Effect of Stabilizer Dihedral and Static Lift on T-Tail Flutter

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The importance of stabilizer dihedral and static lift forces on T-tail flutter speeds is discussed. Based upon strip theory considerations the additional unsteady aerodynamic forces derived from these static forces are introduced into the generalized air forces of the system. The importance and introduction of structural deformations caused by such static forces also are considered. These effects are confirmed by the results of flutter tests on a low-speed flutter model.

Nomenclature

a	= aerodynamic center of section relative to midspan; fraction of local semichord
b	= local strip semichord
b_r	= reference chord
c	= strip chord
$C(k)$	= Theodorsen's function
C_ℓ	= section lift coefficient
$C_{\ell\beta}$	= stabilizer rolling moment due to yaw
k	= reduced frequency parameter $\omega b_r / V$
L_0	= static lift on strip
$L_{\dot{x}}$	= strip aerodynamic lift due to $\partial \dot{x}$
L_y	= aerodynamic side force on stabilizer aerodynamic strip due to roll angle
L_z	= total aerodynamic vertical force on stabilizer aerodyanamic strip
L_β	= lift on aerodynamic strip due to sideslip
S	= aerodynamic strip area
q	= dynamic pressure $\rho V^2/2$
V	= forward velocity
y	= spanwise coordinate
β	= sideslip angle
ΔX	= $y_2 - y_1$
ϕ	= roll angle of stabilizer aerodynamic strip
ρ	= density of air
ω	= frequency, rad
Ω	= sweep of quarter chord line
$\delta x, \delta y, \delta z$	= chordwise, lateral, and vertical displacement components of vibration mode
$\delta \dot{x}, \delta \dot{y}, \delta \dot{z}$	= chordwise, lateral, and vertical velocity components of vibration mode

Subscripts

1	= inboard edge of stabilizer strip
2	= outboard edge of stabilizer strip

Introduction

SINCE the introduction of T-tail aircraft designs, the dynamics engineer has been faced with a situation in which previously neglected parameters have assumed significant importance in the flutter stability of such configurations. The comprehensive work of Baldock,[1] following the loss of the Handley Page Victor from T-tail flutter, pointed out the destabilizing effect of stabilizer dihedral and static lift. As a result, during the flight testing of the aircraft the effect of stabilizer lift was studied by rerigging the ailerons to increase the required balancing tail loads. Later work by Land and Fox[2] also confirmed the destabilizing effect of dihedral at high Mach numbers. At this time it became common for T-tailed aircraft to have zero dihedral. However, in order to increase the T-tail flutter speed of the Boeing 727, negative stabilizer dihedral was employed. The effect of steady stabilizer lift forces more recently was investigated by McCue et al.[3] using a low-speed flutter model. From this work a method of including such effects into routine flutter analysis methods was proposed. In Japan, Ichikawa et al.[4-6] have pursued these effects but appear to have considered the effects of stabilizer dihedral and static lift forces to be interdependent.

At the present time The Boeing Company, engaged in the Advanced Military STOL Transport program, is building an aircraft with a very large and powerful T-tail (Fig. 1). The nature of this program is such that performance requirements impose limits on the aircraft's gross weight, which in turn lead to the desire for a minimum weight, strength-designed structure with no flutter penalty. To this end a stabilizer dihedral of $-4°$ has been employed to improve the T-tail flutter speed with a minimal weight penalty.

This paper reports some of the work that has been carried out to introduce the effects of stabilizer dihedral and stabilizer static lift into routine flutter analyses and calculate trends in agreement with experiment.

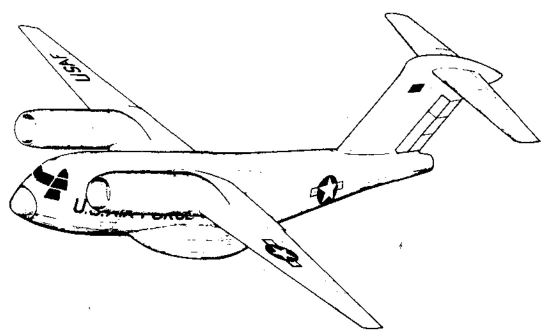

Fig. 1 Boeing AMST aircraft – YC-14.

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Theoretical Background

With the past work on T-tails having established stabilizer dihedral and static lift forces as powerful parameters, a basic understanding of these two effects was necessary. In addition, a means of introducing these effects into analytical methods was required to enable such effects to be analyzed rapidly during initial configuration studies.

Effect of Stabilizer Dihedral

Stabilizer dihedral affects both the structural vibration and aerodynamic characteristics of T-tail empennages. With dihedral, the geometric location of the stabilizer relative to the fin has changed. As a result, antisymmetric motions of the fin generate displacements and rotations both normal and parallel to the stabilizer chord plane. These changes result in small changes to the structural vibration modes of the system. With current analytical tools these effects readily are introduced.

Of greater significance is the change in the unsteady aerodynamic rolling moment generated on the stabilizer. With zero dihedral this rolling moment is developed from two influences: first, when the T-tail yaws, a pressure differential exists between either side of the fin that, acting upon the stabilizer, generates a rolling moment; and second, sideslip of the stabilizer in combination with a steady-state tail load produces an additional rolling moment. With increasing dihedral, the yawing of the fin generates an antisymmetric incidence on the stabilizer that introduces a further rolling moment. Using a simple three-dimensional strip theory aerodynamic program based upon the work of Ref. 7, the relative magnitude of the rolling moment due to dihedral for the fin and stabilizer combination in Fig. 2 is shown in Fig. 3.

The basic flutter mechanism of a T-tail is a combination of fundamental fin bending and torsion modes, and the phasing of modes is such that $C_{\ell\beta}$ provides a destabilizing moment. Hence, the use of negative dihedral in reducing this derivative increases the flutter speed of this mode.

Effect of Steady-State Stabilizer Airloads

In the present analysis, the stabilizer has been divided into a series of chordwise strips, with each strip carrying a steady lift-force distribution derived from the spanwise load distribution on the surface. Translational displacements of these panels cause no changes in the steady-state forces acting upon them, whereas angular displacements modify these forces.

Roll angle displacements of the strips cause a tilting of the steady lift vector that generates a lateral force component on each strip: $L_y = -L_0 \cdot \phi$.

Yaw displacements of the stabilizer cause additional lift forces to be generated due to the effective sideslip of the surface. Using the work of Queijo,[8] the lift on a strip due to sideslip may be expressed as

$$L_\beta = \beta\left[\tan\Omega \cdot L_0 - \tfrac{3}{4} q \int_{y_1}^{y_2} \frac{\mathrm{d}(cC_\ell)}{\mathrm{d}y} \cdot \mathrm{d}y\right]$$

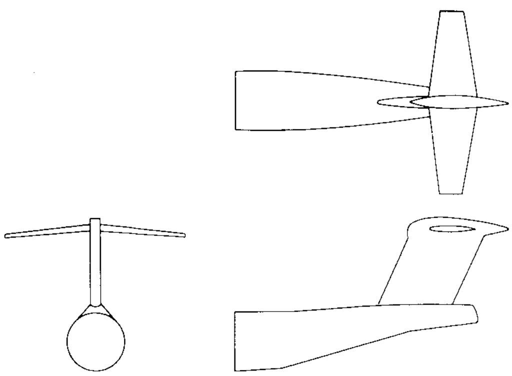

Fig. 2 Tail geometry.

which may reduced to

$$L_\beta = q \cdot \beta\left[\tan\Omega\,(c_l C_{\ell_l} + c_2 C_{\ell_2})\frac{\Delta X}{2} + \tfrac{3}{4}(c_l C_{\ell_l} - c_2 C_{\ell_2})\left(\frac{c_l + c_2}{2}\right)\right]$$

Pitch angle displacements cause changes in the lift forces acting on the strip that are calculated using standard nonsteady aerodynamic theories. Changes in the lift forces also are generated by the derivatives of these displacements with respect to time. Upon the streamwise velocity of the airstream is superimposed the chordwise velocity component of the vibration mode that causes an effective change in the local velocity of a strip and hence its lift,

$$L_0 + L_{\dot{x}} = \rho(V - \partial\dot{x})^2 SC_\ell/2$$

which, if second-order terms are neglected, can be reduced to give

$$L_{\dot{x}} = -qSC_\ell \cdot 2\delta\dot{x}/V$$

Velocity components $\delta\dot{y}$ and $\delta\dot{z}$ produce effective sideslip angles $\delta\dot{y}/V$ and incidence angles $\delta\dot{z}/V$ that are treated as in the previous cases for sideslip and pitch angle displacements.

In the final formulation of the forces, Theodorsen's functions are applied to those lift forces generated by the motions. Also, where force components are generated, their resulting moments are introduced into the final analysis. Therefore, collecting all of the contributions and converting the equation to the general form for oscillatory aerodynamic derivation, the following equations for each aerodynamic strip result in

$$b_r L_y = 2\rho b_r^3 \omega^2 \cdot \frac{L_0}{4q}\left(\frac{-\phi}{k^2}\right)$$

$$b_r L_z = 2\rho b_r^3 \omega^2 \cdot \frac{L_0}{4q} C(k)\left[\frac{-i}{k} \cdot \frac{2\delta x}{b_r}\right] + 2\rho b_r^3 \omega^2 \cdot C(k) \cdot \left[\tan\Omega \frac{L_0}{4q} + \frac{3}{16} \cdot \frac{L_s}{q}\right]\left[\frac{\beta}{k^2} + \frac{i\delta y}{k b_r}\right]$$

$$M_x = 0$$

$$M_y = -\left(\frac{b}{b_r}\right)(0.5 + a)\, b_r L_z$$

$$M_z = -\left(\frac{b}{b_r}\right)(0.5 + a)\, b_r L_y$$

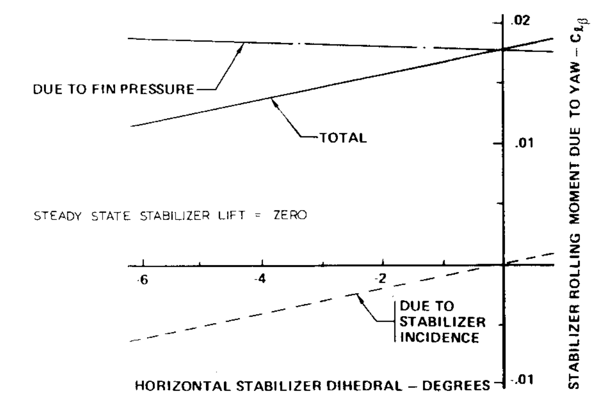

Fig. 3 Variation of stabilizer rolling moment due to yaw with stabilizer dihedral.

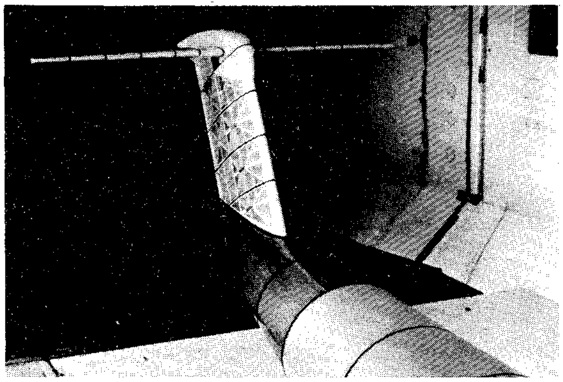

Fig. 4 YC-14 low-speed empennage flutter model.

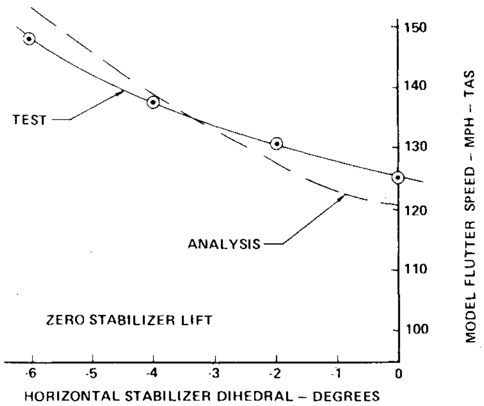

Fig. 5 Effect of stabilizer dihedral on T-tail flutter speed.

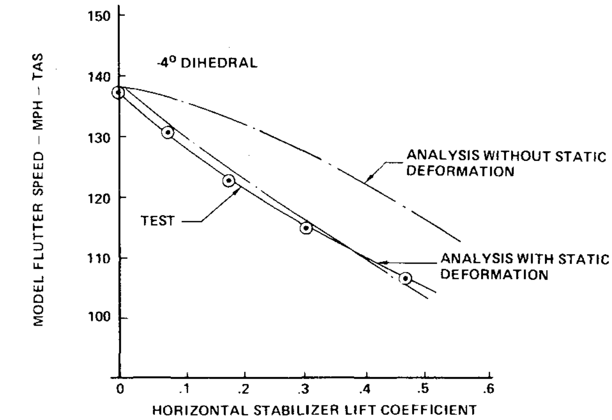

Fig. 6 Effect of stabilizer lift on T-tail flutter speed.

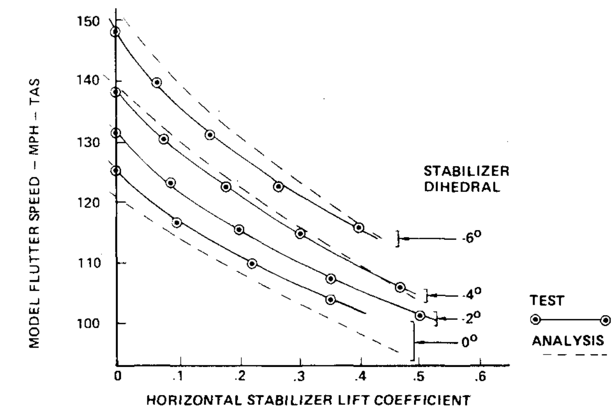

Fig. 7 Overall comparison of test and analysis results.

where

$$L_s(c_l C_{\ell_l} - c_2 C_{\ell_2})(c_l + c_2)/2$$

These aerodynamic forces acting through the vibration mode displacements of the surface provide additional aerodynamic energy that is added to the oscillatory aerodynamic forces calculated for the fin and stabilizer by conventional unsteady aerodynamic theories.

Static Deformation of the Stabilizer

In the initial studies the importance of this parameter was not recognized, but, as is discussed later, its importance was discovered in the experimental work. Two forces are present to modify the jig shape of the stabilizer: the mass of the stabilizer causes it to bend as a function of the local stabilizer load factor, and static airloads acting upon the stabilizer cause the stabilizer to bend. Both effects change the geometry of the stabilizer relative to the remainder of the aircraft. These displacements then cause small changes in the inertia coupling between the vibration modes. Of greater significance is the effect of the spanwise bending slope that, with a net uptail load, increases the dihedral angle of each aerodynamic panel on the stabilizer. Calculations therefore must be carried out to match the deformed stabilizer shape and the stabilizer lift coefficient at the flutter speed.

Experimental Studies

In order to validate the described analytical approach to analyze T-tail flutter, a low-speed flutter model was conducted. This model, (Fig. 4), representing the YC-14 empennage cantilevered at the wing rear spar, was built with a trimming stabilizer to allow the stabilizer incidence to be varied remotely. To measure the stabilizer lift forces, calibrated strain gages were used in the root of each half-stabilizer, so that by using these gages and the stabilizer trim mechanism a required value of stabilizer lift could be maintained during the flutter testing.

In order to investigate the effect of stabilizer lift forces, tests were made over a range of dihedral angles at a series of different values of stabilizer lift. Comparisons of the results of these tests with theoretical predictions are shown in Figs. 5 and 6.

Since initial analytical results indicated smaller speed reductions than did the test results, it became apparent that a further parameter dependent upon stabilizer lift was missing. Examination of photographs taken during the test showed that under the static airloads generated on the stabilizer considerable spanwise bending of the surface occurred. Calculation showed that at the higher lift coefficients, this bending increased the rigid dihedral angle by as much as 3° over the outer 75% of the stabilizer. The deformed shape of the stabilizer under the influence of mass and aerodynamic loading therefore was introduced into the analytical model to modify the geometric relationship of the stabilizer with respect to the fin and body. This resulted in a change in the modal displacements generated on the stabilizer by fin and body motions and an increase in the effective stabilizer dihedral angle. With this effect introduced, the comparison of the test and analysis results became very close. A further iteration for the effect of this stabilizer deformation on the static load distribution was not included in this analysis. Figure 7 is an overall comparison of test and analysis results over the full range of stabilizer coefficients and dihedral angles tested.

Conclusion

Recent tests have shown that, in the analysis of T-tail configurations, the discussed parameters can cause significant changes in the flutter speed of a design. The effect of static distortion in the flutter speed of a low-speed flutter model is magnified because of the relative flexibility of a model in comparison to the full-scale aircraft where the effects are reduced. However, if the objective of a flutter model test is to provide a means of validating analytical techniques, such effects should be included. Also, although the effects of static lift and distortion have been considered here for a T-tail, such effects could have significant effects on wings with large engine nacelles involving chordwise motion of the wing and nacelle.

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