ANALYSIS OF LIMIT CYCLE OSCILLATIONS IN NONLINEAR FIN-ACTUATOR SYSTEMS BY NUMERICAL CONTINUATION

Zihao Liu, Zhigang Wu* and Chao Yang

Beihang University,
No. 37 Xueyuan Road, 100191, Beijing
China

ABSTRACT

Flutter in fin-actuator systems can severely damage aircraft structures, making it a critical concern in aeroelasticity. The servo actuator in the fin-actuator system is inherently a complex dynamic system, and may also involve nonlinearities such as freeplay, friction and current saturation. These nonlinearities can lead to nonlinear flutter primarily characterized by limit cycle oscillations (LCOs). As lightweight electromechanical actuators are applied to replace traditional hydraulic actuators, the occurrence of such issues has significantly increased.

So far, many researchers have conducted studies on modeling methods for fin-actuator systems, establishing high-fidelity models that can accurately describe complex nonlinear behaviors. However, these models are often highly complex and are usually implemented using graphical block diagram modeling tools such as MATLAB/Simulink. Consequently, the analysis of nonlinear flutter still relies predominantly on the time-domain integration method. Since the occurrence of LCOs is influenced by initial conditions, it is necessary to assign appropriate initial state of the system when performing time-domain integration, and sometimes the generation of LCOs may be strictly dependent on the choice of initial state. Time-domain integration methods may fail to accurately capture the bifurcation points of LCO branches, leading to wrong predictions of the velocity range within which LCOs occur.

This study investigates a fin-actuator system with freeplay in the transmission mechanism of the actuator. The time-domain numerical continuation method is employed to track the branches of LCOs, which can avoid the influence of initial conditions. First, a high-fidelity model of a fin-actuator system shown in Fig.1 is developed in a block diagram simulation platform. The model integrates the structural dynamic equations of an all-movable fin, an aerodynamic model based on the piston theory, and an electromechanical actuator model with freeplay nonlinearity. Subsequently, numerical continuation combined with the shooting method is applied to analyze the LCOs. To calculate the residual function and its Jacobian matrix for the shooting method, a computational scheme is established that interfaces with the simulation platform. In this scheme, a fourth-order Runge-Kutta method with a very small step size is employed to overcome the algebraic loop problem and enhance numerical stability. Since the step size is fixed, the simulation time cannot precisely match the LCO period. Therefore, linear interpolation is applied to obtain the state variables at the exact time equal to the period. Finally, a stability analysis based on Floquet multipliers is employed to acquire the stability of the LCO branches.

Through the time-domain numerical continuation, this study has captured the fundamental relationship between the flow velocity and the characteristics of LCOs in the fin-actuator system with freeplay, such as the variation of the amplitude with the flow velocity shown in Fig.2. A parameter variation analysis of the fin-actuator system is also conducted to identify the key parameters influencing the LCO characteristics. The analysis method established in this paper enables the direct application of numerical continuation to the block diagram model of the system established in graphical simulation platforms such as MATLAB/Simulink and the LCO branches can be tracked precisely. This approach enhances the practicality of time-domain

numerical continuation and contributes to solving nonlinear flutter problems in engineering. Furthermore, the proposed method can be extended to analyze LCOs in more complex systems, such as the nonlinear aeroservoelastic system of an entire aircraft.

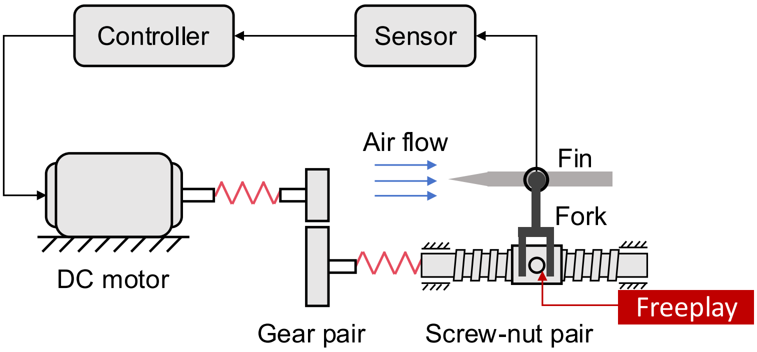

Fig.1 Schematic diagram of the fin-actuator system

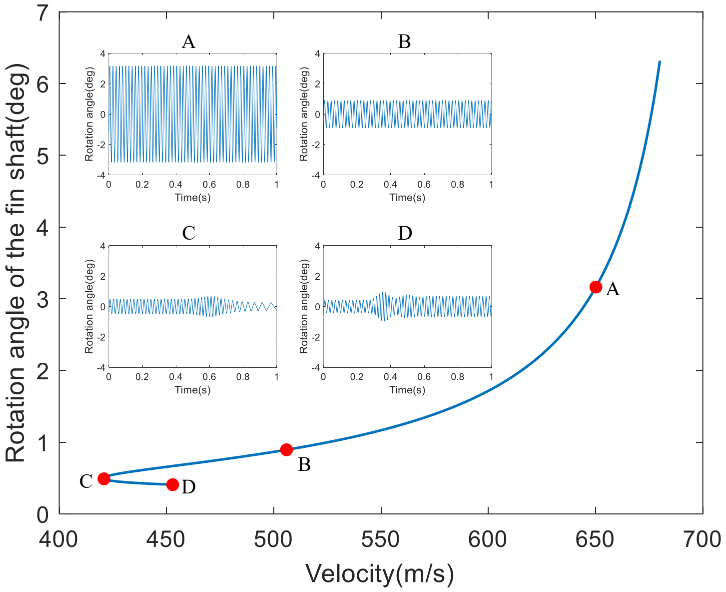

Fig.2 Variation of the LCO amplitude with the flow velocity