STUDY OF AEROELASTIC PROBLEM OF RUDDER SYSTEM WITH ELECTRIC ACTUATOR AND STRUCTURAL NONLINEARITIES

Wei Qian[1,*], Wei-Zhe Feng[1], Chong-Xu Han[1], Xin-Yu Ai[1]

[1]School of Mechanics and Aerospace Engineering, Dalian University of Technology, Dalian, China, 116024
[*]Corresponding: qianwei@dlut.edu.cn

Abstract

Stiffness of actuator is important for the aeroelastic behavior of rudder system which impacts the design of all-movable control surface of an aircraft. However, the conventional aeroelastic analyzing method took the supporting stiffness of a rudder system as a constant consciously or unconsciously, which led to mistakes in predicting the aeroelastic property of all-movable control surface. In this paper, the aeroelasticity problem for a complete rudder system with actual electric actuator and structural nonlinearities (e.g. free-play and friction) are studied. A Simulink model for a rudder system considering electromechanical part of actuator, elastic part of wing structure as well as free-play and friction nonlinear parts in the drive link is established. Through this model, the aeroelastic property of the all-movable control surface with rudder system can be obtained by time-domain simulation. Meantime, a test model with actual electric actuator is designed and manufactured, nonlinear dynamic test is carried out for estimation of nonlinear parameters including free-play angles and friction coefficients. Finally, the time-domain simulation results and dynamic test results are compared with each other for validating effectiveness of the established model. This paper gives a methodology for studying the aeroelastic property of rudder system supported by practical mechanism.

Keywords: Aeroelasticity, Rudder System, All-movable Control Surface, Ground Test.

1. Introduction

The rudder system is the control mechanism of an aircraft, it receives the control command of the guidance system, drives the rudder surface (including the full moving rudder, trailing edge rudder, aileron, etc.) to deflect, generates control torque, and adjusts the aircraft to the required flight attitude [1,2]. The rudder system is subjected to the coupling effect of aerodynamic force, elastic force, inertial force and control force during operation, which is easy to occur coupling divergence phenomena such as flutter and aeroservoelastic instability, resulting in instantaneous structural damage or loss of control [3,4]. Many aircrafts have had problems of aeroelasticity and aeroservoelastic coupling divergence of the rudder system, resulting in plane crashes.

Recent years, with the wide application of electric steering gear, nonlinear factors such as free-play and friction often exist in the deceleration mechanism of steering gear and the transmission mechanism of rudder system due to machining, assembly error and wear, etc., resulting in the free-play and friction nonlinear dynamics problems of rudder system, which cause great difficulties in the structural dynamics modeling and parameter identification of missile rudder system. It also seriously affects the control accuracy and aeroelastic stability of the rudder system. The USA F-22 had to invest a lot of manpower and material resources to study the gap nonlinear dynamics and aeroelasticity, and carried out a large number of ground vibration tests and wind tunnel tests because of the limit cycle oscillation caused by the non-linearity of the rudder clearance [5]. The free-play, friction and other nonlinear factors cause the rudder system to produce complicated nonlinear effects. Under the action of aerodynamic force and controlling force, the rudder system often shows periodic limit cycle oscillation when the linear flutter critical speed is lower, and even more complex nonlinear dynamics phenomena such as chaos appear [6,7], which causes great difficulties for the structural design and control system design of the missile rudder system.

In order to maintain good safety and controllability of the aircraft rudder system, it is necessary to construct a precise model of a rudder system which can be used to precisely determine the static and dynamic stiffness of the actuator. In this paper, an integrated modelling method of rudder system is proposed to estimate the supporting stiffness of the actuator. In the numerical model, all the elements including motor, gear pairs and control surface are included, and the free-play and friction nonlinearities are also included. Meantime, a test model with actual electric actuator is designed and manufactured, nonlinear dynamic test is carried out for estimation of nonlinear parameters including free-play angles and friction coefficients. Equivalence stiffness for the supporting system is determined by harmonic balance method, and validated using the test results.Finally, the time-domain simulation results and dynamic test results are compared with each other for validating effectiveness of the established model.

2. Integrated Modelling of Rudder System

2.1 Dynamic Modelling of Actuator and Drive Elements

The main use of the steering gear is the actuator, which produces the attitude control torque of the projectile body; The second is to provide enough support stiffness for the rudder to withstand the hinge torque of the rudder. Most research on steering gear modeling considers the first use. The research focuses on the dynamic response and signal tracking of the steering gear. In most cases, flutter and other aeroelastic divergence is caused by the coupling of bending and torsional modes of the rudder surface, and the bending and torsional mode characteristics of the rudder surface are largely related to the dynamic stiffness of the steering gear. The dynamic stiffness of the steering gear refers to the dynamic torque required to generate a unit torsion Angle at the output end of the steering gear, which reflects the characteristic that the support stiffness provided by the electric steering gear to the rudder surface changes with the frequency of the external load, so it is also called "complex stiffness". By using a modular modeling theory, a detailed model of actuator (Figure 1) is modelled as shown in Figure 2. Considering the nonlinear factors such as free-play and friction often exist, the polygonal stiffness [7] for free-play model and Lugre model of friction is used in the modelling of nonlinearity elements, as shown Figure 3.

Figure 1 – Electric actuator.

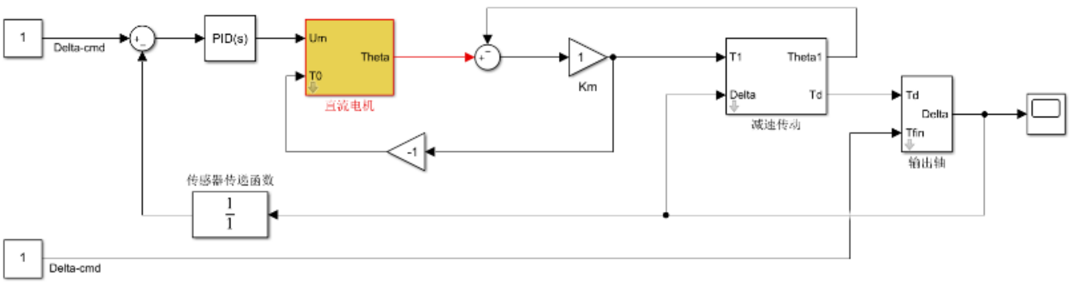


Figure 2 – Simulink model of the actuator.

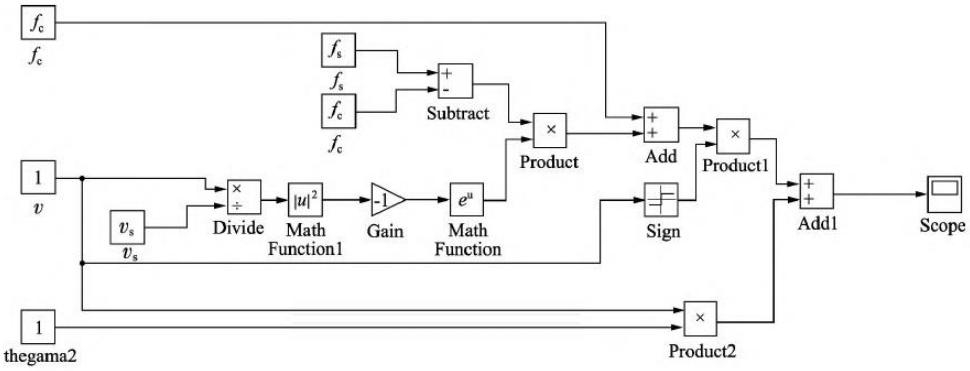


Figure 3 –Friction nonlinearity element.

2.2 Elastic Plant Modelling of the Wing Surface

Section 2.1 gives the detailed modelling of supporting system of the rudder system, in order to construct an integrated model for the time-domain simulation of the dynamic system, the elastic plant for wing surface must be constructed. In this section, the modal approach is used to construct an open-loop elastic plant model for the wing surface with the input as the shaft angle and the output as the concentrated exciting points. The aeroelastic equation for the wing structure with none structural damping is,

$$\boldsymbol{M}\ddot{\boldsymbol{q}}+\boldsymbol{K}\dot{\boldsymbol{q}}=\frac{1}{2}\rho V^2(\boldsymbol{Q}_0\boldsymbol{q}+\boldsymbol{Q}_1\frac{b}{V}\dot{\boldsymbol{q}}+\boldsymbol{Q}_2\frac{b^2}{V^2}\ddot{\boldsymbol{q}}) \tag{1}$$

Where， $\boldsymbol{Q}_0,\boldsymbol{Q}_1,\boldsymbol{Q}_2$ can be obtained by using rational function approximation [7]. In order to integrate with the module of actuator established in section 2.1, Eq.(1) should be transformed into state space model, i.e.,

$$\begin{cases}\boldsymbol{X}_1=\boldsymbol{A}_1\boldsymbol{X}_1+\boldsymbol{B}_1\boldsymbol{u}_1\\ \boldsymbol{Y}_1=\boldsymbol{C}_1\boldsymbol{X}_1\end{cases} \tag{2}$$

Where,

$$\boldsymbol{A}_1=\begin{bmatrix}-\bar{\boldsymbol{M}}_s^{-1}\bar{\boldsymbol{B}}_s & \frac{1}{2}\rho V^2\bar{\boldsymbol{M}}_s^{-1}\boldsymbol{Q}_0-\bar{\boldsymbol{M}}_s\boldsymbol{K}_0\\ \boldsymbol{I} & \boldsymbol{0}\end{bmatrix} \tag{3}$$

$$\boldsymbol{B}_1=\begin{bmatrix}-\bar{\boldsymbol{M}}_s^{-1}\\ 0\end{bmatrix}\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix} \tag{4}$$

$$\boldsymbol{C}_1=[0 \quad \cdots \quad 0 \quad 1] \tag{5}$$

Eq.(2) can be used as a state space plant integrated with actuator and nonlinear modules as illustrated in section 2.1. However, some key parameters involved in the model must be tested using experimental results. Therefore, a rudder system with actuator and nonlinearity configuration is designed and manufactured.

3. Design and Manufacture of Test Model for Rudder System

A model of rudder system for an all-movable control surface is designed manufactured, as shown in Figure 4. The bending and torsion stiffness system is shown in Figure 5. And the free-play and friction configuration are shown in Figure 6. The linear elastic modes are shown in Figure 7.

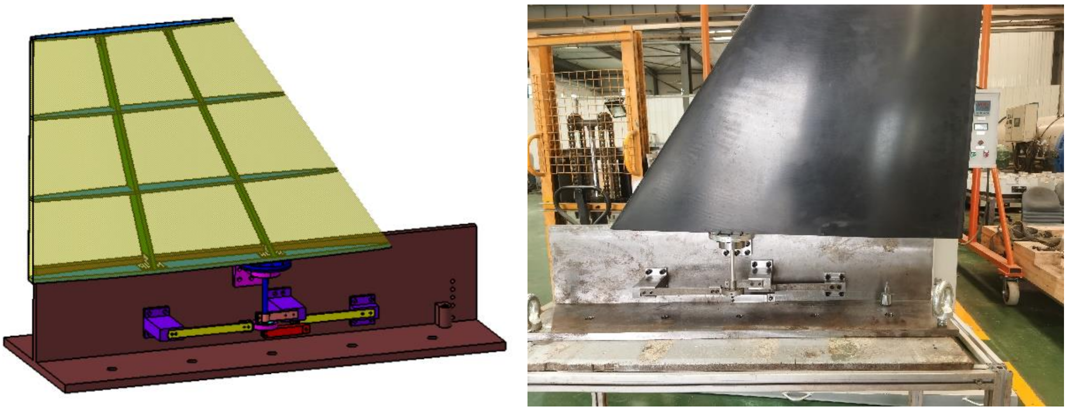


Figure 4 – Digital and actual model for the all-movable control surface

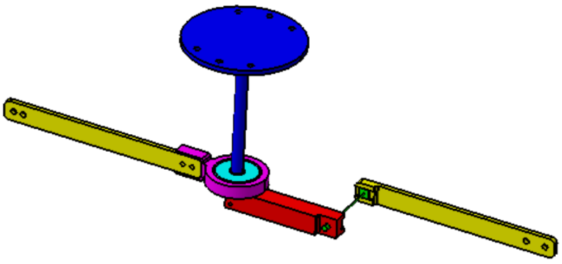


Figure 5 – Bending and torsion stiffness model and electric actuator

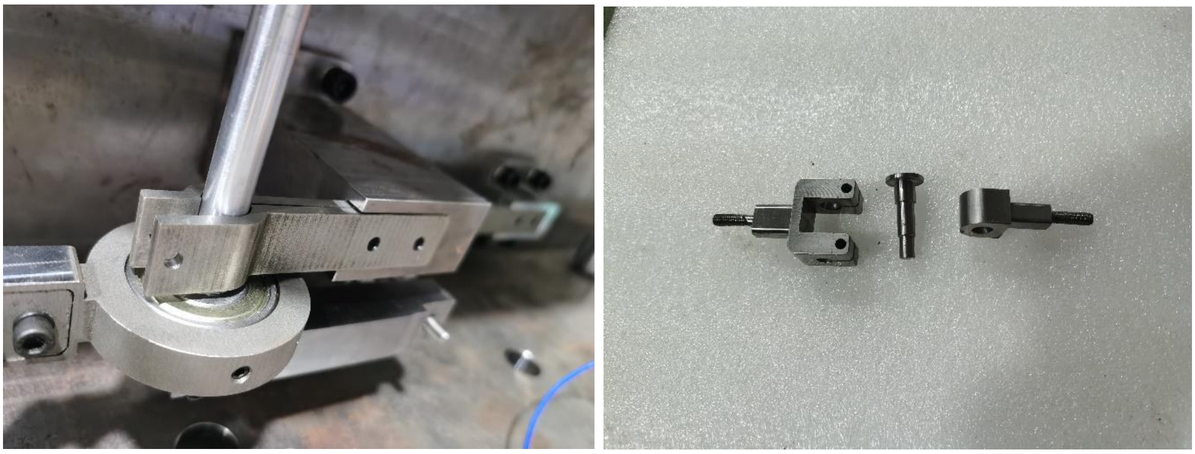
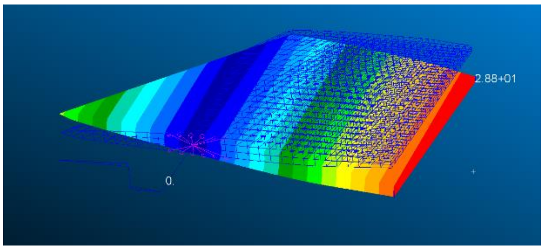
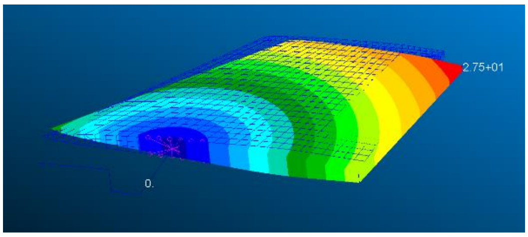


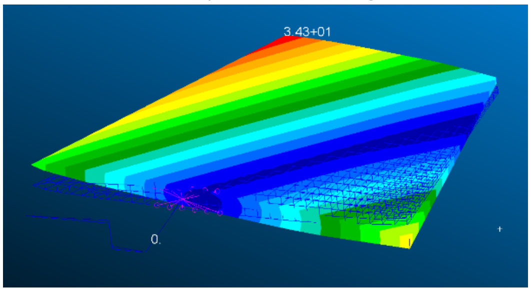
Figure 6 – Friction and free-play configuration



First Bending Mode



Second in-plane bending mode



First torsional mode

Figure 7 – Linear elastic modes of the wing surface

4. Ground Test of the All-movable Control Surface

Nonlinear dynamic response test is carried out for validating the constructed detailed model for rudder system. First, the estimated parameters are used to verify the numerical model including free-play angles and friction coefficients. Then, the electromagnetic shaker is used as the input of the rudder system, and the accelerometer is used to obtain the dynamic response of accelerations, as shown in Figure 8. The results of simulation and test are shown in Figure 9. By using FFT transformation technique, the frequency-domain results is shown in Figure 10, and the equivalent stiffness is shown in Figure 11. From Table 1, we can see that the simulated and test results coincided well with each other.

Figure 8 – Bending and torsion stiffness model

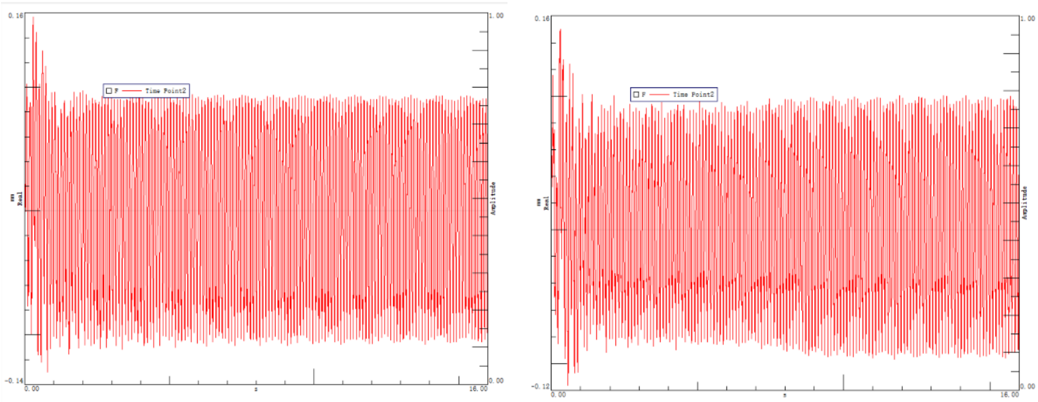


Figure 9 – Results of Numerical Simulation and Test

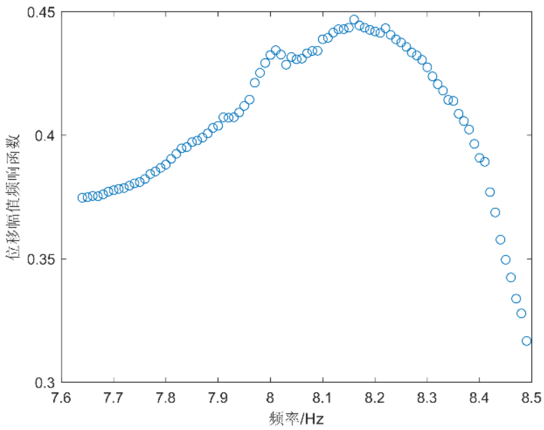


Figure 10 – Amplitude-frequency curve

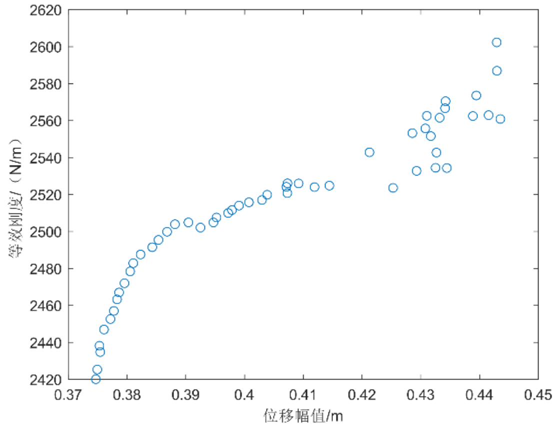


Figure 11 – Equivalent Stiffness Estimated by Test Data

Table 1 Result Comparison of Simulation and Test

Parameter	d/m	d/m	d/m
Nonlinearity(freeplay)	0.0001	0.0003	0.0005
Estimated results	0.0001113	0.0003236	0.0005259
Relative Error	11.13%	7.87%	5.18%

5. Conclusion

This paper presented a combined numerical modelling and test methods for studying the dynamic and aeroelastic problem of an actual rudder system for all-movable control surface. Through using this approach, a complete rudder system can be taken as object for studying the supporting stiffness of the control surfaces, free-play and friction nonlinearities can be involved in the drive link of the Simulink model of rudder system. Based on the estimated free-play angles and friction coefficients, the model can be validated, and the final time-domain simulation results can coincide well with the test results, which validate the effectiveness the proposed approach.

6. Copyright Statement

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