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# Nonlinear Aeroelastic Analysis of a Wing with Control Surface Freeplay

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## Summary

In this paper, nonlinear aeroelastic characteristics of a wing with control surface freeplay were investigated. The transonic small disturbance equation was applied to calculate unsteady aerodynamic forces in subsonic/transonic region. The fictitious mass method was used to apply a modal approach to nonlinear structural models. Nonlinear aeroelastic time responses were calculated by the coupled time integration method. In this study, it was found that aerodynamic nonlinearity, initial flap angle and freeplay angle affect aeroelastic characteristics.

## Introduction

The nonlinearity in the aeroelastic analyses can be divided into aerodynamic and structural one. The shock wave, viscosity, turbulence are included in the aerodynamic nonlinearity. Among these, the shock wave in transonic region lead to a fall in the flutter speed of aircraft structures such as the transonic dip. On the other hand, the structural nonlinearity is classified into distributed and concentrated one. The distributed nonlinearity is spreaded out over the entire structure such as a material nonlinearity while the concentrated nonlinearity acts on specific location. The freeplay, friction and hysteresis are included in concentrated nonlinearity. Especially freeplay is inevitable for control surfaces because of normal wear of components and manufacturing mismatches.

Nonlinear aeroelastic analyses of a wing with concentrated nonlinearities have been investigated by several researchers. Laurenson and Trn demonstrated those for a two dimensional model with freeplay[1]. It was found that LCOs can be initiated at velocities below the linear flutter boundary using the describing function method. Kim and Lee investigated a two dimensional flexible airfoil with freeplay where the airfoil was modeled using beam elements[2]. Kousen and Bendiksen studied a typical airfoil section model with freeplay at the torsional degree-of-freedom in the subsonic and transonic regions using Euler equation[3]. Kim and Lee investigated aeroelastic responses of a two degree-of-freedom system with freeplay nonlinearity in the transonic and low-supersonic regimes[4]. Bae *et. al.* studied the aeroelastic characteristics of a wing with freeplay in the frequency and time domain analyses[5]. Recently, Yoo *et. al.* developed an efficient aeroelastic analysis method

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to deal with aerodynamic nonlinearity and structural freeplay nonlinearity for the all-movable wing[6]. The fictitious mass method was used for nonlinear structural models. The transonic small disturbance (TSD) equation was used to calculate unsteady aerodynamic forces in the transonic region. However, there were few predominant studies on aeroelastic problems for a wing with control surface freeplay while the aerodynamic nonlinearity was considered.

The present study is a numerical investigation for the nonlinear aeroelastic characteristics of a wing with control surface freeplay. The methods for nonlinear aeroelastic analysis are similar to reference[6]. Using those methods, an efficient aeroelastic analysis of the aerodynamic and structural nonlinearities is achieved. Performing nonlinear aeroelastic analysis, effects of aerodynamic nonlinearity, initial flap amplitude, and freeplay magnitude are investigated for nonlinear aeroelastic characteristics of a wing in subsonic/transonic region.

## Theoretical Backgrounds

The equation of motion of an aeroelastic system with structural nonlinearities can be written as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+\{R(u)\}=\{F(t,u,\dot{u})\} \tag{1}$$

where $[M]$, $[C]$, $\{u\}$, and $\{F\}$ are mass matrix, damping matrix, displacement and external aerodynamic force vector, respectively. $\{R(u)\}$ is the restoring force vector including structural nonlinearities. $\{R(u)\}$ is expressed as

$$\{R(u)\}=[K]\{u\}+\{f(\theta)\} \tag{2}$$

where $[K]$ is the linear stiffness matrix, $\{f(\theta)\}$ is the restoring force vector due to structural nonlinear factors and is given as

$$f(\theta)=\begin{cases} K_\theta(\theta-s) & ,\theta>s \\ 0 & ,-s\le\theta\le s \\ K_\theta(\theta+s) & ,\theta<-s \end{cases} \tag{3}$$

where $K_\theta$, $\theta$ and $s$ are linear stiffness, flap angle and freeplay angle at the freeplay node, respectively. Usually, the aeroelastic analysis is conducted by using a modal approach with limited number of low frequency modes to reduce the computational time. In general, the normal mode approach can not be used directly due to stiffness variation with the displacement for air vehicle wings with freeplay. To overcome this difficulty, Karpel proposed the fictitious mass (FM) method[7]. It is discussed the application of the FM method to a wing with freeplay in reference[6]. After the modal matrix, $[\phi_b]$, is obtained from the fictitious mass model, the displacement vector can be expressed as

$$\{u(t)\} = [\phi_b]\,\{q(t)\} \tag{4}$$

where $\{q\}$ is the generalized displacement vector. Transformation of equation (1) into the modal coordinate system gives

$$[GM]\,\{\ddot{q}\} + [GC]\,\{\dot{q}\} + \{GR\,(u)\} = \{Q(t,q,\dot{q})\} \tag{5}$$

where $[GM]$ and $[GC]$ are the generalized mass and damping matrices, respectively. $\{GR\}$ is the generalized restoring force vector defined as $[\phi_b]^T[K]\,[\phi_b]\{q\}$-$[\phi_b]^T\{f(\alpha)\}$. $\{Q\}$ is the generalized external aerodynamic force vector. The theoretical background and verification are discussed in references[6,8].

## Results and Discussion

As a numerical analysis, a wing with control surface model is used. The wing has a root chord length of 0.6396 m, a span length of 0.6226 m. The hinge axis is located at 82 % chord section and 0.3751 m long. For the wing section, 4 % biconvex airfoil is used. Structural analysis method is illustrated in more detail in reference[3].

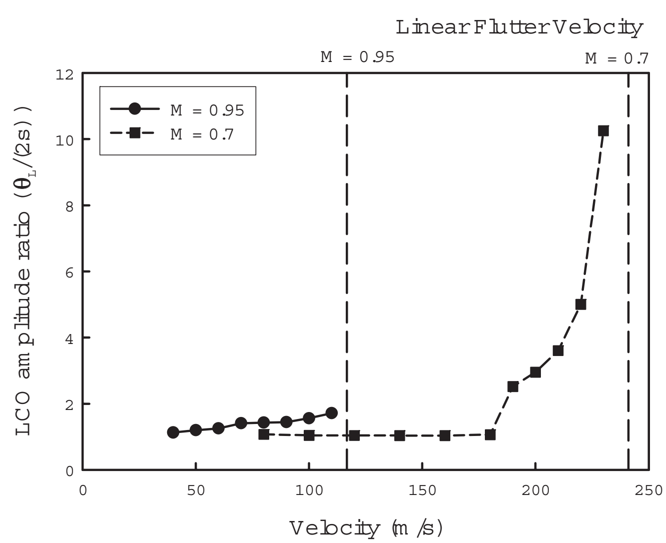
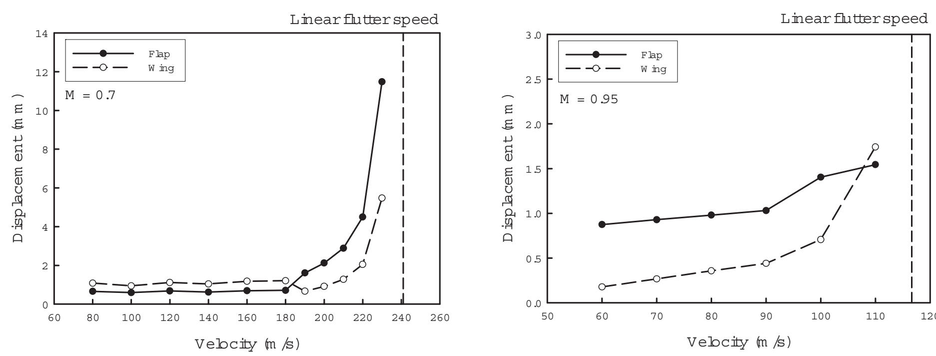
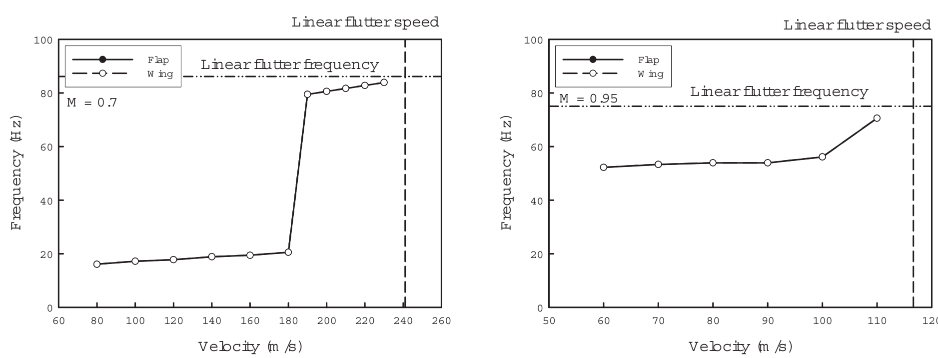



Figure 1: Velocity vs the LCO amplitude ratio.

Figure 1 shows the LCO amplitude ratio against the increment of flow velocity at M=0.7 and 0.95. Linear flutter speed means the flutter boundary of the linear structural model with zero freeplay angle. The freeplay angle $(s)$ of 0.125$^{o}$and angle of attack $(\alpha_0)$ of 0$^{o}$ are used for all cases. The initial disturbance is given by flap angle, $\theta_0$=0.25$^{o}$, defined as the angular displacement about the hinge axis with the rigid body rotation of the wing. The $\theta_L$ is the flap angle at the hinge axis. At M=0.7, flap angle decreases below V=70 m/s. From 80 to 180 m/s, the LCO amplitude ratio is about one. It means that aeroelastic responses of flap angle are bounded to freeplay angle. As airflow velocity increases, the LCO amplitudes increase. At the airflow velocity of around 230 m/s, unstable response is initiated. At M=0.95, the LCO is observed at lower velocity. As the flow velocity is increased, the LCO amplitude is slightly increased. Around the linear flutter velocity, the LCO amplitude is diverged. Such reason can be explained by the pressure distribution. At M=0.95, the shock wave is located in vicinity of flap. Due to the shock wave, the chaotic motion of a wing may occur in the transonic region.



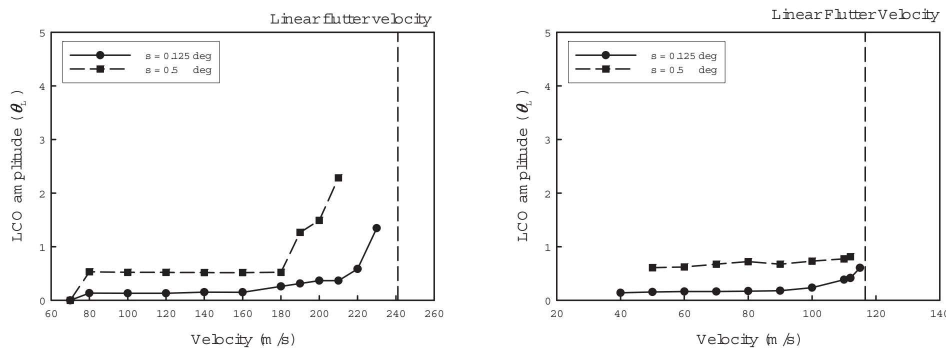

(a) Displacement




(b) Frequency

Figure 2: Displacement and frequency of the flap and wing.

Figure 2 shows displacement and frequency of the wing and flap at the trailing edge tip. At M=0.7 and V=80-180 m/s, the displacements of flap are smaller than those of wing. Above the airflow V=180 m/s, the flap displacements are exponentially increased and larger than the wing displacements. Also, frequencies of flap at higher flow velocity are higher than those at the lower flow velocities and are close to the linear flutter frequency. At M=0.95, the different tendencies of the flap displacement are observed. If the freeplay is considered, both the subsonic and transonic flutter boundaries are lower than linear structure model ones. The responses change from bending-flapping mode to torsion-flapping one as the flow velocity increases.




(a) M=0.7 (b) M=0.95

Figure 3: Comparisons of the LCO amplitude between $s$=0.125$^o$ and 0.5$^o$.

Figure 3 shows comparisons of the LCO amplitudes for $s$=0.125$^{\circ}$ and 0.5$^{\circ}$. Initial flap angle is 1$^{\circ}$ at all cases. In subsonic region, the initiation velocities of the LCO are not changed. At the freeplay angle of 0.5$^{\circ}$, the LCO amplitude always larger than that of 0.125$^{\circ}$. The flutter boundary of $s$= 0.5$^{\circ}$ is reduced about 10 % comparing to $s$=0.125$^{\circ}$. At M=0.95 and $s$=0.5$^{\circ}$, chaotic responses are observed at low velocity. Flutter velocities between each freeplay angle have little difference. For a higher freeplay angle, the LCO amplitude is higher

## Conclusion

In this study, nonlinear aeroelastic analyses are performed for the wing with control surface freeplay. The modal approach using the fictitious mass method is used for computational efficiency. The transonic small disturbance equation is applied to calculate unsteady aerodynamic forces in the subsonic/transonic regimes. The LCO amplitude ratio and displacement of flap and wing are compared in the subsonic and transonic regions. In the subsonic and transonic regions, LCOs are observed in a wide range of dynamic pressure below the linear flutter boundary. Also, the LCO characteristics of the wing and flap are changed as flow velocity increases. When the freeplay angle is larger, the aeroelastic stability is worsened. The present study is contributed to a better understanding of a wing with control surface freeplay in the subsonic and transonic flow regimes.

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