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Special Brief Communication

Effects of multiple structural nonlinearities on limit cycle oscillation of missile control fin

Young-Jin Seo [a], Seung-Jun Lee [b], Jae-Sung Bae [c], In Lee [a,*]

[a] Division of Aerospace Engineering, School of Mechanical, Aerospace and Systems Engineering, KAIST, 373-1 Guseong-Dong, Yuseong-Gu, Daejeon 305-701, Republic of Korea
[b] Thermal-Hydraulics Safety Research Division, KAERI, 1045 Daedeok-daero, Yuseong-gu, Daejeon 305-353, Republic of Korea
[c] School of Aerospace and Mechanical Engineering, Korea Aerospace University, 200-1 Hwajeon-dong, Deogyang-gu, Goyang-City, Gyeonggi-do 412-791, Republic of Korea

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ABSTRACT

Aeroelastic analyses are performed for a 2-D typical section model with multiple nonlinearities. The differences between a system with multiple nonlinearities in its pitch and plunge spring and a system with a single nonlinearity in its pitch are thoroughly investigated. The unsteady supersonic aerodynamic forces are calculated by the doublet point method (DPM). The iterative V-g method is used for a multiple-nonlinear aeroelastic analysis in the frequency domain and the freeplay nonlinearity is linearized using a describing function method. In the time domain, the DPM unsteady aerodynamic forces, which are based on a function of the reduced frequency, are approximated by the minimum state approximation method. Consequently, multiple structural nonlinearities in the 2-D typical wing section model are influenced by the pitch to plunge frequency ratio. This result is important in that it demonstrates that the flutter speed is closely connected with the frequency ratio, considering that both pitch and plunge nonlinearities result in a higher flutter speed boundary than a conventional aeroelastic system with only one pitch nonlinearity. Furthermore, the gap size of the freeplay affects the amplitude of the limit cycle oscillation (LCO) to gap size ratio.

1. Introduction

During the past several decades, most aeroelastic investigations of flight vehicles have been carried out under the assumption of structural linearity. However, the results may not agree well with the physical phenomena due to the presence of structural nonlinearities in the actual structures. Typically, nonlinear aeroelastic responses include flutter, divergence, limit cycle oscillation (LCO), and chaotic motion. Among these responses, LCO is a periodic oscillating response consisted of one or a couple of frequencies. It does not cause an abrupt failure of a structure but cause a structure to be damaged by fatigue. Thus, the effects of structural nonlinearities on the aeroelastic characteristics of flight vehicles should be considered in the design stage. Although the recent research (Demasi and Livne, 2009) shows the importance of the geometrical nonlinearities such as jointed-wing and strut-braced wings, the concentrated nonlinear effects such as free play and hysteresis existing between gears, links, and actuators are still important and unresolvable matter.

* Corresponding author. Tel.: +82 42 869 3717; fax: +82 42 869 3710.
E-mail addresses: youngjinseo@kaist.ac.kr (Y.-J. Seo), cosinesj@kaeri.re.kr (S.-J. Lee), jsbae@kau.ac.kr (J.-S. Bae), inlee@kaist.ac.kr (I. Lee).

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Several researchers have investigated nonlinear aeroelastic problems, including structural nonlinearities. Woolston et al. (1957) analyzed a nonlinear aeroelastic system with freeplay, hysteresis, and cubic nonlinearity and showed that LCO may occur below the linear flutter boundary. Laurenson and Trn (1980) studied the flutter of a missile control surface with freeplay using the describing function method. Lee and Tron (1989) studied the nonlinear aeroelastic characteristics of a CF-18 aircraft with freeplay and bilinear nonlinearities in the hinge of leading-edge flap and a wing-fold using the describing function method. Lee and Kim (1995) studied the LCO and chaotic motion of a missile control surface with freeplay using a time-domain analysis. Conner et al. (1997) and Tang et al. (1999) studied the nonlinear aeroelastic characteristics of a typical section with control surface freeplay both numerically and experimentally. They observed the jumps of LCO amplitudes. Virgin et al. (1999) studied the chaotic motion of a typical section and Tang et al. (2000) studied the nonlinear responses of an airfoil excited by a gust load. Sheta et al. (2002) conducted computational and experimental investigations of a nonlinear aeroelastic system with a fifth-order polynomial spring.

Bae et al. (2004a) studied the nonlinear aeroelasticity of an aircraft wing with freeplay and bilinear nonlinearity and observed three different types of LCOs over a wide range of airspeeds beyond the linear flutter boundary. Bae and Lee (2004b) studied the LCO characteristics of a 2-D model and showed that the LCOs can be observed above or below the linear flutter boundary depending on the frequency ratio between the plunge and pitch modes. Bae et al. (2004c) studied the nonlinear aeroelasticity of a deployable missile control fin and showed that it is more stable than the linear aeroelasticity case due to the nonlinearity of a deployable hinge.

For multiple structural nonlinearities, Breitbach (1980) proposed an iterative procedure in the frequency domain. In his research, the assumed oscillatory amplitudes of nonlinearities are iteratively aligned by minimizing the energy function composed of the difference between the initial and calculated amplitudes. Those aligned amplitudes are used to recast nonlinear stiffness and damping matrix as the linearized stiffness and damping matrix by the describing function method. The amplitudes of nonlinearities are the main concern for multiple-nonlinear aeroelastic analysis. Furthermore, since nonlinearities are distributed on different lifting surfaces, the complex interacting behaviors between multiple nonlinearities and aerodynamics on a single lifting surface are not considered. Laurenson and Trn (1980) dealt with 3-D flexible missile control surface including multiple nonlinearities on pitch and roll axis of a single lifting surface in the frequency domain. The paper analyzed the aeroelastic system including multiple nonlinearities with the assumed oscillation amplitude and the system frequency. However, the interaction between nonlinearities is just considered by fixing one of the nonlinearities and changing the other nonlinearity. This does not show the coupled response between nonlinearities. Lee (1986) performed the structural dynamics modification procedure to shift system frequency and mode shapes by the iterative procedure in the frequency domain. By using the describing function method, he updated the stiffness matrices containing local stiffness variations iteratively under the criteria of assumed LCO amplitude. As for multi-nonlinear aeroelastic systems, he concluded as follows:

“The stability boundary of a system with multiple nonlinearities does not necessarily fall between the high- and low-amplitude boundaries predicted by a linear flutter analysis. Knowledge of the amplitude at each nonlinear spring is needed to properly predict the stability characteristics.”

The purpose of the present study is to investigate the nonlinear aeroelastic characteristics of a missile control fin with multiple structural nonlinearities. Unlike the other researchers, this study emphasizes the importance of the frequency ratio as a key factor of analyzing the flutter characteristics including multiple nonlinearities. Moreover the ratio of the modal amplitude ratios on nonlinearities is used to refine the stiffness variation. By using the ratio concept the equivalent stiffness is modified directly and iteratively in the frequency domain. As a result, this makes the whole procedure simple significantly. The time-domain analyses are performed as well to compare the iterative results.

2. Theoretical background

2.1. 2-D aeroelastic equation of motion

The cross-section AA′ of the missile (Bae, 2002) control fin has plunge and pitch motions, which can be represented by the two-dimensional (2-D) typical section model. This 2-D model provides an easy means of understanding the physical aspects of the aeroelastic characteristics. Although Laurenson and Trn (1980) solved 3-D missile wing with rolling linkage, this research is not focusing on solving a realistic control surface but dealing with aeroelastic problems including multiple nonlinearities by fundamental point of view. Moreover, plunging degree of freedom is due to the structural flexibility and the freeplay nonlinearity is located at a point as a kind of concentrated nonlinearities. Thus, the rolling effect on 3-D wing is roughly approximated as the concentrated nonlinearity on plunging degree of freedom.

If the springs of both the pitch and plunge motions are nonlinear, the aeroelastic equations of the missile control fin can be written as follows :

$$\begin{bmatrix} m & S_\alpha \\ S_\alpha & I_\alpha \end{bmatrix} \begin{Bmatrix} \ddot{h} \\ \ddot{\alpha} \end{Bmatrix} + \begin{bmatrix} C_h & 0 \\ 0 & C_\alpha \end{bmatrix} \begin{Bmatrix} \dot{h} \\ \dot{\alpha} \end{Bmatrix} + \begin{bmatrix} K_h(h) & 0 \\ 0 & K_\alpha(\alpha) \end{bmatrix} \begin{Bmatrix} h \\ \alpha \end{Bmatrix} = \begin{Bmatrix} -L \\ M \end{Bmatrix}. \quad (1)$$