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REVIEW ARTICLE

Nonlinear flutter wind tunnel test and numerical analysis of folding fins with freeplay nonlinearities

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Abstract The flutter characteristics of folding control fins with freeplay are investigated by numerical simulation and flutter wind tunnel tests. Based on the characteristics of the structures, fins with different freeplay angles are designed. For a 0° angle of attack, wind tunnel tests of these fins are conducted, and vibration is observed by accelerometers and a high-speed camera. By the expansion of the connected relationships, the governing equations of fit for the nonlinear aeroelastic analysis are established by the free-interface component mode synthesis method. Based on the results of the wind tunnel tests, the flutter characteristics of fins with different freeplay angles are analyzed. The results show that the vibration divergent speed is increased, and the divergent speed is higher than the flutter speed of the nominal linear system. The vibration divergent speed is increased along with an increase in the freeplay angle. The developed free-interface component mode synthesis method could be used to establish governing equations and to analyze the characteristics of nonlinear aeroelastic systems. The results of the numerical simulations and the wind tunnel tests indicate the same trends and critical velocities.

1. Introduction

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

Because of the existence of structural nonlinearities, the characteristics of vibration and aeroelasticity are changed. The aeroelastic characteristics cannot be analyzed precisely by the traditional linear methods in some situations, and the design process is affected. In recent years, many investigations of nonlinear aeroelastic analysis have been performed. A review on the recent advances in nonlinear aeroelasticity of aircraft was presented by Xiang et al.[1] and the research aeroelastic models with freeplay nonlinearity are mainly airfoils. A three-degree-of-freedom (DOF) airfoil with nonlinearity in the pitch degree was investigated by Li et al.[2] The results showed that limit cycle oscillations (LCOs) occurred and based on the state-dependent Riccati equation method, a state

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feedback suboptimal control law was derived to suppress the vibration. A three-DOF airfoil with a nonlinear torsional spring was investigated by Alighanbari et al.[3,4] and bifurcations and LCOs were observed under the linear flutter boundary by Fourier transform. The nonlinear flutter characteristics of two-DOF foils were researched by Price and Lee.[5] LCOs and chaos motions occurred under the linear flutter boundary, and the vibration characteristics were related to the structural parameters and initial conditions. A series of two-DOF foils with freeplay and frictions in the torsion direction were investigated, and wind tunnel tests were performed by Yang.[6] Similar research on two- or three-DOF foils is abundant. In these studies, nonlinear aeroelastic phenomena and nonlinear analysis methods have been emphasized. However, the actual mechanisms are multi-DOF structures, and analysis methods are difficult to apply in actual cases.

The existence of freeplay makes the relationship between structural stiffness and generalized coordinates nonlinear. As a consequence, the results calculated by the linear modal method may differ from real phenomena. Kan and Patrick investigated the impact of freeplay on the flutter and LCO of an all-movable horizontal tail by adding a gap element at the root, and the calculated flutter/LCO characteristics matched the experimental data.[7] To establish the nonlinear vibration equation, a fictitious mass method was introduced by Karpel et al.[8,9] In this method, fictitious modals are obtained by modal analysis of a structure with a fictitious mass in the DOFs where the stiffness values are changed. The fictitious mass method is widely used in nonlinear aeroelastic analysis. Lee and Kim analyzed an all-movable nonlinear control fin,[10] and the results showed that the nonlinear parameters and initial conditions had strong influences on the nonlinear responses. Different velocities and different ratios between the freeplay and the vibration amplitude caused the vibrational responses to be LCO or chaos motions. Bae et al. established the nonlinear aeroelastic equation of a wing-aileron mode, and the nonlinear characteristics were analyzed.[11] LCOs occurred under the linear flutter boundary. Lee et al. performed a study on a folding wing with freeplay and friction nonlinearities,[12,13] and LCOs were observed. Lee and Tron conducted a study of the aeroelastic characteristics of an F-18 by the fictitious mass method.[14] The results showed that LCOs occurred within a small range, and the angle of attack could suppress vibrations. Although a nonlinear equation could be established by the fictitious mass method, the selected parameters of the fictitious masses are in a suggested range, and the nonlinear stiffness is not directly expressed in the equation.

As the previous introduction shows, research about the numerical analysis of the nonlinear aeroelastic characteristics is sufficient, but the literature about nonlinear flutter wind tunnel tests of missile control fins is limited. Although the configurations of folding wings are different from those of missile control fins, 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. An investigation was made into the nonlinear aeroelastic behavior of a composite wing with a morphing trailing edge by Li et al.[15] The results showed that the freeplay nonlinearity might reduce the convergence speed and accelerate the divergence of aeroelastic responses. Sebastiano and Sergio investigated the effect of the control-surface freeplay on the aeroelastic characteristics and a wind-tunnel model of a T-tail with freeplay.[16] A state-space system with nonlinearity was represented as a feedback loop and a high-order harmonic balance approach was performed to simulate the experimental results. The experimental results and the calculated frequency response function (FRF) and LCO were in agreement. Tang and Dowell performed wind tunnel tests of a folding wing, and the results showed that the flutter speed was related with the folding stiffness and folding angles.[17] However, in Tang's experiment, there was no freeplay in the folding structure, and the flutter speed was the linear result. To observe nonlinear flutter and flutter suppression technique, a three-DOF foil mode with freeplay in the pitching direction was designed, and wind tunnel tests were conducted by Texas University.[18–20] The results of the wind tunnel tests showed that LCOs were observed because of the freeplay. Although the wind tunnel tests of the foils indicated nonlinear flutter and verified the analysis method, the phenomena between the foils and the folding structures are different and the modeling method of the folding wing is more complex. As a result, nonlinear flutter wind tunnel testing for the folding fin is necessary.

In the present work, a series of folding fins with different freeplay angles is designed, and a nonlinear flutter wind tunnel test is conducted. The nonlinear phenomena are observed by accelerometers and a high-speed cameras. By the free-interface component mode synthesis method, a nonlinear aeroelastic governing equation is established by the expansion of the connected conditions. Based on the results of the wind tunnel test, the flutter analysis of the tested folding wings with different freeplay angles is performed.

2. Computation scheme

A folding wing can be separated into two parts: the inner wing and the outboard wing. Therefore, the component mode synthesis method is an effective method to establish the governing equation. The component mode synthesis method was first introduced by Hurty.[21,22] Craig and Bampton expanded the method and introduced the fixed-interface component mode synthesis method, which was an effective engineering method.[23] Then, the free-interface component mode synthesis method was introduced by Hou,[24] and developed by Rubin[25] and Craig and Chang.[26] In the developed method, the residual

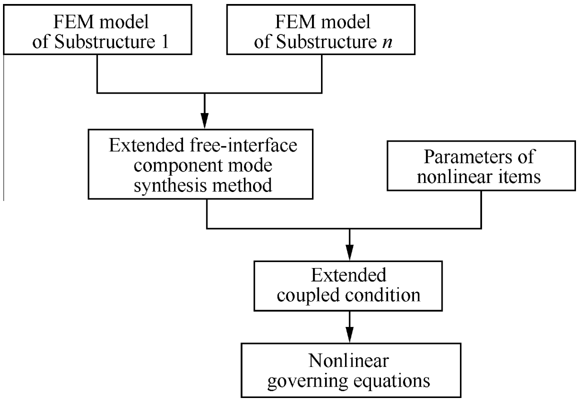

Fig. 1 Process of component mode synthesis method.