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Multidisciplinary Design Optimization of a Built-Up Wing Structure with Tip Missile

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The influence of a wing tip missile on the design optimization of a wing structure is studied. Finite element models of a realistic built-up wing structure are used to represent stiffness and mass properties. The store location and the effect of the store aerodynamics and mass are the variables included. A multidisciplinary optimization technique is used to compensate/restore the lost aeroelastic performance due to the presence of the store. Missile locations are the only configuration variables addressed besides the structural variables. The built-up wing box structure is optimized with constraints on the static strength and flutter speed. The thickness and the cross-sectional areas of the structural elements are the primary variables in the optimization. The aerodynamics of the tip missile has a significant effect on the flutter characteristics. In addition, the flutter behavior of the optimized structure is very sensitive to the tip missile movement along the tip chord. The results indicate that the effect of the tip missile aft movement must be examined in conjunction with the store aerodynamics. ASTROS is the primary tool used.

Introduction

MOST military aircraft are designed to carry external stores. They may be missiles, bombs, fuel tanks, and a variety of pods for carrying monitoring equipment. The presence of these stores affects the structural, aerodynamic, and aeroelastic performance of the aircraft. The stiffness and inertia effects of the store can significantly affect the dynamic behavior of the wing. However, the interference effect of store aerodynamics may be problem dependent.

Turner[1] studied the effect of store aerodynamics on wing and store flutter. An analytical study was made using MSC/NASTRAN with an elastic axis structural dynamics model. A large number of wing/store configurations were considered to generate general guidelines. Nevertheless, it was only possible to develop specific guidelines for use with a particular aircraft.

Modeling of the stores is a large part of the store aerodynamics representation. Approximations of a tip missile without fin geometry in the aerodynamic model were investigated by Striz and Jang.[2] The end plate approximation gave the best and most economical results, more than any other approximations for the F-5 wing. However, the relative location of the missile fins to the wing was found to be an important point in selecting the scheme of the aerodynamic idealization of the tip stores.[3]

The structural models to be used in an aeroelastic analysis are also an issue to be addressed. The structural models that were used in the flutter analysis of a wing with a tip store[1,4] were represented by equivalent beam models. These may be an oversimplification and may not be very useful in resizing the individual structural elements.

Many efforts are being made to marry high-fidelity aerodynamics with aeroelasticity.[5,6] The general implementation of high-fidelity aerodynamics into the iterative structural design environment is expected to be available in the near future. Aerodynamics including wing/store configurations should be the next challenge in computational aeroelasticity.

ASTROS[7,8] can perform structural design and analysis subject to multidisciplinary constraints. The Eastep et al.[9] study is an excellent example of ASTROS's capability, which encompasses various kinds of design constraints and structural materials. Stritz and Venkayya[10] examined the influence of the structural and aerodynamic model on flutter analysis using ASTROS. Wing box finite element models were demonstrated to be a good start for a conventional redesign process, as well as optimization.

ZAERO, the ZONA aerodynamic module unified for all Mach number ranges, was added as an aerodynamic enhancement to ASTROS. This enhanced ASTROS was named ASTROS*. The steady and unsteady aerodynamic modules have been examined by comparison to the wind-tunnel test data of stored wing configurations and other benchmark problems.[11] Because the higher-order panel methods implemented in ASTROS* facilitated making an aerodynamic model of bodylike stores, it now became possible to conduct multidisciplinary design tasks with a reasonable fidelity of the store aerodynamics.

This study benefited from this state-of-the-art multidisciplinary design optimization tool that is capable of handling realistic structures and stores including aerodynamics. The objective of the present study was to model realistic wing store combinations and to provide more tangible information to guide future certification efforts. The focus of the study was to determine the influence of the store aerodynamics on aeroelastic behavior. Obviously, the mass effect was included. Although, only finite element models were used to represent the stiffness and mass properties, more than one aerodynamic modeling scheme was used. The store location was the variable considered.

The optimization capability of ASTROS* was used to enhance the lost aeroelastic performance due to the presence of stores. The wing and store configurations of two different store locations were selected as the baseline configuration for the sample design study. The configuration changes from the baseline configuration were defined by changing the store locations. The effects on aeroelastic instability were investigated for the wing and store models used in the present study. Store modeling effects in terms of mass and aerodynamics were also assessed.

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Formulation of the Design Study

A statement of the optimization problem for the design study is as follows: Find the set of design variables v that will minimize an objective function

$$F(v) \tag{1}$$

subject to constraints

$$g_j(v) \leq 0.0, \qquad j = 1, \ldots, n\text{con} \tag{2}$$

$$h_k(v) = 0.0, \qquad k = 1, \ldots, ne \tag{3}$$

$$v_i^{\text{lower}} \leq v_i \leq v_i^{\text{upper}}, \qquad i = 1, \ldots, ndv \tag{4}$$

where g specifies the $n$con inequality constraints and h refers to the ne equality constraints. Equation (4) specifies upper and lower bounds (side constraints) on each of the design variables, which are typically used as manufacturing constraints on the design variables. The most common design objective in the flight vehicle is the weight. Stresses are used as constraints for static strength. In addition there are constraints derived from aeroelastic stability. In this study, stress constraints and flutter constraints were considered for the static strength and the aeroelastic stability of the design model.

The basic equations of static structural analysis are represented as

$$\boldsymbol{P} = K\boldsymbol{u} \tag{5}$$

where $\boldsymbol{P}$ is a vector of applied loads that include both aerodynamic and inertia loads. The flexibility effect of the structure is included in the load calculation. K is the stiffness matrix of the finite element model, and $\boldsymbol{u}$ is the resulting displacement vector. The number of load vectors in $\boldsymbol{P}$ constitutes the number of design conditions. After the displacements are solved for, the stress and strain values in all of the elements are computed and compared to the stress and strain constraints to see if they are exceeded.

The aeroelastic response of a flight vehicle is a result of the mutual interaction of the inertial and elastic structural forces, the aerodynamic forces induced by the static or dynamic deformation of the structure, and the external disturbance forces. A flutter analysis usually involves a search of the structural stability boundary of an aircraft structure in terms of its flight speed and altitude or the corresponding dynamic pressure. If F_a are the aerodynamic forces induced by the structural deformation, the flutter equation of the aeroelastic system can be written as

$$\bar{M}\ddot{x}(t) + \bar{K}x(t) - F_a(x) = 0 \tag{6}$$

where $\bar{M}$ and $\bar{K}$ are the mass and stiffness matrices generated from the structural finite element model and $x(t)$ is the structural deformation. This equation can be transformed into the frequency domain by the introduction of the reduced frequency,

$$k = \omega b / V \tag{7}$$

where ω is the harmonic oscillatory frequency, b is the reference aerodynamic chord, and V is the freestream velocity. Then the flutter equation for the flutter condition can be written as

$$\left[\omega^2 M + K - q_\infty A\right]\boldsymbol{q} = 0 \tag{8}$$

where q_∞ is the dynamic pressure of the freestream and $\boldsymbol{q}$ is the vector of generalized coordinates. M and K represent the generalized mass and stiffness matrices in the modal approach. A represents the aerodynamic matrix which is obtained from the aerodynamic influence coefficient (AIC) matrix. The AIC matrix relates the structural deformation defined at the aerodynamic model to the resultant aerodynamic forces on the aerodynamic model. The tip missile necessitates the consideration of body aerodynamics. The unsteady pressure for the body components involves coupling terms with the perturbation velocities of the steady mean flow, which brings in the thickness effects. By contrast, the unsteady pressure for a lifting surface is uncoupled from the steady mean flow. The normal forces on the bodylike components are more complicated than the winglike components. Details of the AIC matrix formulation may be found in Ref. 12.

Determining the sensitivity of the objective function and constraints is necessary to change the design variables during the optimization process. In the present study, the design variables are the thickness of the structural members such as the skin, the spars, and the ribs. The weight of design model includes the weight of the structural members and the nonstructural masses. Usually the nonstructural masses are not dependent on the structural design, and they are not included in the objective function. The gradients of the objective function F with respect to the thickness variables would be greater than zero, that is,

$$\frac{\partial F}{\partial x_i} > 0 \tag{9}$$

The gradient of the stress constraints in each element can be calculated using the equilibrium equations given in Eq. (5). The derivatives of the element stiffness matrix will be contained. The element stiffness matrix is a function of the thickness variable and is generally a nonlinear function. Nevertheless, this derivative involves only the element in question for the thickness variable.

The flutter velocity and the frequency gradients with respect to the design variables can be written as[9]

$$V_{,i} = -\left(\frac{b\omega}{k^2}\right)K_{,i} - \left(\frac{b\omega^3}{2k}\right)\bar{\lambda}_{,i} \tag{10}$$

$$\lambda_{,i} = \frac{\left[\boldsymbol{p}^t(K_{,i} - \lambda M_{,i})\boldsymbol{q} - \lambda \boldsymbol{p}^t A_{,k}\,\boldsymbol{q}K_{,i}\right]}{\boldsymbol{p}^t(M + A)\boldsymbol{q}} \tag{11}$$

where $\lambda = \omega^2$, $\bar{\lambda} = 1/\omega^2$, and $\boldsymbol{p}^t$ is the left-hand eigenvector corresponding to $\boldsymbol{q}$. The key derivatives in Eqs. (10) and (11) are the element mass and the element stiffness matrices with respect to the design variables. The derivative of the aerodynamic matrix is with respect to the reduced frequency and not the design variables. The element mass matrix and stiffness matrix are functions of the thickness variable.

The MICRO-DOT algorithm[13,14] is used as the search technique in the optimization. This algorithm employs a technique wherein the bounds on the move direction are first determined and a polynomial interpolation technique is used to find the minimum within these bounds. The generality of mathematical programming algorithms is offset by the amount of computer resources required in their application. Some techniques can be employed to minimize the size of the optimization task, to wrest the maximum amount of usefulness out of each analysis of a particular design and to find balance between performing too many structural analyses and too few. Reference 15 provided the basis for many of the concepts.

Models for the Design Study

A wing model, which represented a typical fighter aircraft wing, was selected for the wing/store integration design study. This model should have an appropriate structural layout, as well as an aerodynamic configuration such as the thickness to chord ratio. If the tip store attachment is required, an appropriate structural arrangement of the internal structural members (spars, ribs) was necessary for modeling the store attachment. Figure 1 shows the ICW2001 model, which is a modified intermediate complexity wing model. The wing internal fuel was modeled to make a realistic wing configuration. In the present model, the fuel tank region was assumed to cover bays 3–8 between the leading-edge spar and the trailing-edge spar. Here, 80% of the usable volume was assumed, and JP-4 fuel, specific weight 48 lb/ft^3 (768.9 kg/m^3), was used, which yields 166 lb (75.3 kg) of fuel weight. The nonstructural mass items, which represent the weight of the out-of-wing-box structures plus miscellaneous structural weight (such as fastener, stiffeners, sealants, etc.), were also included.

An AIM-9 type missile was selected as the missile store. Public domain[16] data were used in the structural modeling. The missile geometry was assumed to be a cylinder with a hollow cross section. The wall thickness was assumed to be constant through the length. All of the weight including propellant and systems was assumed to be uniformly distributed in the cylinder. A missile model was constructed with a weight of 191 lb (86.6 kg), and the pitch and yaw mass moment of inertia was calculated as 45 slug-ft^2 (61 kg-m^2). The structural and aerodynamic model of the missile is shown in Fig. 2.

Effect of the Tip Missile

An ICW2001 wing plus a tip missile configuration was considered. A missile is attached to the ICW2001 model by locating its c.g. (assumed to be at the center of the missile span) at the 25% of tip chord. This locates the missile nose at 45.5 in. ahead of the tip leading edge. The missile launcher was not included. The aerodynamic model of this configuration is shown in Fig. 3.

For the dynamic analysis set selection of the missile model, a systematic observation was made of the analysis results from the various missile degrees of freedom. The effects on the flutter analysis results were examined by eliminating the missile analysis degrees of freedom that had no effect on the wing aerodynamics. The motions that change the local wing vertical attitudes will only affect the present wing aerodynamics model. The analyses set degrees of freedoms of the missile were finalized to be 3 and 5 (displacement in the z direction and rotation about the y axis). The wing root was fixed by constraining all of the root degrees of freedom.

The natural frequencies of first six modes generated by ASTROS* are shown in Table 1. The same analyses were done using MSC/NASTRAN. Comparisons were made with the ICW2001 model.

Figure 4 shows a comparison of the mode shapes of the ICW2001 and the tip missile configuration. The natural frequencies were generally lowered by the addition of a missile mass at the wing tip. Also a significantly different pattern of mode shapes was developed by the attachment of a missile at the wing tip. The first mode shows the first bending. The first torsion was very clearly isolated as the second mode, followed by the second bending mode. Compared to the ICW2001 results, the difference of the natural frequencies from the first to the second is very much reduced by the development of the torsional second mode.

A flutter analysis was made with an input Mach number of 0.8. A sea-level density ratio was used throughout the calculations. The effect of the missile attachment to the wing was considered in two ways. In the one case, the missile was considered as a mass item only. In this case, only the wing aerodynamic model was used for the

Table 1 Comparisons of natural frequencies between tip missile at 25% chord model and clean wing model

	Clean wing, Hz		Missile at 25% chord, Hz	
Mode	ASTROS	MSC/NASTRAN	ASTROS	MSC/NASTRAN
1	8.53	8.53	3.63	3.63
2	29.64	29.63	6.05	6.05
3	36.67	36.67	21.26	21.26
4	61.41	61.41	41.93	41.93
5	79.70	79.70	55.70	55.69
6	96.65	96.64	74.48	74.48

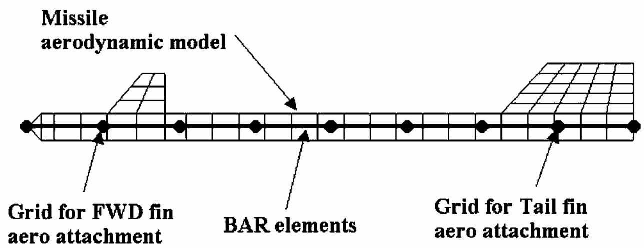


Fig. 2 Missile model (finite element and aerodynamic).

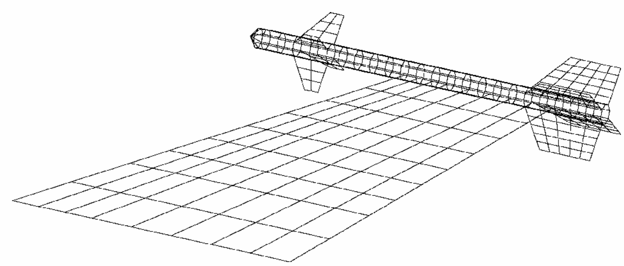


Fig. 3 Aerodynamic model of the ICW2001 wing plus tip missile configuration.

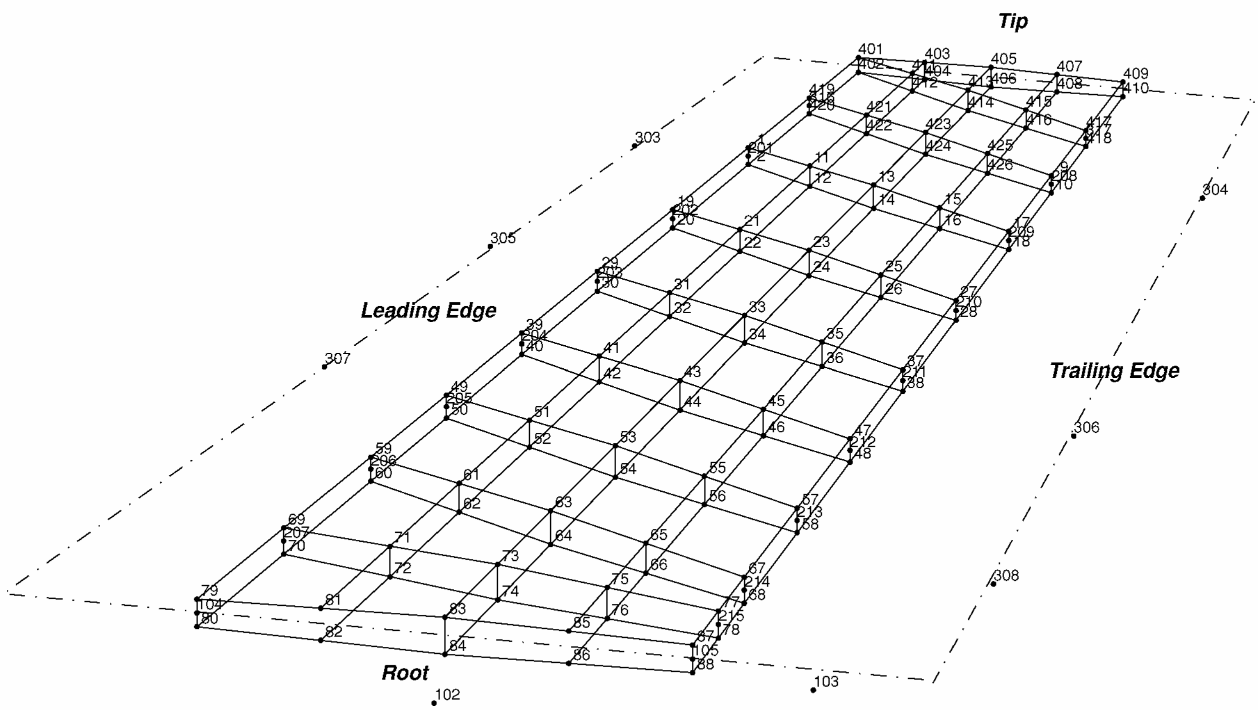
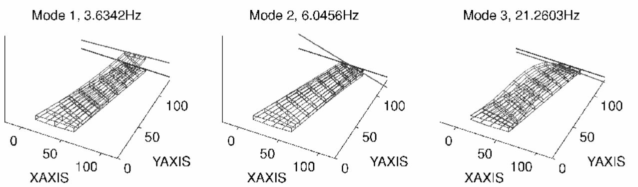


Fig. 1 Aerodynamic planform and the ICW2001 finite element model; planform data: semispan = 108 in., root chord = 90 in., tip chord = 46 in., leading-edge sweep = 30 deg, and maximum-thickness/chord = 4%.

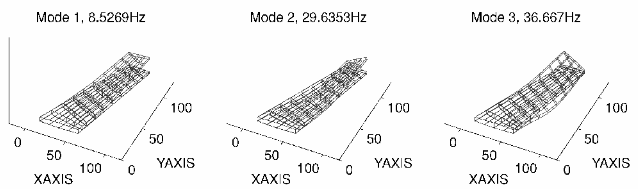
flutter analysis. The missile contributes mass and its own structural characteristics. In the other case, the aerodynamics of the missile was added in the flutter analysis. The effect of the missile aerodynamics on the wing was considered and vice versa.

Figure 5 shows the air speed vs damping and frequency for the ICW2001 and the tip missile configurations. The results from the p–k method are shown. Data for modes greater than the first four are not plotted for clarity. The slope of the V–g plots is very steep near the flutter crossing speed for the model without the store aerodynamics. These slopes become a little less pronounced for the models with the store aerodynamics, but still indicate a rapidly divergent type of behavior. For all of the cases, the frequencies of the first and second modes come together around these speeds.

As shown in Table 2, the flutter speeds and frequencies were significantly decreased by the attachment of the tip missile mass. The flutter speeds by ASTROS* were reduced by 26%. Store aerodynamics induces an additional decrease of the flutter speed. By the consideration of the store aerodynamics, the flutter speed was reduced by 17% from that of the missile mass only model. Notice



a) Wing plus tip missile configuration



b) Clean wing (ICW2001) configuration

Fig. 4 Mode shape comparisons of the ICW2001 with and without a wing tip missile.

that the Doublet-Lattice Method of MSC/NASTRAN always yields lower flutter speed than the ZONA aerodynamics.

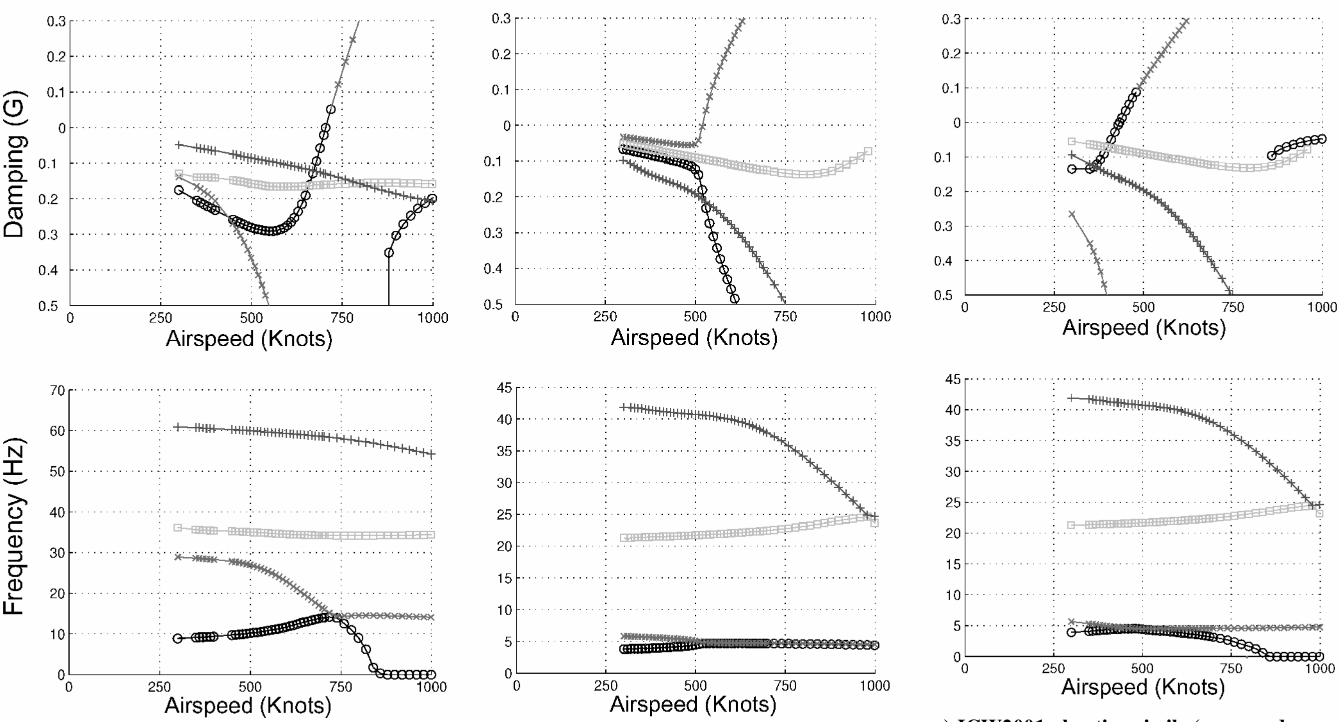
Optimization of the Wing Structure with a Tip Missile

Sample designs were made for two baseline tip missile configurations where the tip missile c.g. positions were at 0 and 25% of the tip chord, respectively. The wing structural model was optimized for each baseline configuration to satisfy stress and flutter constraints. A stress analysis was done with the static design loads that were calculated by a steady trim analysis. The flutter speed of the clean wing (705 kn) was used as the flutter constraint. The subsonic ($M = 0.8$) flight speed was used in the sample designs. The store aerodynamics was included throughout the optimization process.

Figure 6 shows an example of the changes in the optimized skin thickness from the clean wing to the wing with a tip missile. The skin-thickness distribution optimized for the clean wing configuration shows that the thickness was mostly determined by the minimum thickness constraints. Inboard of the trailing-edge spar region is the only area greater than the minimum thickness constraint. The skin-thickness distribution optimized for the tip missile at the 0% chord configuration shows that the skin panels forward of the wing root became thicker compared to the clean wing.

The missile positions were varied with the wing structural model optimized for the baseline tip missile configurations. Considered c.g. locations of the missile were −20, 0, 12.5, 25, and 50% of the tip chord. For all cases, the missile model was also varied with mass only and mass plus aerodynamics.

As shown in Fig. 7, for the tip missile at 25% chord baseline configuration, the flutter speed generally increased by the forward movement of the missile c.g. By the consideration of the store aerodynamics, the flutter speeds show a very steep increase for the missile positions forward of the baseline design configuration (25% tip chord). At the locations forward of the 0% chord, the aeroelastic instability type was changed from flutter to divergence and ended up with almost the same speed as the missile mass-only model. For the missile mass-only model, flutter was the aeroelastic instability type throughout the missile c.g. positions considered in the present study. The flutter speeds showed a relatively mild increase by the forward movement of the missile c.g. position. The flutter speed for the mass-only model was conservative in the 12.5% missile c.g.



a) ICW2001 **b) ICW2001 plus tip missile (mass)** **c) ICW2001 plus tip missile (mass and aerodynamics)**

Fig. 5 Airspeed vs damping and frequency for various configurations: ○, mode 1; ×, mode 2; □, mode 3; and +, mode 4.

Table 2 Flutter analysis results, ICW2001 model with and without a tip missile, tip missile at 25% chord, with input Mach number = 0.8

Model configurations	Flutter speed, kn		Frequency, Hz	
	ASTROS*	MSC/NASTRAN	ASTROS*	MSC/NASTRAN
ICW2001	705	692	14.0	14.2
With missile mass	520	507	4.8	5.0
With missile mass and aerodynamics	433	380	4.4	5.0

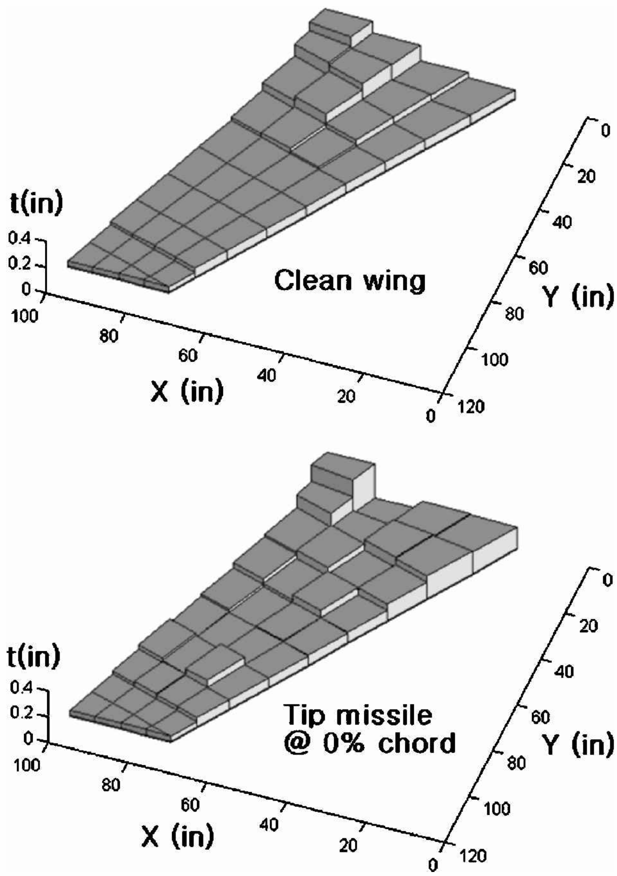


Fig. 6 Optimized thickness distributions, lower skin.

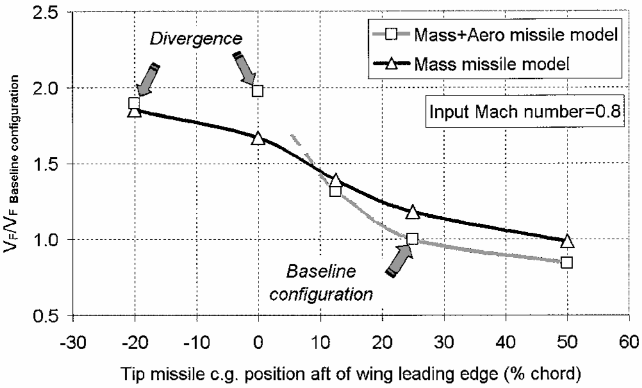


Fig. 7 Flutter speed for various tip missile c.g. positions; baseline configuration: tip missile at 25% of tip chord.

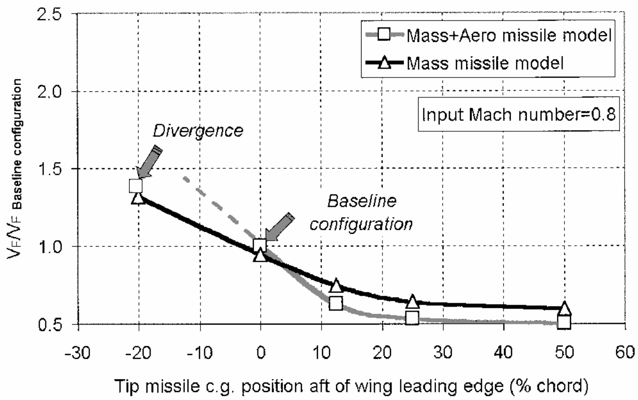


Fig. 8 Flutter speed for various tip missile c.g. positions; baseline configuration: tip missile at 0% of tip chord.

position and forward. For store positions aft the 12.5% chord, however, an analysis without store aerodynamics could not give us a safer prediction of the flutter speed.

As shown in Fig. 8, for the tip missile at 0% chord baseline configuration, the flutter speed generally increased by the forward movement of the missile c.g. Consideration of the store aerodynamics does not change the flutter speed sensitivity by store movement compared to the mass-only model. For the missile mass-only model, flutter is the aeroelastic instability type throughout the missile c.g. positions considered in the present study. The flutter speed from the mass-only model is conservative just forward of the baseline configuration. For the store positions aft the 0% chord, however, the store aerodynamics is required for a conservative prediction of the flutter speed.

The weight of the wing structure was not increased much by the missile installation at 0% of the tip chord. It is believed that the flutter speed is the most dominant factor for the wing structure resizing from the clean wing configuration to the tip missile configuration. The position of the missile mass forward of a certain position, which might be the elastic axis of the wing, would have a positive effect on the flutter speed. However, enormous additional weight was necessary to install the tip missile at 25% of the tip chord. The lost flutter speed by the tip missile attachment was recovered by increasing the structural member sizes.

Even though these two baseline store configurations may be extreme variant cases, the present results indicated that the designed weight of the wing structure is very much dependent on the tip store location of the baseline configuration. Once the baseline configuration is determined during the practical design procedure, a limited variation of the configuration is normally allowed to minimize the impact on the complete aircraft system. The flutter speed of the optimized wing is apparently sensitive to the store location changes. By the aft movement of 12.5% of the tip chord, the optimized wing for the 0% tip store will lose 36% of its flutter speed when the store aerodynamics were considered, whereas the optimized wing for the 25% tip store will lose 15% of its flutter speed by the 25% aft movement.

Store aerodynamics played an important role in the conservative flutter speed prediction when the wing structure was optimized. When the tip missile was moved aft from the 0% baseline configuration, a flutter analysis, using the mass-only store model, resulted in 20% higher flutter speeds than those from the store aerodynamics model.

Conclusions

By the use of a realistic wing and store model, this study focused on the influence of a wing tip missile on the design optimization of the wing structure. ASTROS was the primary tool used. ASTROS*, which is a special version of ASTROS with ZONA aerodynamics, was extensively used.

The focus of this study was to determine the influence of the store aerodynamics on aeroelastic behavior. The analysis results showed that the tip store aerodynamics of the present models reduced the wing flutter speed of a mass-only model when a tip missile was located at 25% of the tip chord.

The optimization capability of ASTROS was used to enhance the lost aeroelastic performance due to the presence of the store. The wing and store configurations at 0 and 25% of the tip chord were selected as the baseline configuration for the sample design study. The effect of a deviation from the baseline configuration was examined by changing the store c.g. locations at the wing tip. The effects on the aeroelastic instability were investigated for the wing and store models used in present study. Store modeling effects in terms of mass and aerodynamics were also assessed.

The present sample designs indicate that the tip missile aerodynamics should be included in the structural optimization. The configuration changes accompanied by the aft movement of the tip store should be examined in the flutter analyses. In these examinations, the store aerodynamics needs to be included unless the designed wing has a sufficient margin.

As a suggestion for future work, the present study should also be conducted in the transonic and supersonic speed regimes. Store separation issues need to be included to cover the comprehensive operational use of stores.

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