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Dynamic stiffness testing-based flutter analysis of a fin with an actuator

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Abstract Engineering-oriented modeling and synthesized modeling of the fin-actuator system of a missile fin are introduced, including mathematical modeling of the fin, motor and multi-stage gear reducer. The fin-actuator model is verified using dynamic stiffness testing. Good agreement is achieved between the test and theoretical results. The parameter-variable analysis indicates that the inertia of the motor rotor, reduction ratio of the reducer, connection stiffness and damping between the actuator and fin shaft have significant impacts on the dynamic stiffness characteristics. In flutter analysis, test data are directly used in the frequency domain method and indirectly used in the time domain method through the updated fin-actuator model. The two methods play different roles in engineering applications but are of equal importance. The results indicate that dynamic stiffness and constant stiffness treatments may lead to completely different flutter characteristics. Attention should be paid to the design of the fin-actuator system of a missile.
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1. Introduction

Flutter is a catastrophic divergence phenomenon that occurs when aerodynamics and structural elastic vibrations couple with each other. In missile design processes, the flutter characteristics of missile fins have attracted considerable attention. For a missile fin with an actuator (a fin-actuator system), traditional flutter analysis methods treat the actuator as a linear support with constant stiffness. However, experiments have found that actuators provide dynamic stiffness that varies with excitation frequency.[1,2] The constant-stiffness assumption may not be appropriate except when the phase angle of the dynamic stiffness is extremely small.[3] For an all-move fin on a subsonic missile, low aerodynamic pressure results in a large surplus of actuator capacity. In this case, the constant-stiffness assumption regarding the actuator easily meets the necessary engineering precision. For an all-move fin on a supersonic (or even hypersonic) missile, high rotational modal frequency and high aerodynamic pressure impair the dynamic performance of the actuators, making the flutter characteristics of the fin-actuator system more complex. Thus, attention must be paid to the dynamic stiffness of actuators and the effects of that stiffness on the flutter characteristics of the fin. A visual depiction that contrasts constant stiffness and dynamic stiffness is shown in Ref.[3]

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The dynamic stiffness characteristics of actuators have been studied by several research groups, and the coupling mechanisms among the aerodynamic force, fin structure and actuator have been explored in several papers. McDonnell Douglas first proposed the dynamic stiffness testing method in the F-4 fighter project in the early 1970s, and this method was later improved in the development of the F-15 fighter.[2] The stiffness and damping characteristics of several hydraulic servo actuators were studied both theoretically and experimentally in the F-15 project. In 1996, Yehezkely and Karpel performed a nonlinear flutter analysis of missiles with pneumatic fin actuators.[4] Nonlinear factors of the pneumatic actuators were considered in the flutter analysis and a flutter suppression method was proposed. In the same year, Paek and Lee studied the flutter characteristics of a rocket control surface with dynamic actuator properties.[5] In 1997, before the first flight of the F-22 fighter, dynamic stiffness testing of the actuators was also performed.[1] Beginning in 2000, Wu et al. have focused on the design and improvement of test beds for dynamic stiffness testing and several actuators were tested.[6,7] In 2007, Shin et al. conducted a nonlinear flutter analysis of an electric servo actuator with a two-stage reducer and built a fundamental framework to solve the aeroelastic problems of a fin-actuator system.[8] In 2011, the flutter characteristics of a fin-actuator system were reported by Yang et al. considering both structural nonlinearity and dynamic stiffness.[9] In 2013, Zhang et al. introduced a new flutter suppression method by redesigning the distribution of the zeros and poles of the actuator's control law.[3]

Although some fundamental research has been reported in the above-mentioned literature, extensive work is still needed to perfect the theory and testing frameworks, including generalization to more types of actuators, mathematical modeling of a more detailed actuator and more applications that combine both experimental and theoretical analyses. In addition, a basic and systematic procedure for easy consideration of an actuator's dynamic stiffness in engineering applications is also necessary for the aerospace industry.

This paper presents an engineering-oriented flutter analysis procedure that can account for the dynamic stiffness of actuators based on test data. Detailed modeling processes and analytical methods in both frequency and time domains and a dynamic stiffness testing method are given. A flowchart of analysis procedures is depicted in Fig. 1.

2. Mathematical modeling

In this study, the fin-actuator system is composed of an all-move fin and an electromechanical actuator that includes a three-stage reducer and a DC motor. Fig. 2 presents the structure of the fin-actuator system. The reducer is composed of two gear pairs and a lead screw pair. The fin structure is driven to rotate by a fork between its shaft and the screw. A damper lies under the shaft to suppress vibrations in the fin and an angular displacement sensor gives position feedback.

An engineering-oriented method should be simple and efficient. Within acceptable precision, reasonable assumptions should be made to simplify the modeling and calculation process. The fin-actuator system modeling includes electrodynamic modeling of the motor, kinematic modeling of the reducer and structural dynamic modeling throughout. The motor model omits details of the power transform from DC to AC and directly builds the relation between current and output torque. The reducer model uses mass-damping-spring systems to describe the gears, screw and their interactions. The fin structure model is based on the substructure technique and finite element method. Unsteady aerodynamics are modeled using the supersonic double lattice method (DLM).[10,11]

2.1. Model of DC motor

A DC motor is mainly composed of a stator, a rotor, windings, a commutator and a shaft. DC power is converted to three-phase U/V/W alternating current to produce an alternating electromagnetic field to drive the rotor. An angular displacement sensor returns the shaft angle to the controller for position control. The general electrodynamic equations of a motor follow the equations:

Winding voltage equation:

$$iR + L\frac{\mathrm{d}i}{\mathrm{d}t} = u_{\mathrm{a}} - C_{\mathrm{e}}\dot{\theta}_0 - K_{\mathrm{i}}i - K_{\mathrm{a}}\theta_0 \tag{1}$$

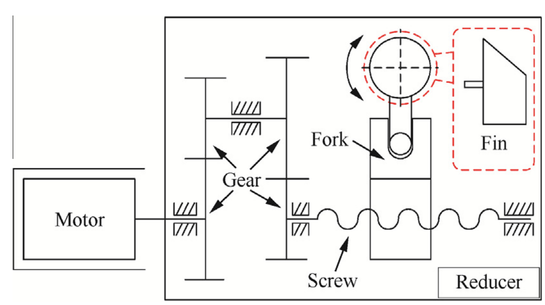

Fig. 2 Schematic diagram of studied fin-actuator system.

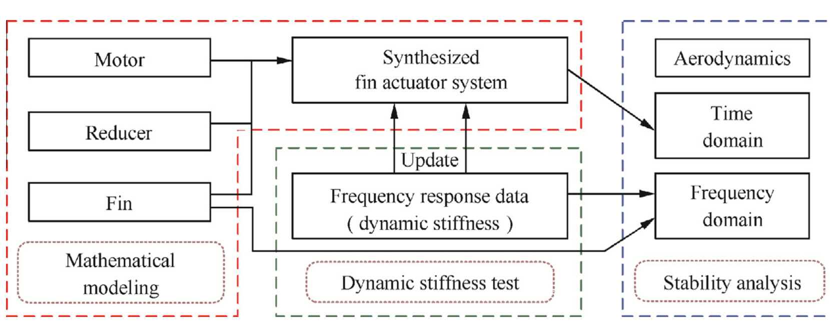

Fig. 1 Flowcharts of analysis procedures.

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