Transonic Aeroelasticity of Wings with Tip Stores

Guru P. Guruswamy*
Sterling Federal Systems, Palo Alto, California
and
Peter M. Goorjian† and Eugene L. Tu‡
NASA Ames Research Center, Moffett Field, California

The presence of tip stores influences both the aerodynamic and aeroelastic performances of wings. Such effects are more pronounced in the transonic regime. In this study, transonic aeroelasticity of wings with tip stores is studied for the first time by a theoretical method using the unsteady, small-disturbance transonic aerodynamic equations coupled with modal structural equations of motion. The aerodynamic and structural equations of motion are simultaneously integrated by a time-accurate numerical scheme. To validate the tip store simulation, aeroelastic computations are made for a typical rectangular wing with a tip store and results are compared with the corresponding wing without the tip store at various flight conditions. Aeroelastic computations are also made for a typical fighter wing with a tip store. Present computations show that it is important to account for the aerodynamics of the tip store, particularly in the transonic regime where the tip store can make the wing aeroelastically less stable.

Introduction

TIP stores are placed on aircraft either for fuel storage or as weapons such as tip missiles. Tip stores change the aerodynamic and aeroelastic characteristics of wings because of their aerodynamic, inertial, and elastic coupling with the wing. Because of the lack of efficient computational tools at transonic speeds, store aerodynamics has been neglected in flutter analysis. Several studies[1,2] have shown that tip aerodynamics significantly influence flutter results at such speeds. The influence of the tip store on the wing flutter characteristics can be noticeably pronounced in the transonic regime because of the presence of shocks. The detailed wind-tunnel experiments[3] conducted at the National Aerospace Laboratory of the Netherlands under the sponsorship of the U.S. Air Force has illustrated the strong influence of the tip missile on the unsteady transonic aerodynamics of the F-5 wing.

An accurate computation of flutter speeds is important in the design and performance of aircraft. A typical flutter analysis requires several unsteady aerodynamic computations. To date, wing/store aerodynamics and aeroelasticity have been theoretically modeled for only linear subsonic and supersonic flows.[4] So far, no theoretical studies have been conducted for the wing/store flutter in the transonic regime because of the lack of computational tools. Such studies are critical in that they complement wind-tunnel results and they are used to independently conduct theoretical research of wing/store flutter. Such studies can play an important role in the area of active flutter suppression in the transonic regime. Studies based on the experimental data[5] have shown that tip stores have significant influence on the flutter speed of the wing in the transonic regime. To conduct accurate flutter analysis in the transonic regime, an efficient aerodynamic computational method is required to compute unsteady transonics of wings with tip stores.

In a previous study, the present authors have successfully modeled a tip store for the nonlinear unsteady transonic flow regime with moving shock waves.[6] The transonic, small-perturbation aerodynamic equations were used to model the flow. The authors obtained good comparisons with experiment for both steady and unsteady data at transonic Mach numbers for the F-5 wing. This new aerodynamic capability of modeling the tip store has been incorporated into the unsteady transonic code XTRAN3S-Ames,[7] the NASA Ames Research Center's version of the official Air Force/NASA code, XTRAN3S. This transonic, unsteady, small-disturbance code has the capability of conducting static and dynamic aeroelastic analysis by simultaneously integrating aerodynamic and structural equations of motion. So far XTRAN3S has been used only to conduct transonic aeroelasticity of clean wings.[8] In this work, the authors have extended the capability of XTRAN3S to account for both the aerodynamic and structural properties of the tip store.

In this study, the wing/store aeroelastic characteristics of wings have been investigated using XTRAN3S. Detailed aeroelastic computations are made for a typical rectangular wing with a tip store. Results on the effects of the tip store on aeroelastic responses at various transonic Mach numbers and dynamic pressures are presented in detail. Response analyses are also conducted for a typical fighter wing with a tip missile at transonic Mach numbers. For all the cases, results are compared with the corresponding clean (no tip store) wings. The importance of accurate aerodynamic modeling of the tip store for transonic aeroelastic analysis of wings is illustrated.

Formulation of Unsteady Transonic Flow Equations

The three-dimensional modified small-disturbance unsteady transonic equation of motion is given by[9]

$$A\phi_{tt} + B\phi_{xt} = [E\phi_x + F\phi_x^2 + G\phi_y^2]_x + [\phi_y + H\phi_x\phi_y]_y + [\phi_z]_z \tag{1}$$

where

$$A = M_\infty^2; \quad B = 2M_\infty^2; \quad E = (1 - M_\infty^2)$$
$$F = -\tfrac{1}{2}(\gamma + 1)M_\infty^2; \quad G = -\tfrac{1}{2}(\gamma - 3)M_\infty^2$$
$$H = -(\gamma - 1)M_\infty^2$$

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*Principal Analyst. Member AIAA.

†Research Scientist. Associate Fellow AIAA.

‡NASA Co-op Student Trainee. Student Member AIAA.

The flowfield boundary conditions used are

$$\text{Far downstream: } \phi_x + k\phi_t = 0 \tag{2a}$$

$$\text{Far upstream: } \phi = 0 \tag{2b}$$

$$\text{Far above and below: } \phi_z = 0 \tag{2c}$$

$$\text{Far spanwise: } \phi_y = 0 \tag{2d}$$

$$\text{Wing root: } \phi_y - 0 \tag{2e}$$

$$\text{Trailing vortex wake: } [\phi_z] = 0 \tag{2f}$$

$$\text{and } [\phi_x + k\phi_t] = 0 \tag{2g}$$

where the [ ] denote the jump in the quantity across the vortex sheet.

The thin wing surface-flow tangency condition that is satisfied at the mean chord plane is given by

$$\phi_z = f_x + kf_t \tag{3}$$

where $f(x)$ denotes the airfoil surface function and $k = \omega c/U_\infty$ is the reduced frequency based on the full chord (ω is the frequency in radians per second, c a reference chord length, and U_∞ the freestream velocity).

The above equations are transformed so that a swept-tapered wing can be analyzed by using a finite-difference mesh that is aligned with the leading and trailing edges of the wing. Details are given in Ref. 7.

Aerodynamic Modeling of Tip Store

The tip store is modeled as a body based on the small-disturbance theory. For a body that is described by the equation $B(x,y,z,t) = 0$, the small-disturbance flow tangency boundary condition on the surface of the body becomes[10]

$$kB_t + B_x + \phi_y B_y + \phi_z B_z = 0 \tag{4}$$

For a planar body for which all points lie close to $z = 0$, the flow tangency condition is simplified in this study to

$$\phi_z = f_x + kf_t \tag{5}$$

where $B = z - f(x,y,t)$.

Note that the simplified flow tangency condition given by Eq. (5) is similar to the flow tangency condition [Eq. (3)] on the thin wing. Results in Ref. 6 have illustrated that the tangency condition [Eq. (3)] is adequate for typical thin fighter wings with slender missiles such as the F-5 wing. The details of modeling these unsteady flow tangency conditions in the finite-difference scheme is given in Ref. 6.

Aeroelastic Equations of Motion

The governing aeroelastic equations of motion of a flexible wing are obtained by using the Rayleigh-Ritz method (Chap. 3, Ref. 11). In this method, the resulting aeroelastic displacements at any time are expressed as a function of a finite set of assumed modes. The contribution of each assumed mode to the total motion is derived by Lagrange's equation. Furthermore, it is assumed that the deformation of the continuous wing structure can be represented by deflections at a set of discrete points. This assumption facilitates the use of discrete structural data, such as the modal vector, the modal stiffness matrix, and the modal mass matrix. These are generated by a finite-element analysis or by experimental influence coefficient measurements. In this study, the finite-element method is employed to obtain the modal data. Both the stiffness and the mass of the tip store are included in the analysis.

The final matrix form of the aeroelastic equations of motion is

$$[M]\{\ddot{q}\} + [G]\{\dot{q}\} + [K]\{q\} = \{F\} \tag{6}$$

where

$$\{F\} = \tfrac{1}{2}\rho U_\infty^2 [\phi_A]^T [A]\{\Delta C_p\}$$

is the aerodynamic force vector, $[\phi_A]$ the modal matrix, and $[A]$ the diagonal area matrix of the aerodynamic control points.

These equations of motion are solved by numerically integrating Eq. (6) in time by the linear acceleration method. Detailed illustration of the method for the aeroelastic analysis airfoils is given in Ref. 12. The method is briefly described here.

The step-by-step integration procedure for obtaining the aeroelastic response was performed as follows. Assuming that freestream conditions and wing-surface boundary conditions were obtained from a set of selected starting values of the generalized displacement, velocity, and acceleration vectors, the generalized aerodynamic force vector $F(t)$ at time $t + \Delta t$ was computed by solving Eq. (1). Using this aerodynamic vector, the generalized displacement, velocity, and acceleration vectors for the time level $t + \Delta t$ were calculated by numerically integrating Eq. (2). From the generalized coordinates computed at the time level $t + \Delta t$, the new boundary conditions on the surface of the wing were computed. With these new boundary conditions the aerodynamic vector $F(t)$ at the next time level was computed by using Eq. (1). This process was repeated every time-step to solve the aerodynamic and structural equations of motion forward in time until the required response was obtained.

Results

To verify the modeling of the tip store, steady and unsteady transonic results were computed on the F-5 wing at various flow conditions and were compared with the wind tunnel results from NLR.[3] The comparisons were good and those results are presented in Ref. 6. In this section, aeroelastic results for a rectangular and a typical fighter wing are presented.

Rectangular Wing

Aeroelastic response analyses are conducted for a uniform rectangular wing with an aspect ratio of 5.0 which has a parabolic-arc airfoil section with a 6% thickness. A typical store is rigidly attached to the wing at the tip as shown in Fig. 1. The effective planform area and the mass of the tip store are 10 and 10% of the wing, respectively. The mass center of the tip store is located at the 25% tip chord. Flutter results for this wing without the tip store were successfully computed by using XTRAN3S.[13]

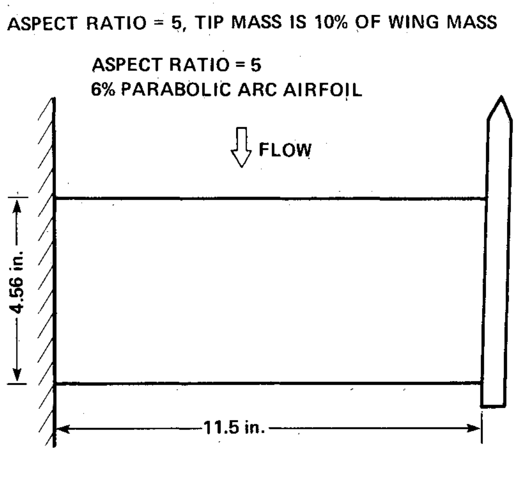

Fig. 1 Planform of rectangular wing model with a tip store.

Aeroelastic analyses were conducted at four Mach numbers, 0.715, 0.795, 0.851, and 0.875. To obtain the nature of the aerodynamic flow, steady aerodynamic computations were made for the wing with the tip store. The plots of the upper surface steady-pressure distribution vs span are shown in Fig. 2 for the four Mach numbers. From this, it is noted that the flow varies from the subsonic to the transonic regime.

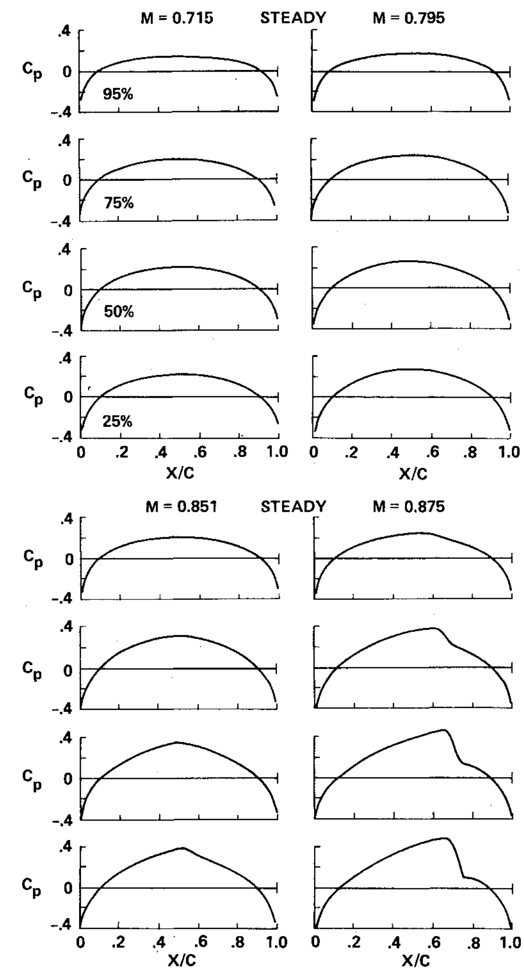

Fig. 2 Steady upper surface pressures of the rectangular wing with tip store.

The mode shapes and frequencies required for the modal equations of motion [Eq. (6)] were obtained by a 16 degree-of-freedom rectangular finite element.[14] Figures 3 and 4 show the mode shapes and frequencies of the first five natural modes for the wing without and with tip store, respectively. The addition of the tip store reduced the frequencies and changed the shapes of the modes.

To illustrate the influence of the tip store on the unsteady aerodynamics, unsteady aerodynamic loads were computed for the first torsional mode (see Fig. 4) at the subsonic Mach number 0.715 and at the transonic Mach number 0.875. For both cases, the wing was oscillating with a reduced frequency of 0.2 based on the full-root chord. The plots of the unsteady lift vs span are shown in Fig. 5 for both $M = 0.715$ and 0.875. In the same figure, the corresponding results for the clean wing are also given. From these unsteady results, it is noted that the tip store has more influence in the transonic regime than it does in the subsonic regime.

Using the modal data, aeroelastic responses were computed by solving Eq. (6). Aeroelastic responses were computed with initial modal disturbances in the first and the second modes. Figures 6–9 show the aeroelastic responses of the first three normal modes at $M = 0.715$, 0.795, 0.851, and 0.875, respectively. In all the figures, the corresponding responses at the same flow conditions are also given for the wing without tip store. From Figs. 6–9, it can be observed that for the given identical flow conditions, the wing with the tip store has less aeroelastic damping than does the clean wing. To further understand the source of the decrease in stability, response analyses were conducted for a wing with the tip store mass only. Figure 10 shows the first modal responses at three Mach numbers for a clean wing, a wing with the tip store mass only and a wing with the tip store mass and aerodynamics. At all three Mach numbers, it is shown that the wing with the tip store mass and aerodynamics is less stable than the other two wings. It is further noted that the wing with the tip store mass only is more stable than the clean wing. This demonstrates that the wing with the tip store can be aeroelastically unstable due to the tip store aerodynamics. Also, Figs. 6–9 show that at higher Mach numbers ($M > 0.795$), the wing with the tip store experiences static divergence.

To compute flutter dynamic pressures Q, response analyses were conducted at all four Mach numbers by varying the dynamic pressure. For example, stable to unstable responses of the first mode at $M = 0.715$ and 0.875 are shown for three dynamic pressures in Figs. 11 and 12, respectively. The flutter

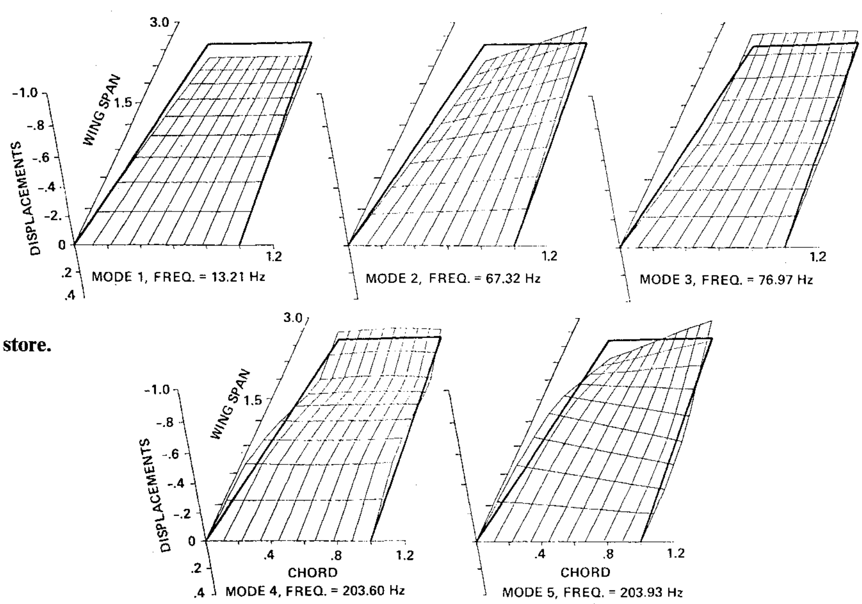

Fig. 3 Mode shapes of rectangular wing without tip store.

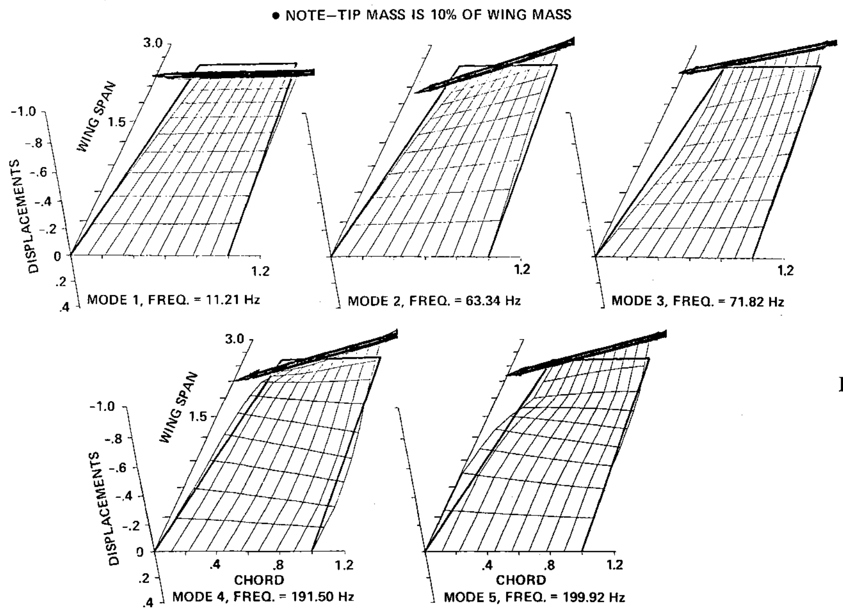

Fig. 4 Mode shapes of rectangular wing with tip store.

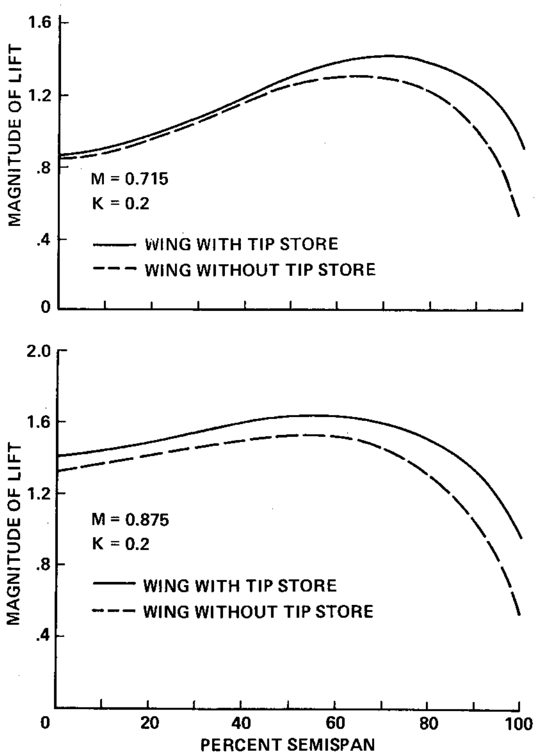

Fig. 5 Unsteady lift comparisons of rectangular wings with and without tip store.

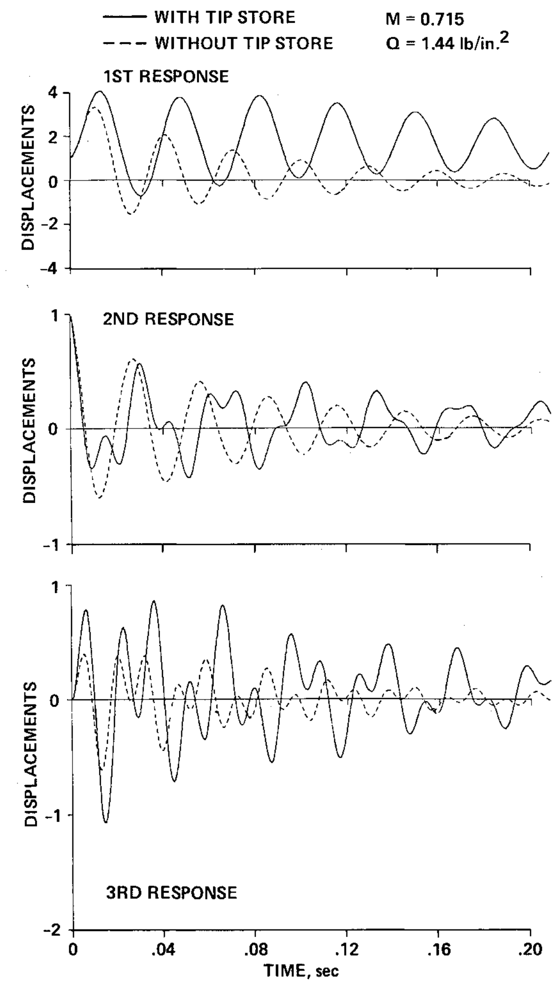

Fig. 6 Aeroelastic responses of wings with and without tip store at $M = 0.715$.

dynamic pressure corresponding to zero aeroelastic damping was computed from the aeroelastic dampings that were computed at various dynamic pressures. Figure 13 shows the plot of flutter dynamic pressure vs Mach number for both the wing with a tip store and for the clean wing. From this figure, it can be seen that the flutter dynamic pressure of the wing with tip store is lower than the corresponding value for the clean wing. Based on the experimentally measured unsteady aerodynamic loads, similar observations were made in Ref. 2 for a fighter wing.

Typical Fighter Wing

Based on the techniques developed above for aerodynamic and structural modeling of the tip store, response analyses were conducted for a typical fighter wing. The planform of the wing is shown in Fig. 14. This wing's planform and airfoil section is the same as that for the F-5 wing analyzed in Ref. 6. Since detailed stiffness and mass data were not available to the authors for a real fighter wing, modes and frequencies were generated from a simple-beam, finite-element model so that it would match a typical fighter wing with a typical tip missile. It was assumed that the tip missile weight was approximately 10% of the wing weight and its center of mass the same as the center of mass of the wing tip. The six modes and the corresponding frequencies for the wing without and with tip missile are given in Figs. 15 and 16, respectively. Because of the increase in mass, the wing with tip missile has lower frequencies and different mode shapes than does the clean wing. Aeroelastic response analyses were conducted at flight conditions corresponding to a transonic Mach number of 0.9 at an altitude of 30,000 ft with zero angle of attack.

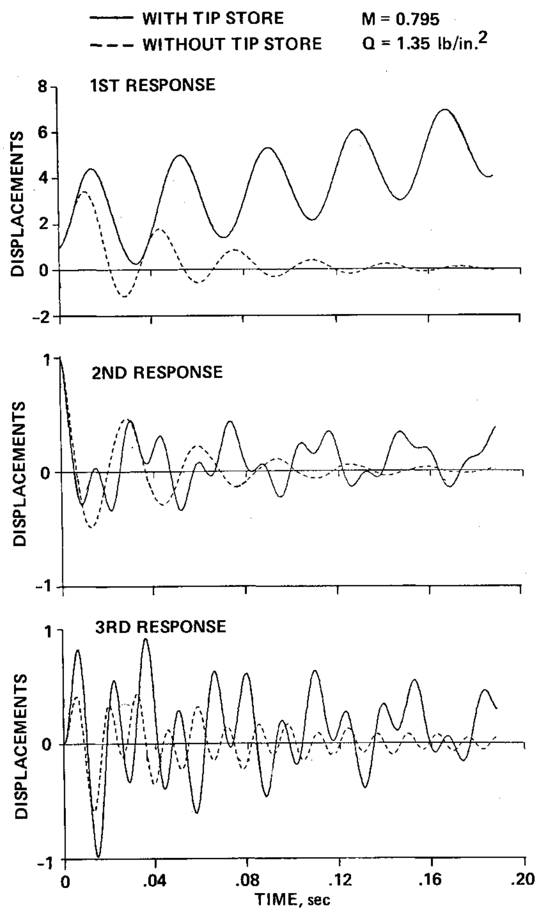

Fig. 7 Aeroelastic responses of wings with and without tip store at $M = 0.795$.

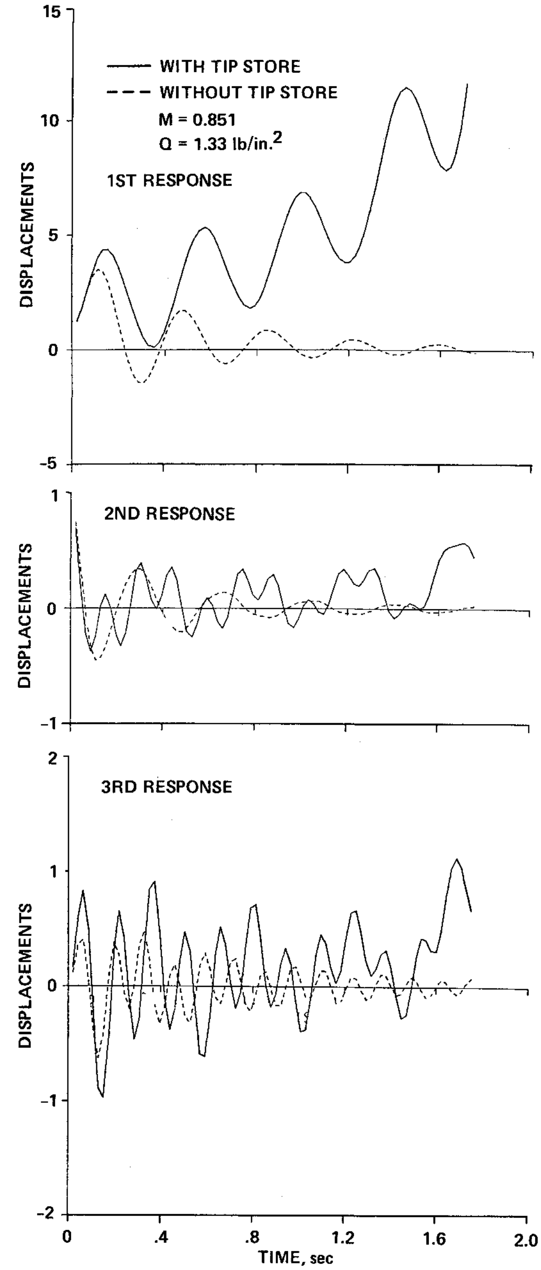

Fig. 8 Aeroelastic responses of wings with and without tip store at $M = 0.851$.

Figure 17 illustrates the effects of the tip store on the unsteady results for the first bending mode (see Fig. 15) of the wing. In Fig. 17, comparing the results with the wing without tip store, it can be seen that the presence of the tip store makes the shock wave stronger and moves it closer to the trailing edge. Such changes caused by the presence of the tip store can effect the aeroelastic response.

Aeroelastic responses were obtained with initial modal disturbances in the first and second modes. Figure 18 shows the aeroelastic response of the first normal mode for $M = 0.90$ at a dynamic pressure of 2.478 psi for the wing both with and without the tip missile. This simulates the flight conditions at an altitude of 30,000 ft. The response of the wing with the tip missile shows less aeroelastic damping than does the clean wing. This again illustrates that the tip missile can make the wing aeroelastically less stable.

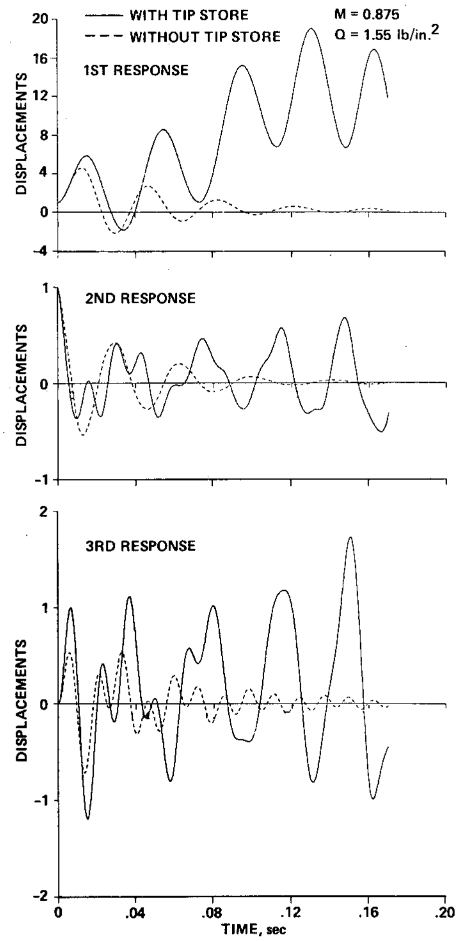

Fig. 9 Aeroelastic responses of wings with and without tip store at $M = 0.875$.

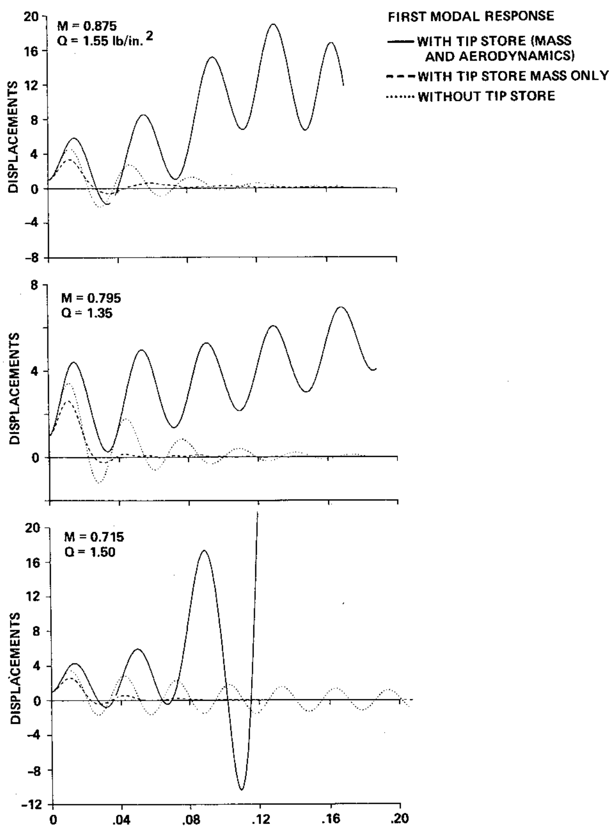

Fig. 10 Influence of tip store aerodynamics on the responses at $M = 0.715$, 0.795, and 0.875.

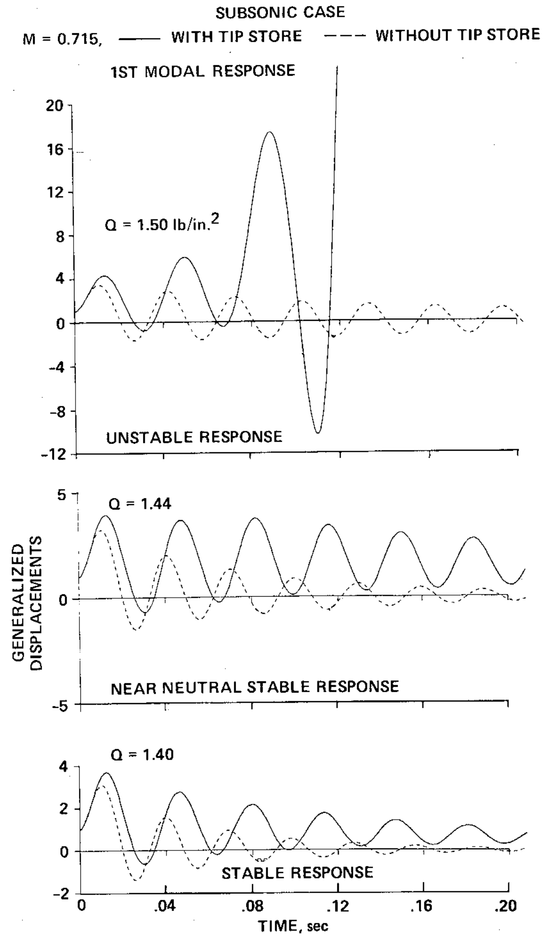

Fig. 11 Effect of dynamic pressure on aeroelastic responses of wings with and without tip store at $M = 0.715$.

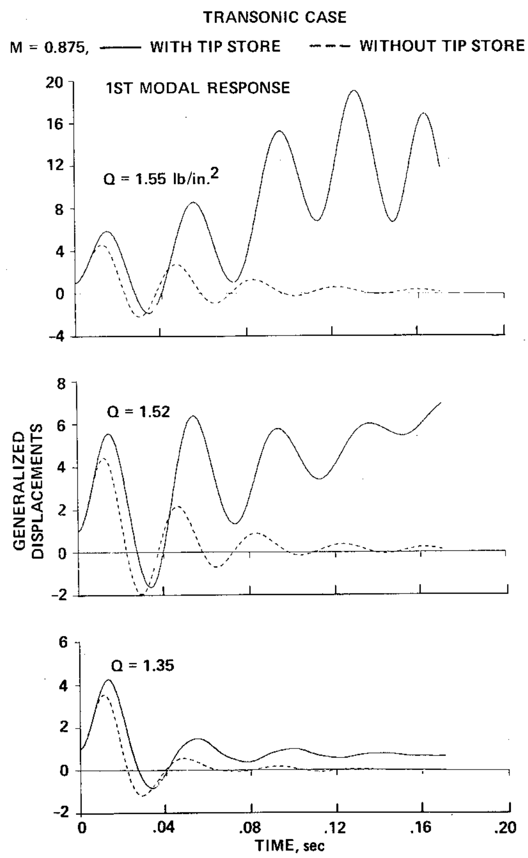

Fig. 12 Effect of dynamic pressure on aeroelastic responses of wings with and without tip store at $M = 0.875$.

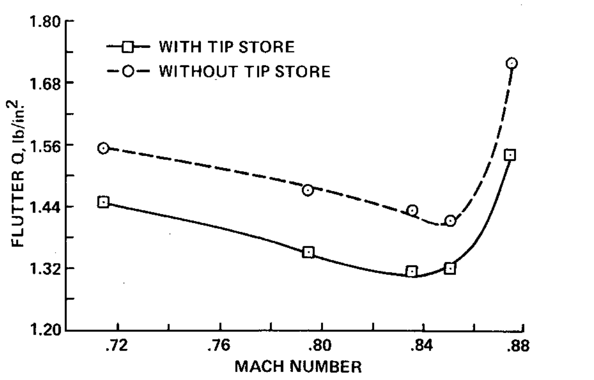

Fig. 13 Effect of Mach number on flutter dynamic pressures for wings with and without tip store.

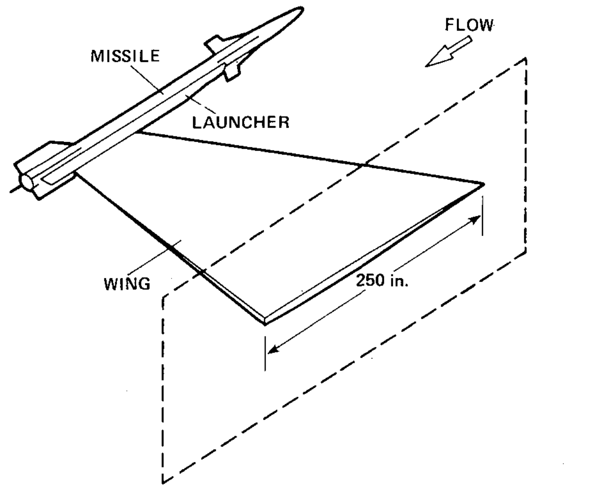

Fig. 14 Typical fighter wing configuration with tip missile.

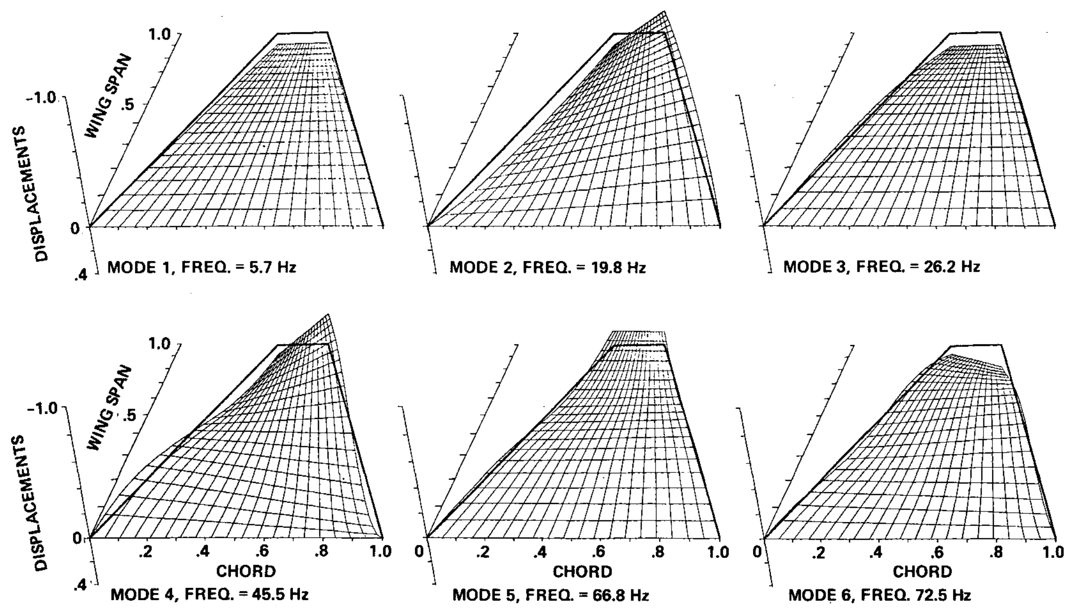

Fig. 15 Mode shapes of the fighter wing without tip missile.

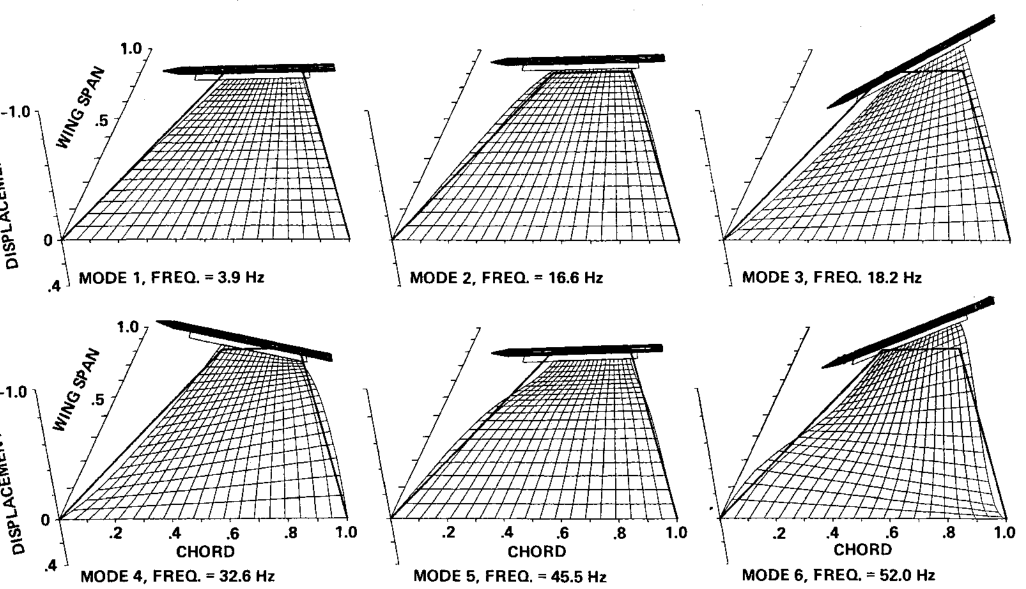

Fig. 16 Mode shapes of the fighter wing with tip missile.

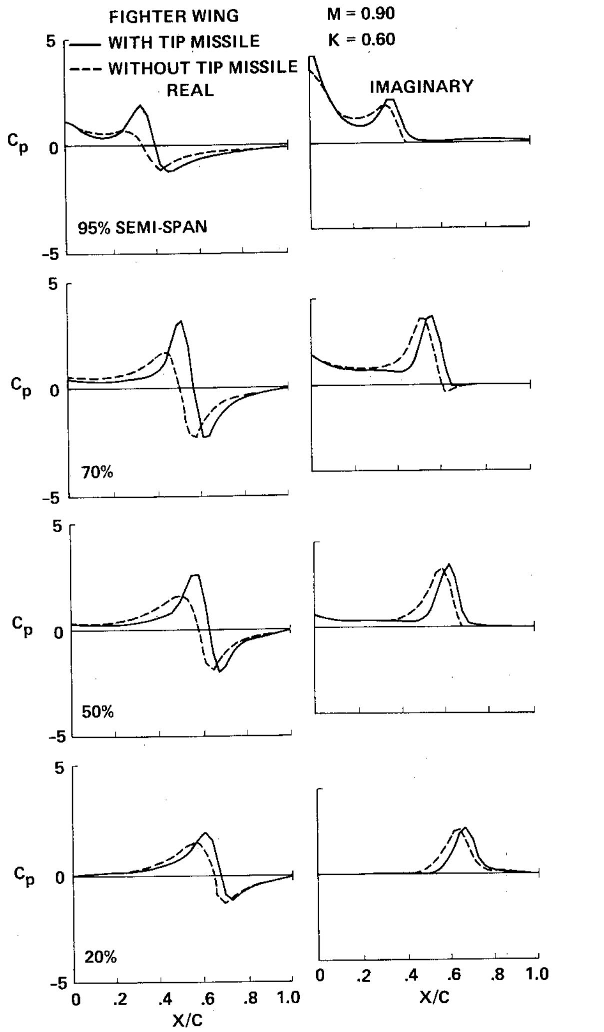

Fig. 17 Unsteady pressures for the first normal mode of the fighter wing with and without tip missile.

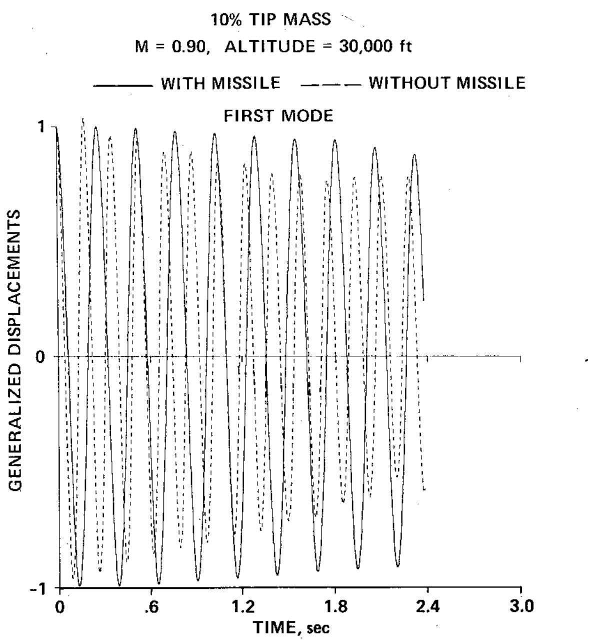

Fig. 18 First normal modal responses of the fighter wing with and without tip missile.

Conclusions

A procedure has been developed to conduct transonic aeroelastic analysis of wings with tip stores. Both the aerodynamic and structural properties of the tip store are considered. Keeping the practical aeroelastic applications in view, a tip store is modeled by using the transonic small-perturbation theory and is incorporated into the XTRAN3S-Ames code.

Aeroelastic analyses were conducted for a typical rectangular wing and for a typical fighter wing with a tip store. Detailed computations for a rectangular wing show that the tip store can make the wing aeroelastically less stable. Limited computations for a fighter wing also illustrate the same phenomenon.

Results of this study will be of valuable use in the area of active flutter suppression at transonic Mach numbers. Since the simulation in this analysis is close to wind-tunnel simulation, the present development can be an efficient complement to wind-tunnel/flight tests and can reduce the design cost considerably.

Acknowledgments

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