by red line and black line respectively. When the dynamic pressure is up to 26.94kpa, namely the velocity of the incoming flow 209.7m/s, the vibrational broken of the fin occurs, and the responses of the accelerometers reach the measuring range. The wreckage of the fin is showed in Fig. 5, the connection between the inner wing and the fin shaft and the root bolts are broken. The photos when vibrational divergence occurs are showed in Fig. 6, and the sample rate of the high speed camera is 500 frames per second.

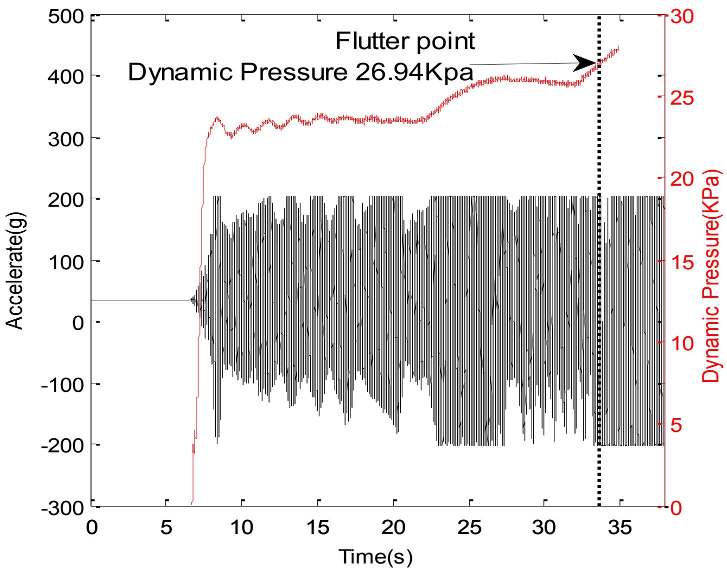

Fig. 4 The wind tunnel test results of the No.1 fin

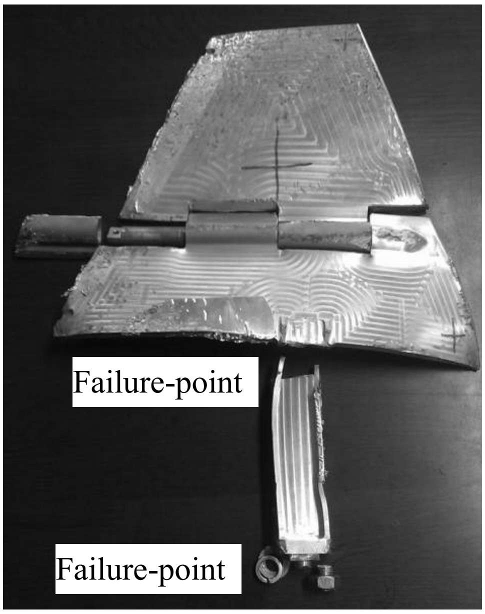

Fig. 5 The wreckage of the No.1 fin

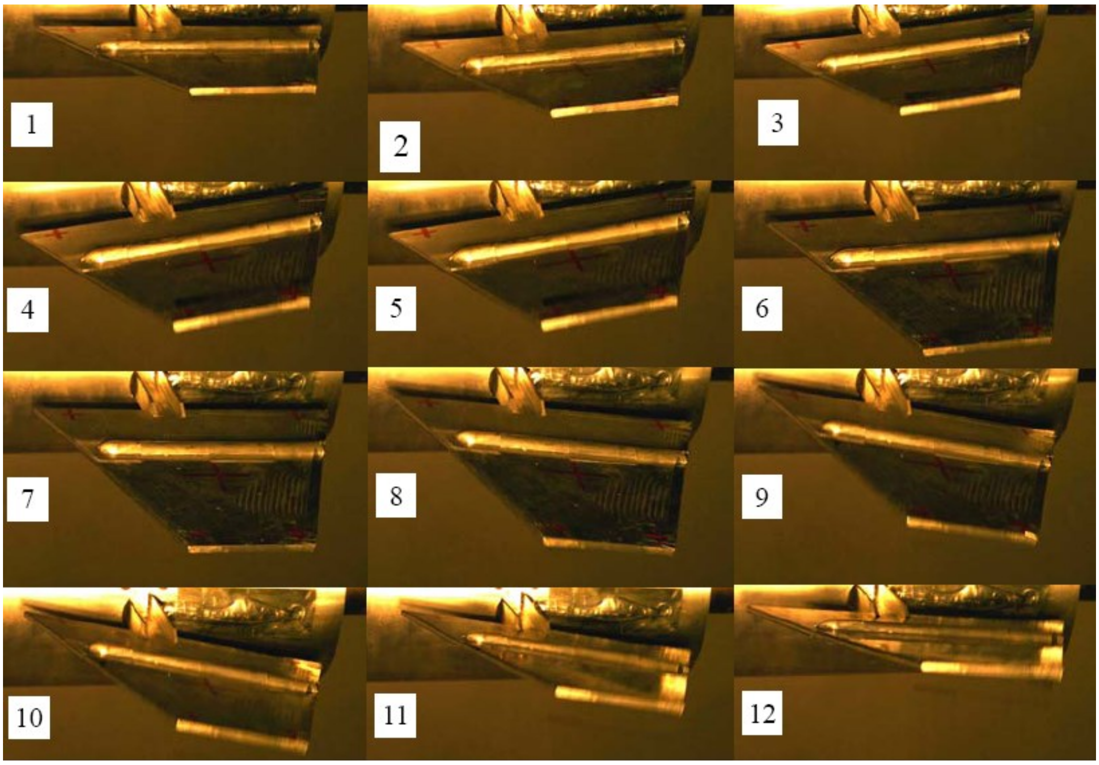

Fig. 6 The photos of a vibration period when the vibrational divergence occurs

The Fourier transform is investigated of the vibrational responses to get the vibrational frequency, which is showed from Fig. 7 to Fig. 9. Along with the increase of the velocity, the vibrational frequency decreases. When the divergence occurs, the vibrational frequency is 50.05Hz, which is showed in Fig. 9.

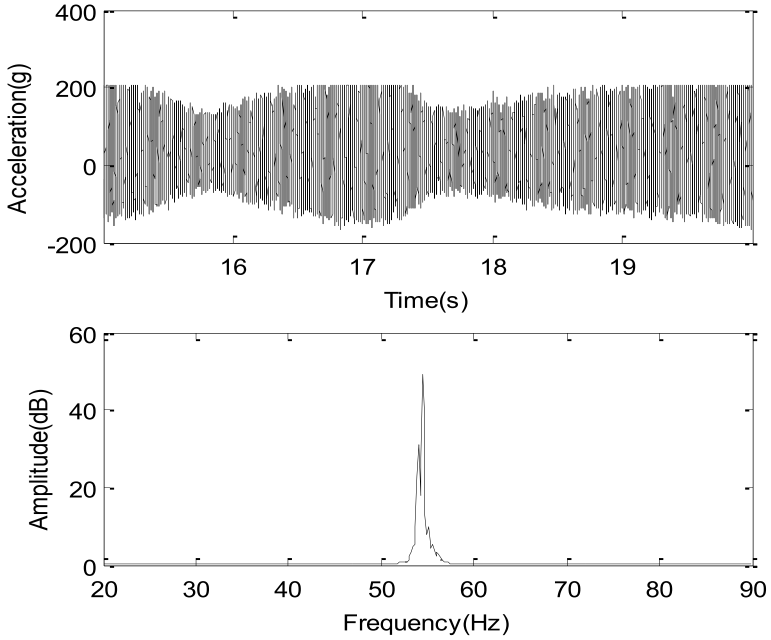

Fig. 7 The accelerate responses of the No.1 fin and Fourier transform (time: 15.0s-20.0s)

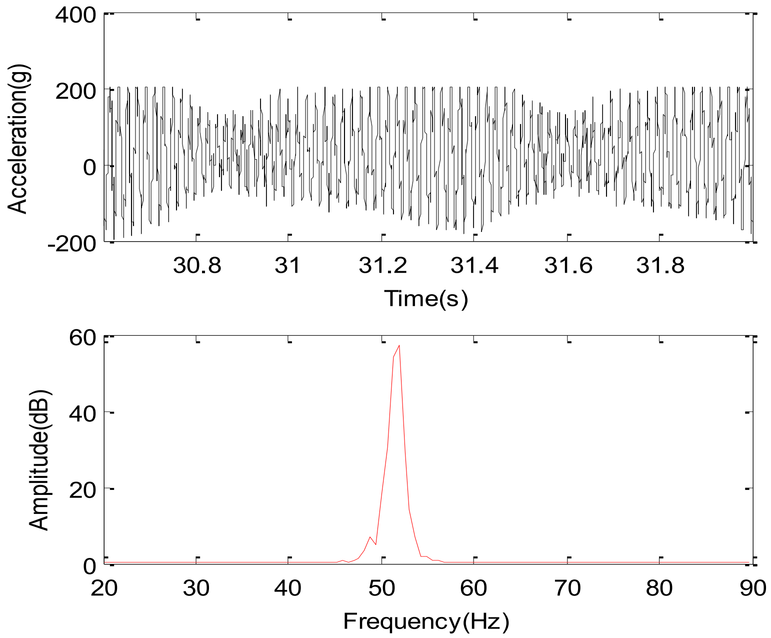

Fig. 8 The accelerate responses of the No.1 fin and Fourier transform (time: 30.6s-32.0s)

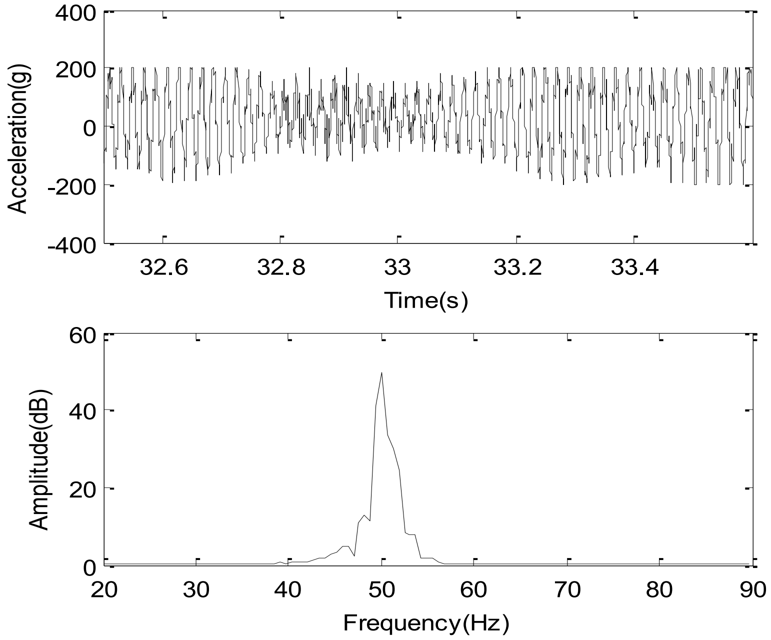

Fig. 9 The accelerate responses of the No.1 fin and Fourier transform (time: 32.5s-33.6s)

Base on the test of the linear result, the No.2 fin with freeplay is tested, which is showed in Fig. 10. The dynamic pressure is increased gradually by 24kpa-26kpa-28kpa. The vibrational divergence occurs at the top of the adjust process, of which the dynamic pressure is 30.68kpa, namely the flow velocity 223.8m/s. The vibration responses are analyzed by Fourier transform, which is showed from Fig. 11 to Fig. 13. There are LCOs in the vibration process, and the vibrational frequency decreases along with the increase of the velocity.

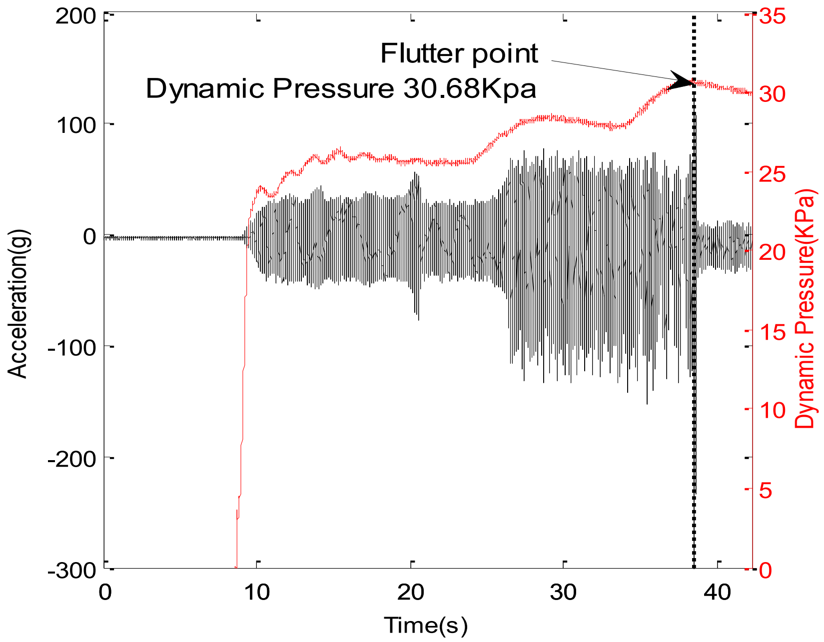

Fig. 10 The wind tunnel test results of the No.2 fin

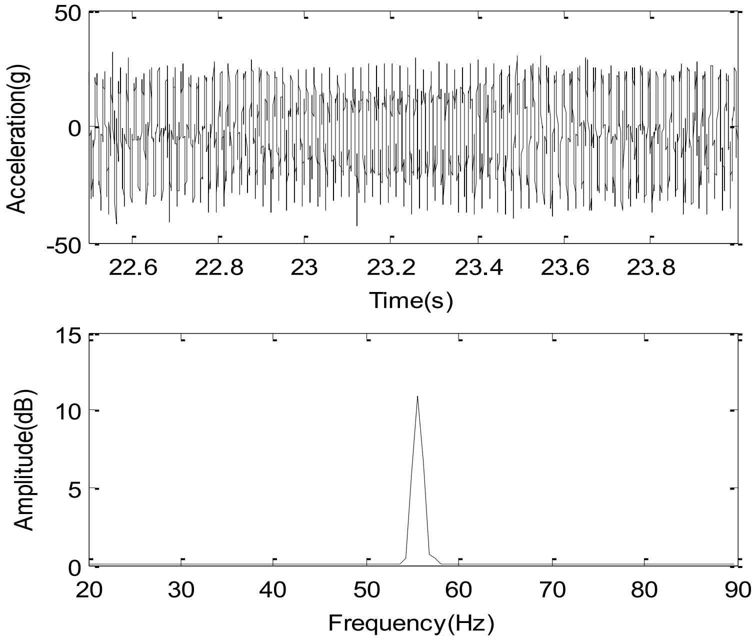

Fig. 11 The accelerate responses of the No.2 fin and Fourier transform (time: 22.5s-24.0s)

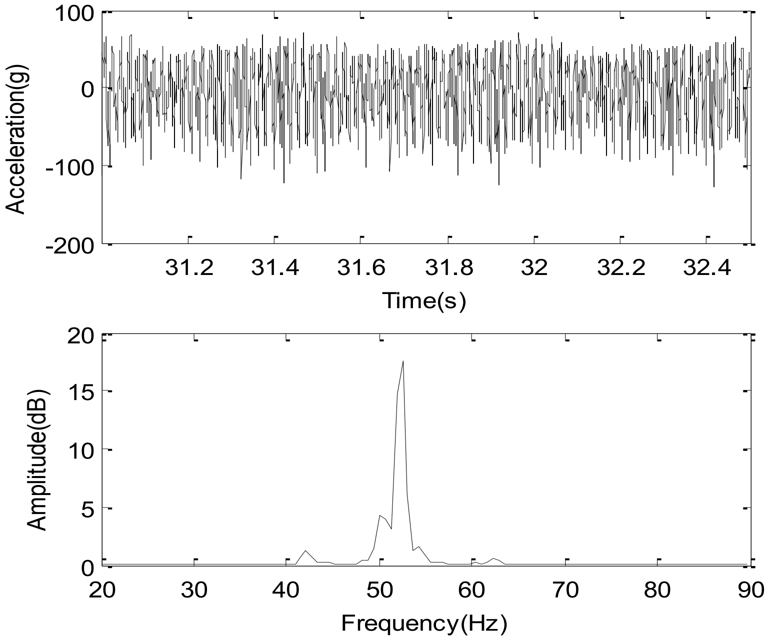

Fig. 12 The accelerate responses of the No.2 fin and Fourier transform (time: 31.0s-32.5s)

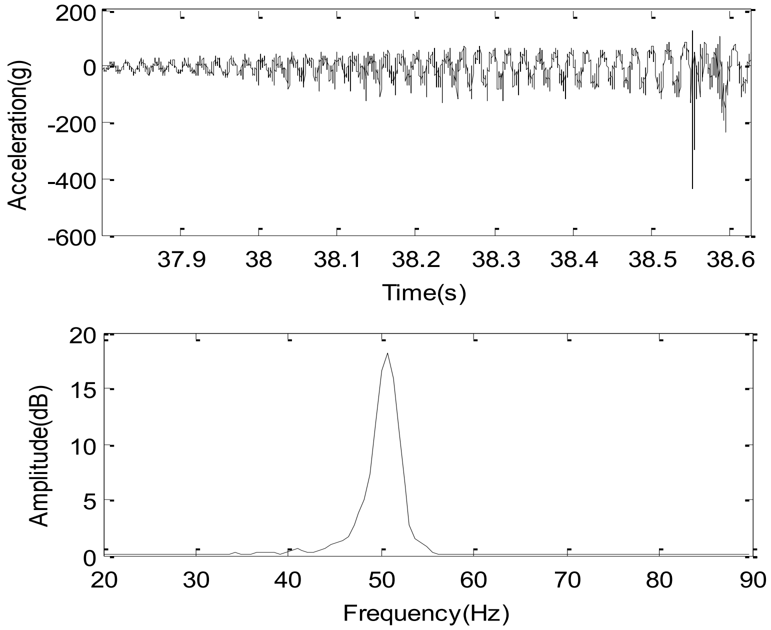

Fig. 13 The accelerate responses of the No.2 fin and Fourier transform (time: 37.80s-38.63s)

The No.3 fin is tested in the same process, and the result is showed in Fig. 14. The vibrational divergency dynamic pressure is 41.80kpa, namely the flow velocity 261.2m/s. The LCOs is not observed in the test process, and this might be affected by the rapid increase of the dynamic pressure.

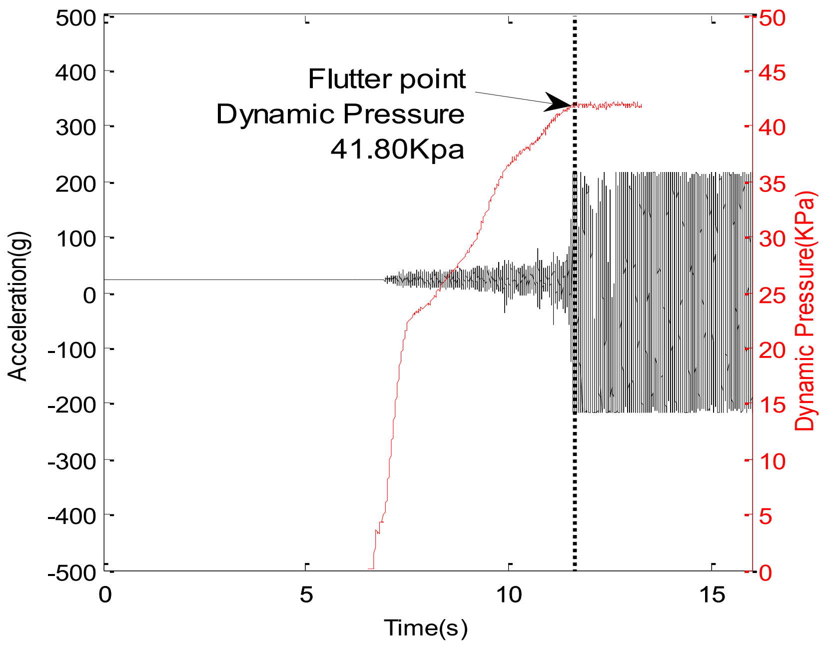

Fig. 14 The wind tunnel test results of the No.3 fin

The flutter results of three fins are combined in a table, which is Table. 2. Along with the increase of the freeplay angle, the vibrational divergency velocity which is higher than the linear flutter boundary increases. The existence of the freeplay makes the flutter speed of the present model increase, and the linear calculation could make the fight safety. By the comparison between the No.1 fin and the No.2 fin, the vibrational divergency frequencies are almost the same. But the flutter frequency of the No.3 fin is lower, and this is caused by the higher divergency speed.

Table. 2 The test flutter results of three fins

No.	Freeplay	Divergency dynamic pressure(kpa)	Divergency speed(m/s)	Divergency frequency(Hz)
1	No freepay	26.94	209.7	50.05
2	Smaller	30.68	223.8	50.66
3	Larger	41.80	261.2	47.0

2.3 The results of nonlinear wind tunnel tests under different AOAs

At the ordinary flight condition, the aerodynamic load is applied on the structure. In order to investigate the influence of the aerodynamic load to the nonlinear flutter speed, folding fins with the same freeplay angle are tested in the wind tunnel under different AOAs. The freeplay angles of fins are generated by the same manufacturing tolerance. The situations of the AOAs are showed in the Table.3.

Table. 3 The tested situations of the AOAs

No.	Freeplay	AOA (degree)
1	Yes	0
2	Yes	1
3	Yes	2
4	Yes	3

As showed in Fig. 15, the flutter dynamic pressure of the folding fin is higher than the linear boundary, which could be repeated by tests. As long as the increase of the AOA, the flutter speed of the folding fin decreases, which is showed from Fig. 15 to Fig. 18. When the AOA is large, the flutter speed is close to the linear boundary. The aerodynamic load could suppress the influence to the freeplay.

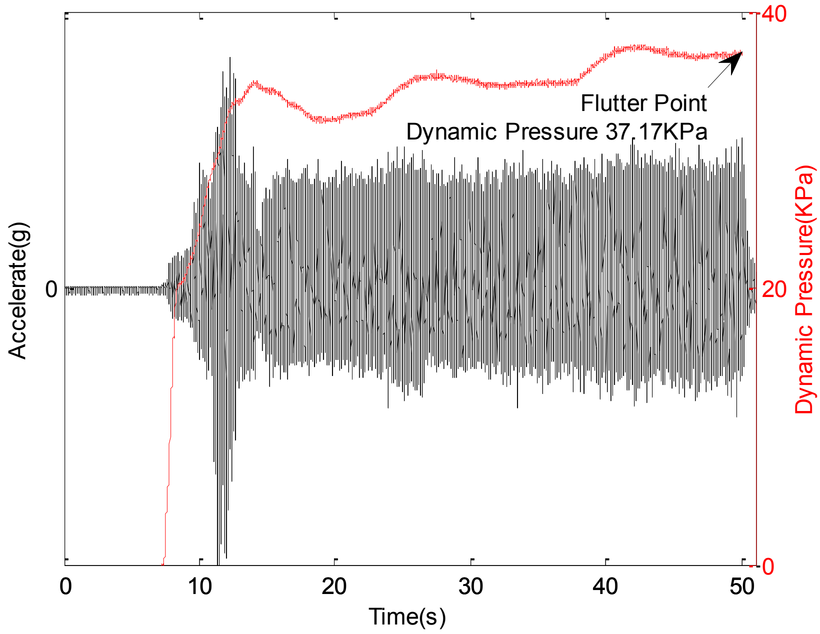

Fig. 15 The wind tunnel test results of the folding fin under AOA 0°

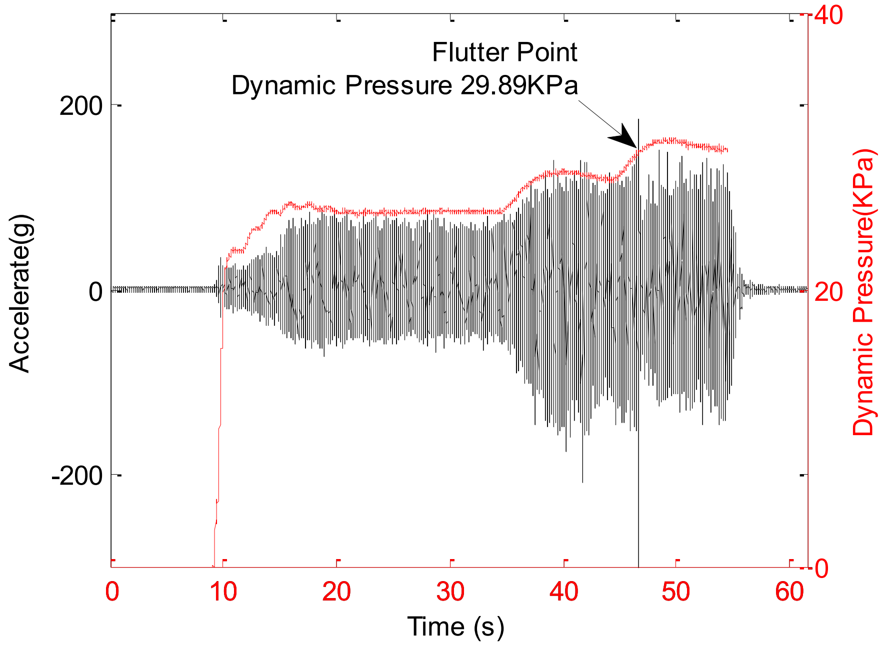

Fig. 16 The wind tunnel test results of the folding fin under AOA 1°

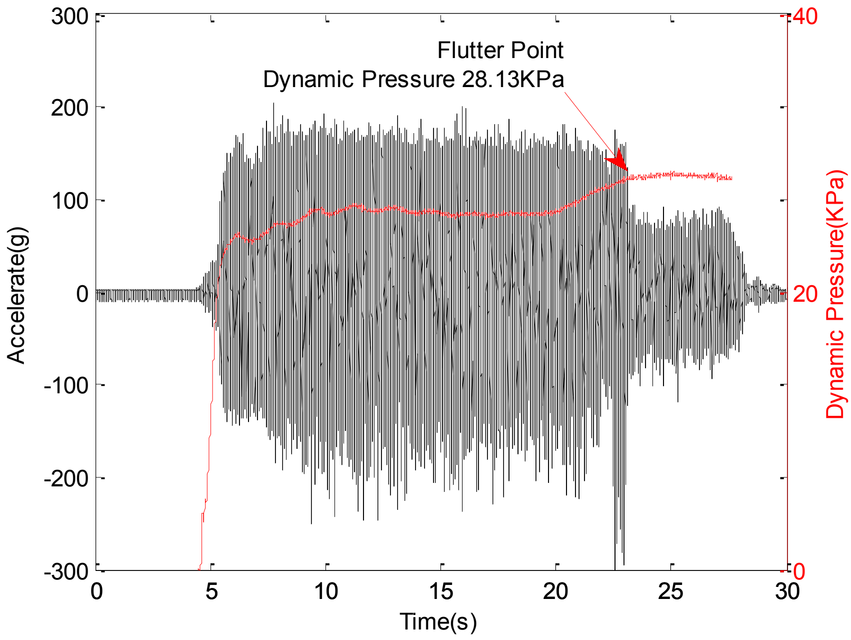

Fig. 17 The wind tunnel test results of the folding fin under AOA 2°

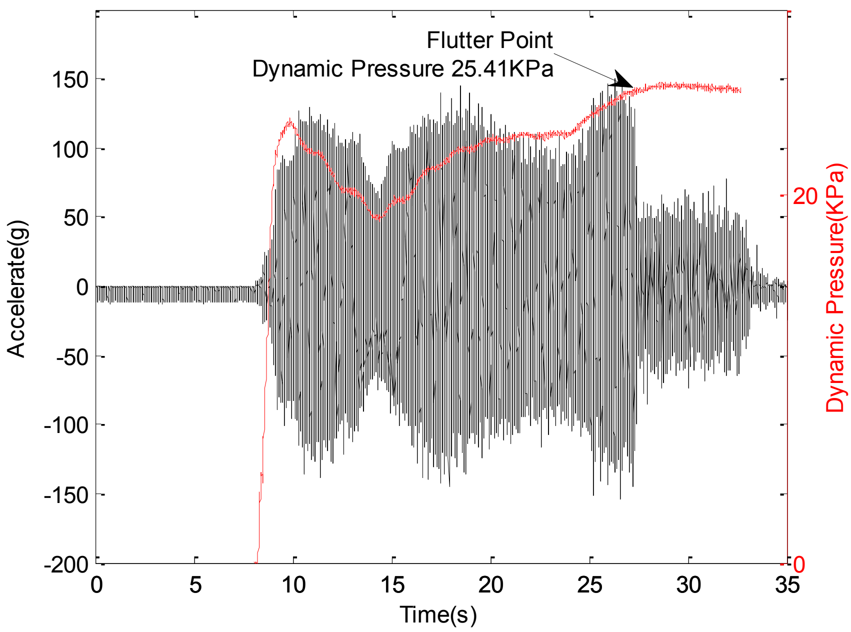

Fig. 18 The wind tunnel test results of the folding fin under AOA 3°

3 CONCLUSIONS

In this study, the wind tunnel tests of control fins with nonlinear folding stiffness are carried out. Based on the mismachining tolerance, the fins with different freeplay angles are designed. The tests of different AOAs are carried out. The conclusions are as follows.

(1) The divergence speed increases because the existence of the freeplay when the angle of attack is 0° . The larger freeply will make higher divergency speed. The analysis based on the linear flutter analysis could make the flight to be safety. Along with the increase of the flow velocity, the vibrational frequency decreases.

(2) When speed is within the linear flutter boundary and the divergency speed, LCOs exist. The vibration is convergency when the speed is below the linear flutter boundary.

(3) The flight AOA could suppress the influence of the freeplay. Although the flutter speed is higher than the linear boundary, the flutter speed decreases until to the linear condition as long as the increase of the AOA. In most actual flight conditions, AOAs might not be small and the tests show that the folding freeplay has no influence to the flutter speed.

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