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Study on nonlinear aeroelastic response of a all-moving rudder surface

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Abstract: *With the application of all-moving rudders in aircraft more and more, the phenomena of limit cycle oscillation, bifurcation and chaotic motion caused by the free-play nonlinearity in the transmission structure of all-moving rudder have become a research topic.A nonlinear structure model of the all-moving rudder surface was established based on the virtual mass method in this paper.Time domain integral method was established to solve the nonlinear system of all-moving rudder surface, studying the influence of different clearance size and different wind speed on the aeroelastic response of the nonlinear system.The results showed that the amplitude of limit cycle increases with the increase of equivalent velocity until divergence. Under the same incoming flow velocity and gust loads, the amplitude of the limit cycle of the free-play nonlinear system increases gradually with the increase of the gap, indicating that the increase of the gap will increase the oscillation amplitude of the structure and even affect the divergence velocity.*
Key words: *Gap nonlinearity; Limit cycle oscillation; Virtual quality method*

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I. Introduction

Due to its excellent handling performance and efficient structure, all-moving rudder has been widely used in today's aircraft. However, the control system of all-moving rudder will inevitably produce gaps in the manufacturing and using process, and the free-paly nonlinearity caused by this gap has attracted extensive attention from aeroelastic researchers. The existence of free-play nonlinearity will make the aeroelastic calculation method based on linear calculation theory no longer applicable, which may lead to nonlinear phenomena such as limit cycle oscillation and affect the handling quality and flight safety.

As shown in Figures 1 and 2, limit cycle oscillations of aircraft include two types. One is supercritical flutter, which is larger than the linear flutter velocity, and the other is subcritical flutter, which is smaller than the linear flutter velocity. For supercritical flutter, when the vehicle speed is higher than the flutter speed, the system starts to oscillate in the limit cycle, and the structural nonlinearity of the system tends to suppress the vibration and reduce the vibration amplitude. However, before reaching the flutter speed of subcritical flutter, the system will conduct limit cycle oscillation earlier, which will cause damage to the structure [1].

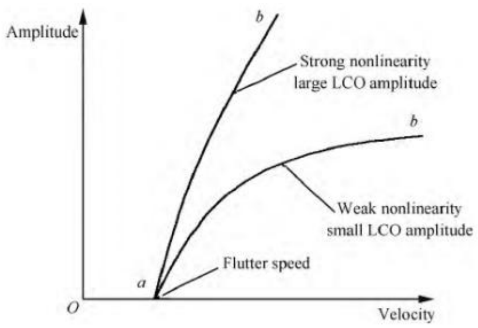


Figure 1: Supercritical flutter

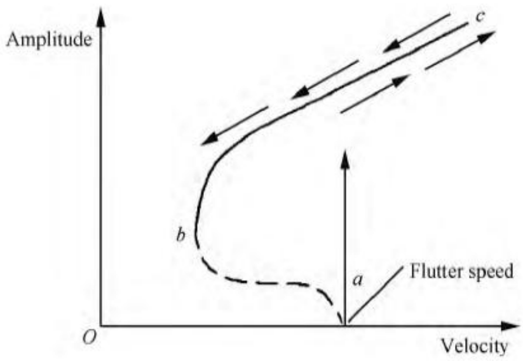


Figure 2: Subcritical flutter

In 1957, Woolston et al.[2] analyzed the flutter problem of structures with nonlinearities and found that it had complex LCO motion phenomenon, which promoted other scholars to study such problems.In 1997, Conner, et al. [3] studied the structural response problem of a control surface with hinge clearance and designed experiments to demonstrate it. In 2002, Safi, et al. [4] studied a binary wing model with gap nonlinearity and found the relationship between the amplitude of limit cycle oscillation and the gap size.Price, et al. [5] studied subsonic wing with nonlinear structure in incompressible flow, analyzing that by using numerical integral method and the describing function method respectively for nonlinear system, the result showed that although the describing function method can effectively forecast system LCO movement, but cannot get its initial conditions on the influence of the nonlinear system response.Kholodar [6] analyzed a binary wing with nonlinear clearance on the trailing edge control surface and the bifurcation phenomenon and LCO frequency of the model under preload, and analyzed its instability and high-frequency oscillation phenomena under preload.Lee and Chen [7] established a folding wing hinge structure model with gap nonlinearity as shown in Figure 3, and conducted theoretical analysis and verification to testify the effectiveness of the ternary model. In 2013, Firouz-Abadi et al. [8] studied the limit cycle flutter characteristics of the three-element rhomboid wing model with clearance nonlinear degrees of freedom in pitching, floating and fluttering, and obtained the influence of clearance on wing flutter characteristics at supersonic/hypersonic speeds.

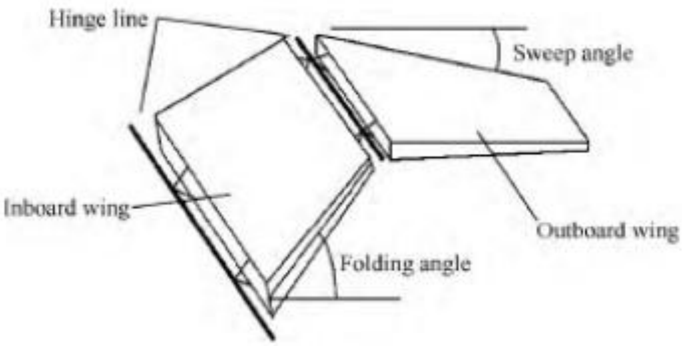


Figure 3: Nonlinear gap model of hinge structure

II. THEORETICAL BASEMENT

2.1 VIRTUAL QUALITY METHOD

The Fictitious Mass (FM) method is used to generate virtual mass modes by applying virtual mass to the gap degrees of freedom of the structure, and then removing the virtual mass from the generalized mass matrix, in order to prevent the construction of the state-space equation from affecting the dynamic characteristics of the original structure.A moment of inertia is applied to the nonlinear degrees of freedom of the all-moving rudder surface nonlinear system because the virtual mass is large enough to generate the rigid body rotation mode of the rudder surface about the rotating axis in the virtual mass mode. The equation of motion of virtual mass method is [3]:

$$-\left[\omega_{FM}^2 (M_{norm} + \Delta M_{FM}) + K_{norm}\right]\left[\Phi_{FM}\right] = 0 \quad (1)$$

$[M_{norm}]$ and $[K_{norm}]$ are corresponding mass matrix and stiffness matrix of Nominal Structure;

$[\Delta M_{FM}]$ is virtual mass matrix;

ω_{FM} is model natural frequency in virtual mass state；

$[\Phi_{FM}]$ is modal matrix in virtual mass state。

If there is a gap in the rotation of the rotary shaft of the fully movable rudder surface, the rotational stiffness of the corresponding gap segment is 0, and the external stiffness of the gap segment is that of the Nominal Structure as shown in Figure 4.

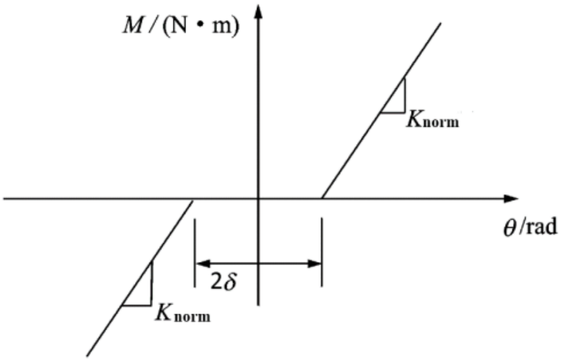


Figure 4:The relationship between the rotation Angle and torque of the rotating shaft with clearance

2.2 TIME-DOMAIN INTEGRATION METHOD FOR GAP NONLINEAR SYSTEMS

The transient time domain dynamic response of anall-moving rudder system with free-play nonlinearity is analyzed by discrete time domain state space method. It is assumed that the nonlinear characteristics of the nonlinear aeroelastic system can be quantitatively described by a series of nonlinear parameters, and the response of the nonlinear system, such as displacement, velocity and acceleration, can be defined as a function of the nonlinear parameters.By using nonlinear parameters, the nonlinear system can be decomposed into multiple linear subsystems and a set of discrete piece-linear time-domain state-space equations can be generated. The nonlinear parameters are calculated at each time step, and then the time-domain state equation of the current time step is obtained by interpolation, so the transient response of the nonlinear system can be calculated at the current time step.

III. MODELING AND ANALYSIS OF ALL-MOVING RUDDER SURFACE

3.1 REALIZATION OF ALL-MOVING RUDDER SURFACE MODEL AND CLEARANCE

The all-moving rudder surface designed in this paper is shown in Figure 5. Through the design of the support system, realizing the bending, torsion and decoupling of the rudder surface.

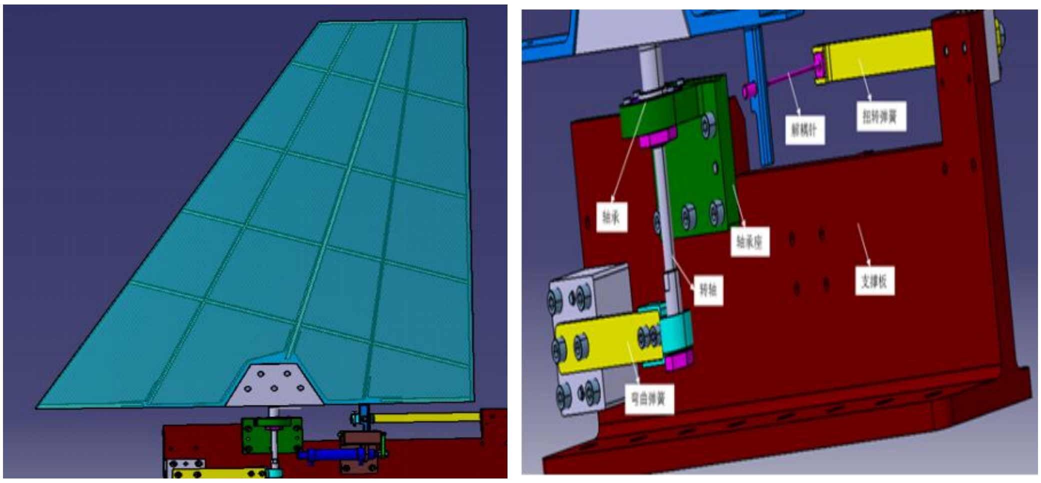


Figure 5: Basic parameters of all-moving rudder surface

Based on the bending-torsion decoupling device, a device which can realize the bending-torsion two-dimensional gap is designed. The device can realize different clearance sizes of the nonlinear system of the all-moving rudder surface, so as to achieve the purpose of studying the influence of different clearance sizes on the nonlinearity.

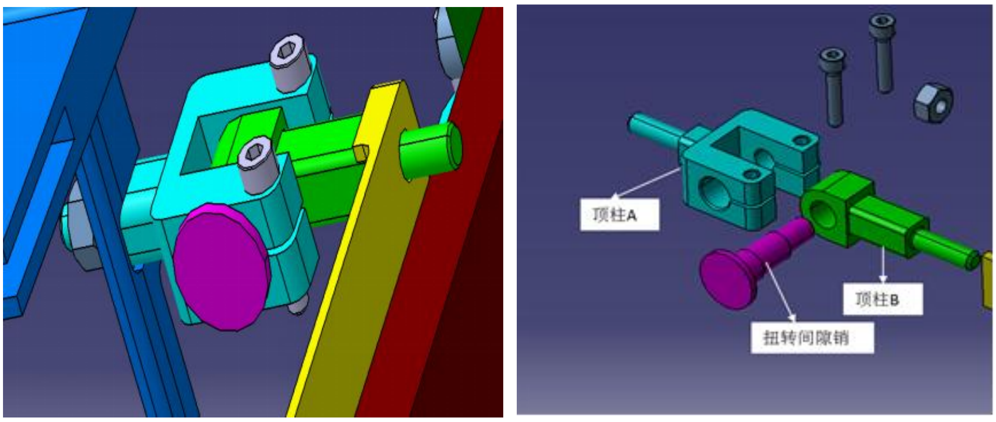
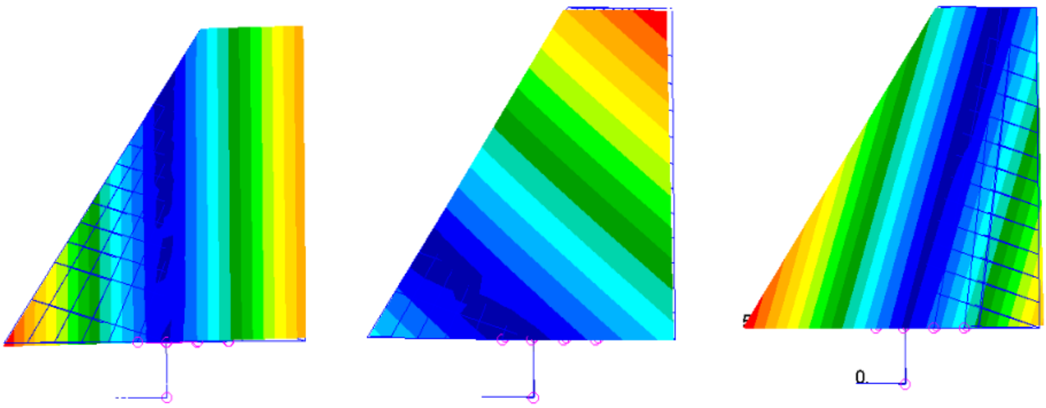


Figure 6: Design of torsional clearance

3.2 VIRTUAL MASS MODES

A moment of inertia of 106kg*m2 is applied to the nonlinear degrees of freedom of the nonlinear system on the all-moving rudder surface. The first three virtual mass modes are calculated, in which the first mode is the rigid mode caused by the virtual mass, the second FM mode is the bending mode, and the third FM mode is the torsional mode.



(a) rigid mode (b) bending mode (c) torsional mode.

Figure 7: Structural modes calculated by virtual mass method

3.3 ANALYSIS OF NONLINEAR AEROELASTIC RESPONSE OF ALL-MOVING RUDDER SURFACE

The rotation clearance of the rotating shaft was set to 0.1°, and the equivalent velocity was set to V/Vg (where Vg=20 m/s, which is the critical speed of linear flutter), respectively 0.55, 0.7, 0.95 and 1.0. The wing surface was taken as the observation site, and the calculation results for the first 20s were shown in Figure 8.

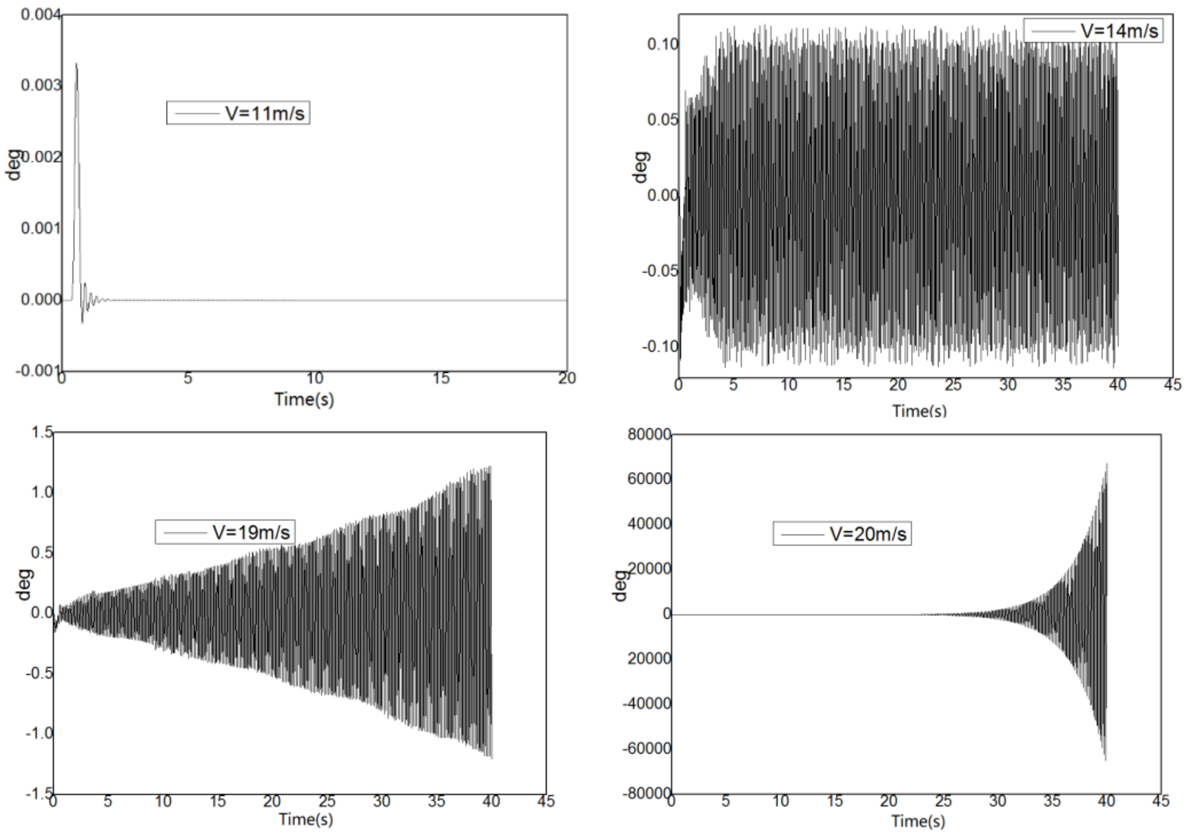


Figure 8: Dynamic response at different speeds

The amplitudes of the three rotating gaps were respectively set as 0.5°, 0.1° and 0.01°. At the equivalent velocity V/Vg=0.7, the time-domain dynamic response analysis was conducted to study the influence of the gap angle on the oscillation and flutter characteristics of the limit cycle. The time-history curve is shown in figure 9.

By comparison, it can be seen that under the same incoming flow velocity and gust load, the gap gradually increases, and the limit cycle amplitude of the free-play nonlinear system gradually increases, indicating that the gap increase will increase the oscillation amplitude of the structure and even affect the divergence velocity.

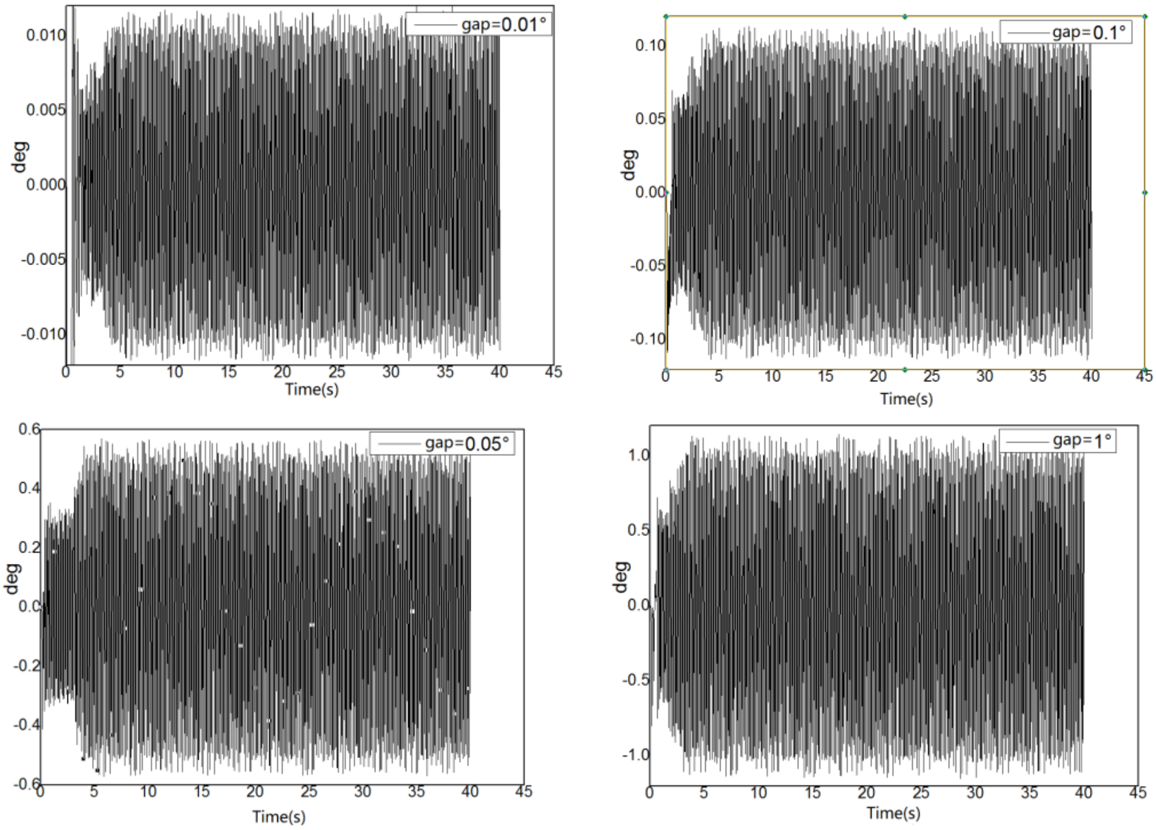


Figure 9: Dynamic response under different clearance sizes

IV. CONCLUSION

(1) A model is designed to simulate the clearance of the all-moving rudder surface, which can realize the different clearance sizes of the nonlinear system of the all-moving rudder surface;
(2) The finite element model of the all-moving rudder surface was established, and the virtual mass method was used to model the nonlinear system. Virtual mass modes were generated by applying virtual mass to the gap degrees of freedom of the structure.
(3) The transient time domain dynamic response analysis of the nonlinear all-moving rudder system with clearance is carried out by the discrete time-domain state-space method.
The results show that the amplitude of limit cycle increases with the increase of equivalent velocity until divergence. Under the same incoming flow velocity and gust load, the gap gradually increases, and the limit cycle amplitude of the gap nonlinear system gradually increases, indicating that the gap increase will increase the oscillation amplitude of the structure, and even affect the divergence velocity. So free-play nonlinearityisnon-negligiblefor the design of aircraft.

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