Experimental/theoretical correlation study of nonlinear aeroelasticity for a wing-store model with freeplay

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Abstract

A theoretical and experimental correlation study of flutter/limit cycle oscillation (LCO) and also response to a periodic gust excitation is made for a delta wing/store model with freeplay. The quantitative flutter/LCO correlation between the theory and experiment is reasonably good at and near the flutter velocity, but is poor at the higher flow velocities for the von Karman plate structural model. However a higher order structural model used in the present work has improved the correlations at the higher flow velocities.

Keywords: Aeroelasticity; Freeplay; Flutter; Limit cycle oscillation; Gust response

1. Introduction

The emphasis in the field of aeroelasticity is on the interaction among aerodynamic, structural elastic and inertia forces. Limit cycle oscillations (LCO), or nonlinear aeroelastic responses, have received paticular attention in recent years. For a more in-depth discussion of these issues see a recent review paper by Dowell et al. [1]. Modern high-performance aircraft are often required to operate with numerous wing-store configurations. The presence of stores can induce flutter at flow conditions for which the clean wing configuration would be stable. A limit cycle oscillation has been observed in flight test for a wing with stores [2]. LCO may occur because of the interaction of linear structural response and nonlinear aerodynamic forces due to transonic shock oscillation and shock induced flow separation on the wing trailing edge. Another possible cause of LCO is the structural nonlinearity at the attachment between the wing and the store, i.e. a freeplay gap and/or dry friction damping in the bolt connection. Also the wing geometric structural nonlinearity is another possible source for the LCO when a sufficiently large deflection occurs.

Dowell et al. [1] have studied the LCO of three-dimensional wings in transonic flow using various linear and nonlinear reduced order aerodynamic methods. In recent work by Thomas et al. [3], the effect of stores was included in the computation of the linear modal parameters of the structure, however the effect of the store aerodynamics was not considered. Thompson et al. [4,5] have theoretically studied both structural and aerodynamic nonlinearities for wing/store models in forthcoming publications.

For the present studies, the flutter/LCO of a cantilevered delta wing/store model with store freeplay is theoretically studied using either von Karman plate theory with a component modal method or a high fidelity structural model based on the ANSYS commercial finite element code, [6]. A three-dimensional time domain vortex lattice linear aerodynamic model for the delta wing and a slender body aerodynamic theory for the store were combined with above structural equations of motion. A linear reduced order model aerodynamic technique [7] is used. The numerical results from both the von Karman theory and a high fidelity structural model are compared to the experimental results. The theoretical/experimental correlations may be helpful in better understanding the nonlinear aeroelastic response of a delta wing/store model with and without freeplay.

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Computational Fluid and Solid Mechanics 2005
K.J. Bathe (Editor)

2. Theoretical and experimental correlations

A photograph of delta wing model with an external store in the wind tunnel is shown in Fig. 1.

2.1. Flutter

Figure 2 shows the theoretical and experimental (estimated) critical flutter boundary vs. the nondimensional span location of the store. The critical flutter boundary is sensitive to the span location of the store. The correlations between the theory and experiment for the flutter boundary are good. Also, although because of computational costs only a limited number of ANSYS results were obtained, it may be expected that the ANSYS and the von Karman models would give similar results for the flutter boundary.

2.2. LCO

Figure 3 shows the theoretical and experimental LCO velocity response at the wing mid-span of trailing edge vs. flow velocity for a store position of $y/c = 0.161$ without store freeplay. Two theoretical results are included in this figure. One is obtained using a high-fidelity structural model with a full vortex lattice aerodynamic model. The aerodynamic model was constructed using 900 vortex rings on the wing and 4 wing chords for wake were kept in the model. The structural model was constructed in ANSYS using 552 (614 nodes) quadrilateral shell63 elements. The other is obtained using von Karman plate theory with a reduced order aerodynamic model. The aerodynamic vortex lattice model includes 120 vortex elements on the delta wing and 525 vortex elements in the wake, and nine reduced aerodynamic eigenmodes. The higher-order structural theory gives improved agreement with experiment for the higher LCO amplitudes. For the smaller or middle LCO amplitudes, the correlation between von Karman plate theory with a reduced order aerodynamic model and experiment is reasonably good. From a comparison of the computational time between

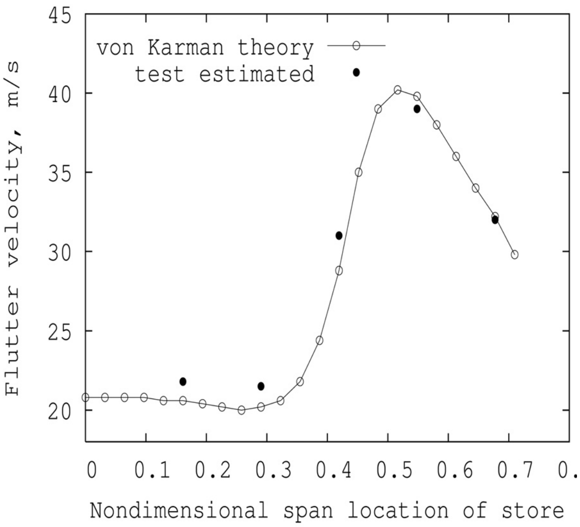

Fig. 2. Flutter velocity vs. nondimensional span location of the store.

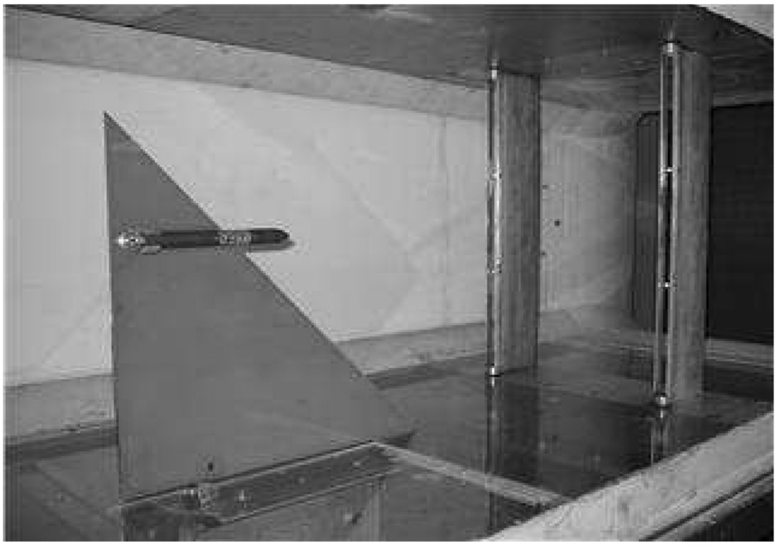

Fig. 1. Photograph of a delta wing model with an external store in the wind tunnel.

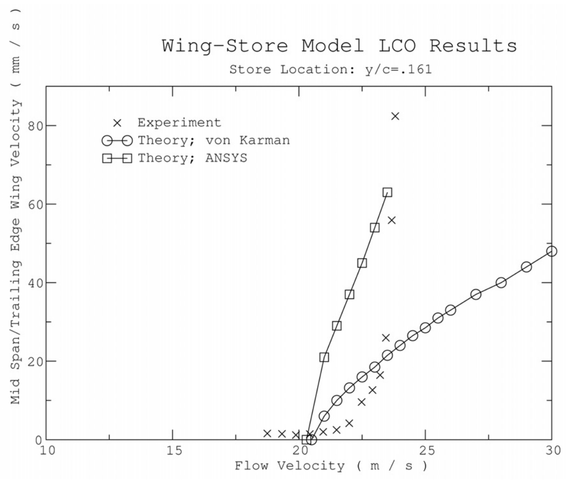

Fig. 3. LCO behavior vs. flow velocity for store position of $y/c = 0.161$.

the von Karman theory and the ANSYS model (the high-fidelity structural model), it is found that it takes approximately 73 hours of CPU time to compute 1 second of data for the ANSYS model. For the von Karman theory with reduced order aerodynamic model, the CPU time is about 3 minutes. The ratio of computational time (cost) of the ANSYS model to the von Karman model is approximately 1460.

Two store freeplay gaps, $d = \delta/h = 0.5$ and $d = 1.0$, were considered where δ is the store freeplay gap and h is the thickness of wing plate. The store position is $y/c = 0.677$. There are three typical initial conditions to be used in the calculations for the model with the store freeplay. Case I.C.1 is for the initial nondimensional wing displacement is $q_1(0)/h = 0.001$; Case I.C.2 is for the initial store pitch angle, $\beta(0) = 0.5°$; Case I.C.3 is for $\beta(0) = 1.0^0$ and others are zero.

Figure 4(a) shows the theoretical and experimental acceleration amplitude at the wing mid-span vs. the flow velocity for several store freeplay gaps. The theoretical calculation uses the von Karman structural model and for the initial conditions of I.C.1. The correlations between the theory and experiment are reasonably good in the flow velocity range lower than $U_\infty = 26.5$ m/s. For the higher flow velocity range, the correlations are not acceptable. Figure 4(b) shows the theoretical and experimental results for d = 0.5 and various initial conditions. The LCO response is sensitive to the initial conditions.

2.3. Gust response

Figure 5 shows a typical wing acceleration frequency response to a periodic gust excitation for a flow velocity of $U_\infty = 28$ m/s that is higher than the linear flutter velocity. It is interesting to note that when the gust frequency is sufficiently high, the nondimensional wing displacement is actually smaller than the LCO amplitude. It appears that a weak gust excitation with a high frequency can diminish the LCO amplitude.

3. Conclusions

The quantitative flutter/LCO correlations between the theory and experiment are reasonably good in the range near the flutter velocity but is poor at the higher flow velocities for the von Karman plate structural model. A higher-order structural model used in the present work has improved the correlations at the higher flow velocities. Also for the gust response, the quantitative theoretical/experimental correlations are reasonably good except in the range of the dominant resonant frequency of this nonlinear system when using the von Karman plate structural model.

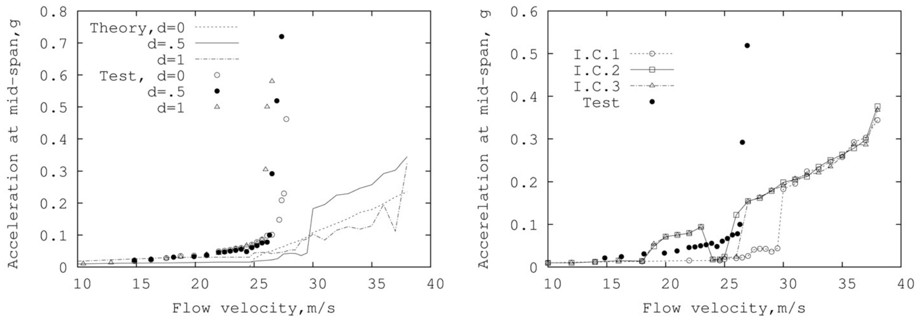

Fig. 4. (a) LCO wing response amplitudes vs. flow velocity for the span location of store at $y/c = 0.677$ and various freeplay gaps, (b) for a freeplay gap, d = 0.5 and various initial conditions.

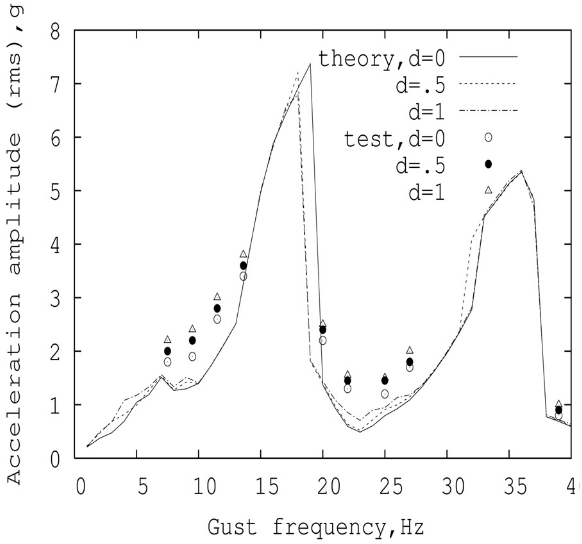

Fig. 5. Gust frequency response for $U_\infty = 28$ m/s, and the several freeplay gaps, d = 0, 0.5 and d = 1.

Acknowledgments

This work was supported under AFOSR Grant, Dynamic and Control of Nonlinear Fluid-Structure Interaction under the direction of Drs. Dean Mook and Clark Allred. We would like to thank graduate student, Sid Rupani, for his participation in the data acquisition phase of the wind tunnel test.

References

[1] Dowell EH, Edwards J, Strganac T. Nonlinear aeroelasticity. Aircraft 2003;40(5):857–874.

[2] Denegri CM, Jr. Limit cycle oscillation flight test results of a fighter with external stores. Aircraft 2000;37(5):761–769.

[3] Thomas JP, Dowell EH, Hall KC. Modeling limit cycle oscillation behavior of the F-16 fighter using a harmonic balance approach. AIAA Paper 2004–1696.

[4] Thompson DE Jr, Strganac TW. Nonlinear analysis of store-induced limit cycle oscillations. Nonlinear Dynamics 2004; accepted.

[5] Beran PS, Strganac TW, Kim K, Nichkawde C. Studies of store-induced limit cycle oscillations using a model with full system nonlinearities. Nonlinear Dynamics 2004; accepted.

[6] ANSYS User Manual, Release 5.5.1, Swanson Analysis Systems, Inc., Houston, PA, 1998.

[7] Dowell EH, Hall KC. Modeling of fluid-structure interaction. Annual Reviews of Fluid Mechanics 2001;33:445–490.