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Flutter and Oscillatory Pressure Tests on a 727 Aileron in a Wind Tunnel

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This paper presents the subcritical flutter characteristics of a rigid, full-scale 727 wing segment with inboard aileron and tab that was tested in a low-speed wind tunnel. The airplane lateral control system was simulated, and testing was performed with and without the internal pressure balance panel. Subcritical damping characteristics of the binary flutter mode were measured for three cases of tab mass balance and compared with analyses. In addition, oscillatory pressures in the region of the control surface and aileron hinge moments were measured for a wide range of reduced frequencies. The flutter test confirmed the stability of a lightly damped aileron and tab flutter mode that had been identified analytically using doublet-lattice unsteady aerodynamics. The aileron and tab flutter mode was observed to reach a limit cycle amplitude in the wind tunnel. Correlation of test results with analysis was found to be dependent on the scaling of the aileron and tab aerodynamic derivatives. A qualitative agreement was found with the calculated oscillatory pressures and hinge moments.

Introduction

CONTROL surface flutter problems have always been of primary concern to the aeroelastician, and very often the surfaces contain a conservative amount of mass balance. However, using detailed analyses and tests, one can deviate from such a conservative design and reduce the control surface balance weight. An example of this is the 727 inboard aileron which was mass balanced with its center of gravity well ahead of the hinge line. As a part of a weight reduction program, the aileron mass balance was removed and the wing-aileron-tab system was reanalyzed for flutter. The results showed the airplane to be free of flutter to $1.2V_D$ with aileron mass balance removed. A flight flutter test of the airplane was conducted up to the V_D/M_D boundary to confirm this prediction. However, flutter analysis of a tab-rod failure case showed a marginally stable flutter root at a speed of 160 knots true airspeed (KTAS) at 16,000 ft altitude. The flutter mode was a two-degree-of-freedom aileron and tab instability and did not involve wing motion. Correction of the theoretical aerodynamic coefficients of the aileron and tab, using static wind-tunnel results, had a destabilizing effect on the flutter mode. Because of the conflicting analysis results, it was decided to conduct a test to confirm the flutter margin. A wind-tunnel test was selected over airplane flight test because of certain definite advantages. These advantages are fourfold:

1) The modes involved only aileron and tab rotations.

2) The flutter speed was within the range of low-speed tunnels.

3) Full-scale hardware was available from an airplane in storage.

4) Additional data under controlled conditions were obtained, including pressure measurements to evaluate the effect of the internal pressure balance panel and for parametric studies.

Subcritical flutter tests were conducted on the wind-tunnel flutter model using the transient test technique[1] with a transient random excitation.

The objectives of the test program were to 1) define the subcritical damping characteristics of the inboard aileron with power-on control system stiffness and a free tab; 2) study the effect of tab mass balance, internal pressure panel, and aileron control stiffness on the aileron-tab flutter mode; 3) and, as a secondary objective, obtain qualitative oscillatory pressures and the aileron and tab hinge moments as a function of speed, frequency, and aileron amplitude.

The aerodynamic balance of the 727 inboard aileron is obtained by an internal pressure panel hinged to the leading edge of the aileron and contained within the cavity of the wing trailing-edge structure. The external pressure due to control surface rotation, occurring at a gap slightly forward of the control surface hinge line, is vented into this cavity and results as a pressure difference across the internal panel. The pressure difference produces a balancing hinge moment on the control surface.

Experimental Apparatus and Test Procedure

Test Facility and Flutter Model

The wind-tunnel tests were conducted in the Convair low-speed tunnel at San Diego on a full-scale wing segment model including 727 production hardware. A schematic diagram of the test setup is shown in Fig. 1. The closed-circuit wind tunnel has a test section measuring 8×12 ft and a maximum speed of about 230 KTAS.

The test specimen consisted of hardware removed from the second production Boeing 727 airplane. This included the right-hand inboard aileron and tab assembly, the pressure balance panel and seals, a portion of wing rear spar and ribs supporting the aileron. Also a portion of the production aileron control system (quadrant and aileron rod) was used in the flutter model. The segment of the wing span was simulated ahead of the wing rear spar to establish the flow over the aileron and tab. The simulated wing segment had a constant leading-edge sweep angle equal to the average of the airplane basic and extended sweep angles. The wing trailing-edge sweep angle was constructed equal to the sweep of the aileron-tab trailing edge. The wing segment was designed to have a NACA 0010 symmetric cross section. A push-rod spring arrangement was designed to take the place of the hydraulic actuator and cable system of the airplane. The aileron rotational stiffness variation was accomplished by changing the spring stiffness on the push-rod assembly. Three sets of springs representing 100, 50, and 25% of the nominal aileron rotational frequency were tested in the tunnel.

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A spoiler was built into the wing section on each side, just forward of the rear spar, to suppress any flutter instability. The spoilers were deployed by a linear hydraulic actuator triggered by either the dynamic response of the tab or manually by the test crew. Activation of the spoiler also shut down the tunnel.

Instrumentation and Forcing Functions

The locations of the test measurements and transducers are shown in Fig. 2. The instrumentation system used to generate the input force, monitor the output signals, and record and process the necessary data for any given test condition is shown in Fig. 3.

For the subcritical flutter tests, excitation was provided by a Western Hydraulics 5400 in.-lb capacity servo-controlled actuator located at the hinge line of the aileron. A random signal was applied to the actuator for a selected period of time by a noise generator. The responses of the system were measured by rotary variable differential transducers (RVDT) at the aileron and tab hinge lines and by linear Enstran accelerometers on the aileron and tab trailing edges. Both the input and responses were recorded on a magnetic tape and selected signals were processed by an HP 5451B Fourier Analyzer.

For the oscillatory pressure measurements, a known sinusoidal moment was applied to the aileron continuously at selected frequencies. The aileron and tab rotations were measured by the RVDT's. The oscillatory pressures were measured by eight Kulite dynamic pressure transducers. The reference pressure for transducers P_1-P_7 was in the stagnation air beneath the tunnel floor. P_8 was a differential pressure transducer mounted across the internal pressure panel. The aileron hinge moment was measured by a torque cell mounted between the aileron and the rotary actuator. The tab hinge moment was measured by a strain gage bridge mounted on the tab lockout beam. The transducer signals were recorded on magnetic tape for all test runs.

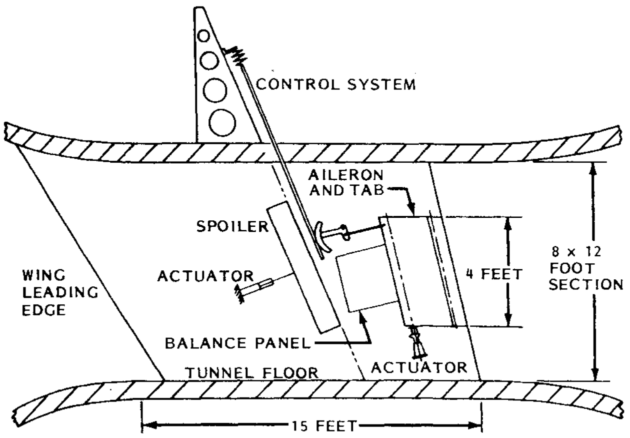

Fig. 1 Wind-tunnel test setup.

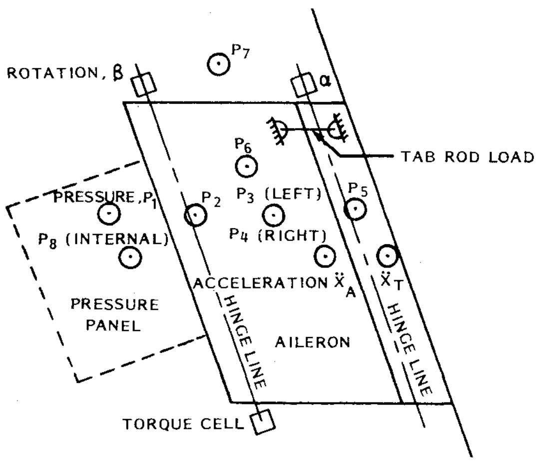

Fig. 2 Instrumentation locations.

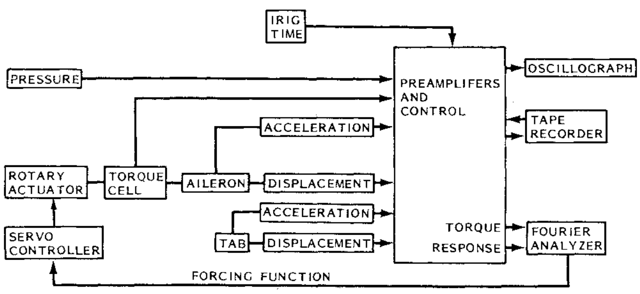

Fig. 3 Instrumentation block diagram.

Test Procedure

Preliminary tests were conducted to determine transducer sensitivities, to define the resonant frequencies of the three spring configurations, and to determine optimum controller settings for model excitation.

Subcritical testing of each aileron-tab configuration was conducted by applying a transient random force input to the aileron-tab system. For each tunnel speed, the transfer function between the response and input was calculated on line using the Fourier analyzer. Modal damping and frequency were calculated from the complex plane transfer function plot. Plots of these parameters as a function of tunnel speed were maintained to provide an indication of approaching instability.

Flutter testing for the selected configurations was conducted by disconnecting the aileron actuator and gradually increasing the tunnel speed until the point of impending flutter was reached or until the tunnel limit speed was reached. All the relevant data were recorded on tape. The above tests were conducted for configurations with and without aileron mass balance, different tab mass balance, and with and without the internal pressure panel.

Oscillatory pressure testing was conducted by removing the push-rod spring restraint on the control system and locking the tab at 0 deg with respect to the aileron. The desired tunnel conditions were established and the aileron was oscillated at various frequencies and amplitudes. Data from pressure transducers, the aileron RVDT, actuator torque cell, and strain gage on the tab beam were recorded on tape. The tests were repeated at other tunnel speeds and for control surface configurations with and without the internal pressure panel.

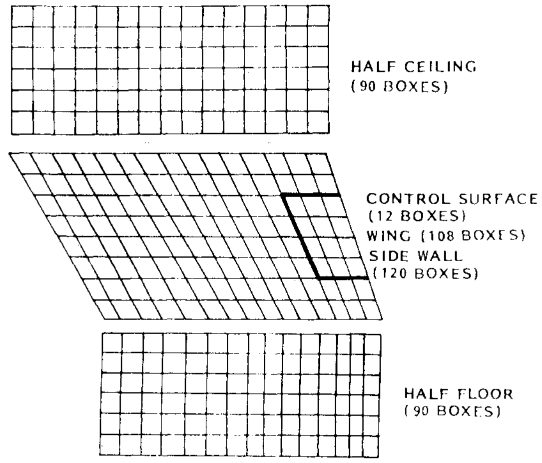

Fig. 4 Doublet box pattern.

Analytical Study

The analytical model used for the correlation study contained the segment of the wing with the inboard aileron and tab. The investigations were made using the ATLAS computing system.[2] The tab-rod failure case was reduced to a two-degree-of-freedom problem involving the aileron rotation and free tab rotation. Doublet-lattice unsteady aerodynamic theory[3] was used to obtain the unsteady pressures and generalized air forces on the system. The initial analysis was made for the 727 wing segment with six boxes on the control surface and without any wind-tunnel effects. The effect of box size was studied by increasing the number of control surface boxes to 35 and 140. The study yielded essentially the same results irrespective of the box size. Finally, the effect of wind-tunnel walls, ceiling, and floor was included in the analytical model. The box geometry used for this study is shown in Fig. 4. A total of 420 boxes was used in the analysis to represent one-half of the wind tunnel and the model aerodynamically. The doublet-lattice theory does not account for internal pressure panel effects and therefore two methods were used to modify the theoretical data to agree with previous static wind-tunnel test results. The first method involved scaling the aerodynamic data for all k values by the $k=0$ test to analysis ratio. For the second method, the aerodynamic paneling of the aileron and tab, forward of their hinge lines, was adjusted to match steady-state hinge moments.

Discussion of Results

The effect of aileron mass balance on the subcritical damping characteristics of the aileron-tab binary flutter mode is shown in Fig. 5. The characteristics show a similar trend for both configurations, and indicate the possibility of tab flutter instability in the absence of sufficient structural damping or control system friction. However, flutter did not occur at a wind-tunnel speed of up to 230 KTAS for either aileron mass balance configuration with the tab center of gravity at its aft production limit. The results show that the zero airspeed structural damping differed for the mass balanced and unbalanced aileron conditions. The lowest structural damping measured in the wind tunnel was 0.065, which was much lower than the 0.151 damping measured during the certification ground vibration test of the airplane conducted in 1962. Hence the probability of flutter occurrence was felt to be negligible for the tab-rod failure case. This supported the earlier decision to remove the mass balance from the inboard aileron.

The effect of tab mass balance on the damping characteristics of the flutter mode is shown in Fig. 6, where the symbols represent the subcritical test points. The fact that a flutter instability can occur for the unbalanced tab was confirmed by flutter testing. For the balanced tab, the subcritical damping curve indicates the possibility of a flutter

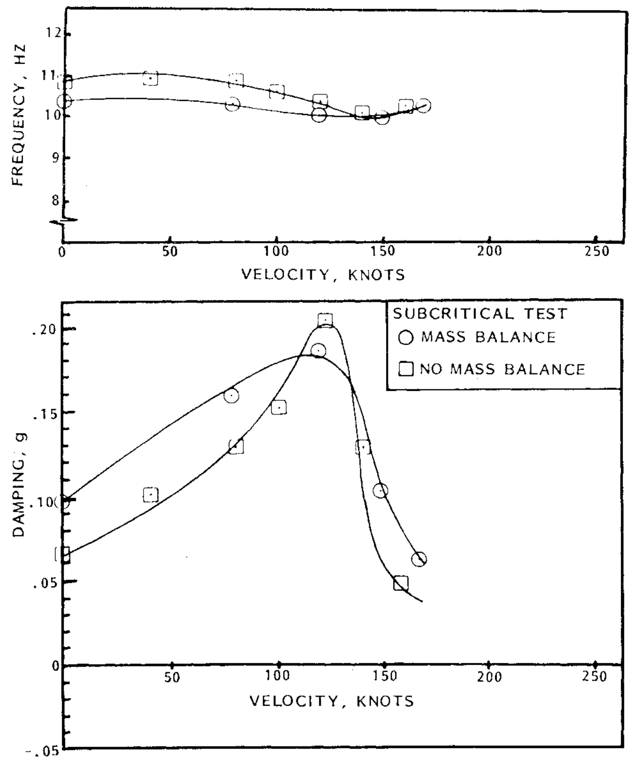

Fig. 5 Effect of aileron mass balance (internal pressure panel included).

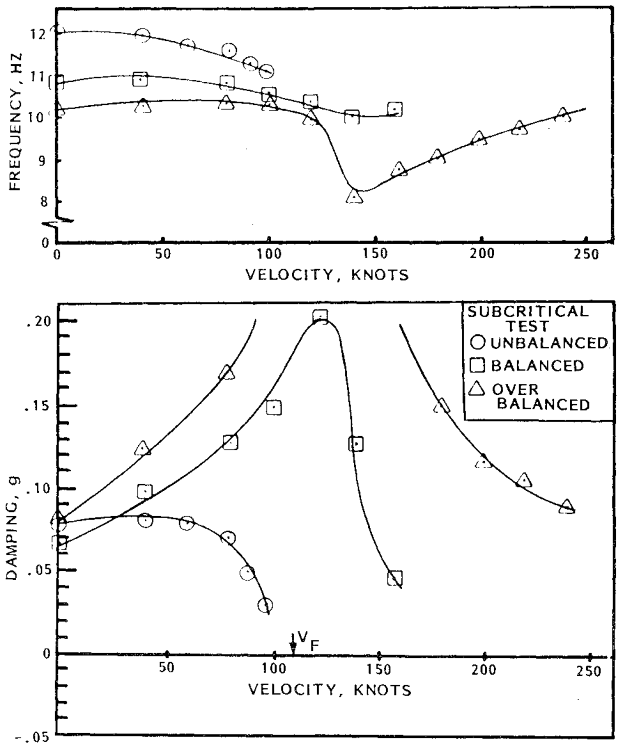

Fig. 6 Effect of tab mass balance (internal pressure panel included).

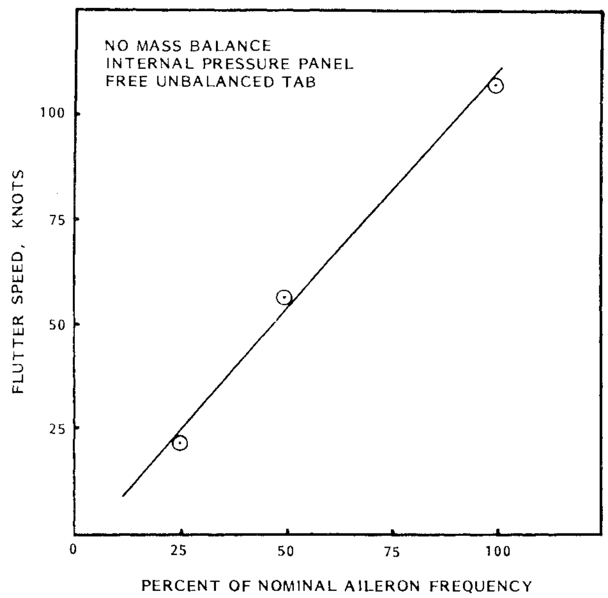

Fig. 7 Effect of aileron control system stiffness.

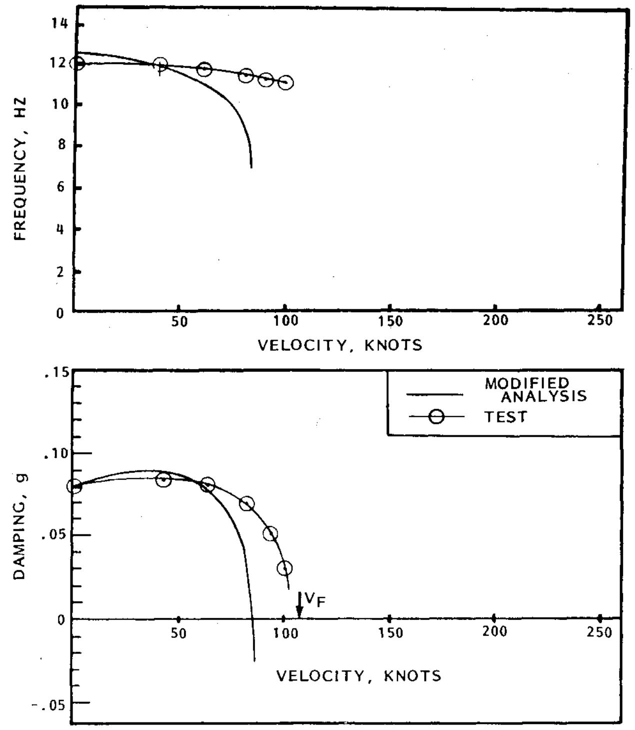

Fig. 8 Analysis and test results for unbalanced tab (internal pressure panel included).

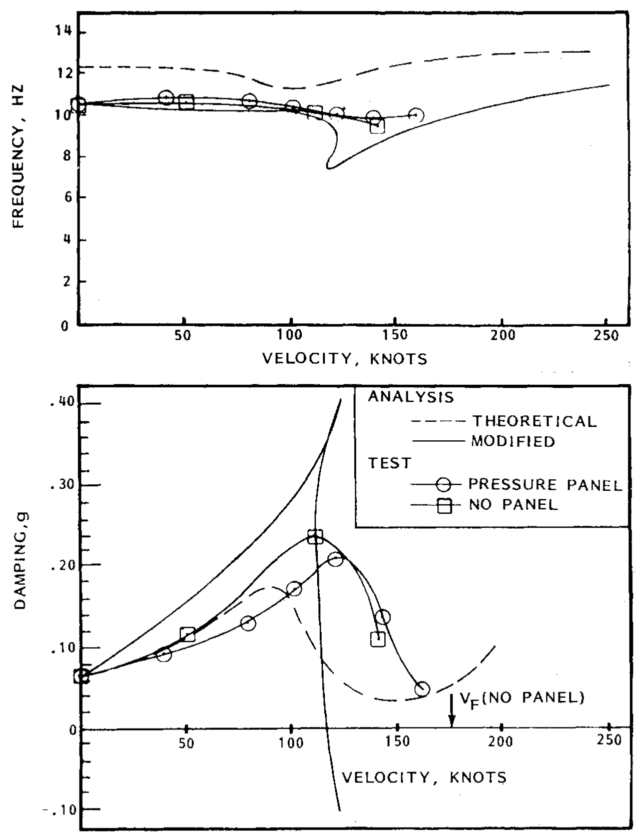

Fig. 9 Analysis and test results for balanced tab.

instability for low structural damping. However, this configuration was found to be free of flutter up to the tunnel limit of 230 KTAS. For the overbalanced tab condition, the aileron and tab would be stable even in the absence of structural damping in the system. This demonstrates that increasing the tab mass balance offers an alternative solution for the tab-rod

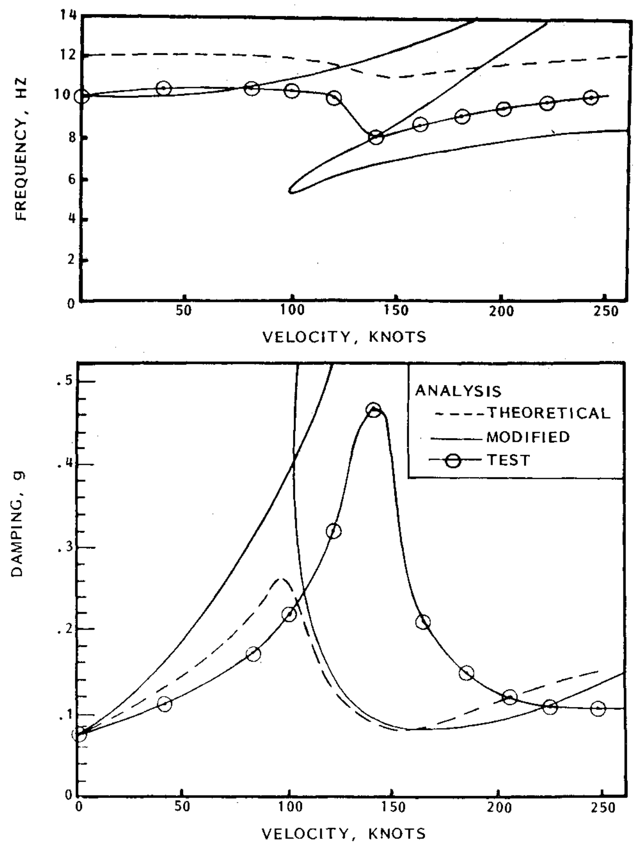

Fig. 10 Analysis and test results for overbalanced tab (internal pressure panel included).

failure case if the structural damping is insufficient to stabilize the system.

The control system stiffness has a significant effect on the flutter speed, as shown in Fig. 7. The flutter speed was found to be nearly proportional to the aileron rotational frequency. The nominal frequency represented control system power-on. The same flutter mode was shown by analysis to exist for power-off conditions but at a much lower frequency and speed.

Correlation of analytical and experimental results is shown in Figs. 8-10 for the three tab balance conditions. There is a reasonable agreement between the test and analysis for the unbalanced tab condition in Fig. 8. However, a greater change in the frequency was predicted in the vicinity of the flutter speed, and the predicted speed is lower than the test value.

In Fig. 9, the flutter analysis, using the theoretical aerodynamics, predicted a shallow flutter crossing in the absence of structural damping. Shifting the curve to match the measured zero airspeed structural damping resulted in a stable mode, as shown in the figure. However, modifying the unsteady aerodynamic derivatives to match static wind-tunnel values had a large destabilizing influence on the flutter mode. This sensitivity was due mainly to the change in the tab and coupled aileron-tab aerodynamic derivatives. Subcritical testing confirmed the general character of the flutter mode and showed a reduction in damping to below the zero airspeed damping level. However, flutter testing showed the aileron configuration with the internal pressure panel to be stable up to the tunnel speed of 230 KTAS. With the pressure panel removed, a mild aileron-tab flutter was encountered at about 175 knots. The mild flutter was apparently due to the reduction in damping with the panel removed. It should be noted that the aileron frequency used in the theoretical analysis was 12.3 Hz, as measured on the airplane. In the wind tunnel, however, this frequency was found to be 10.7

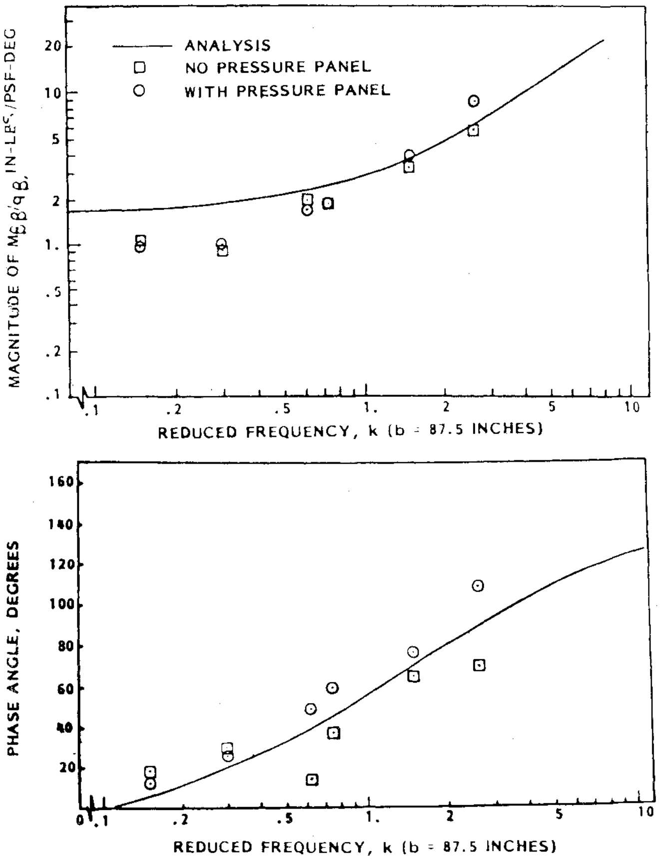

Fig. 11 Effect of reduced frequency on aileron hinge moment.

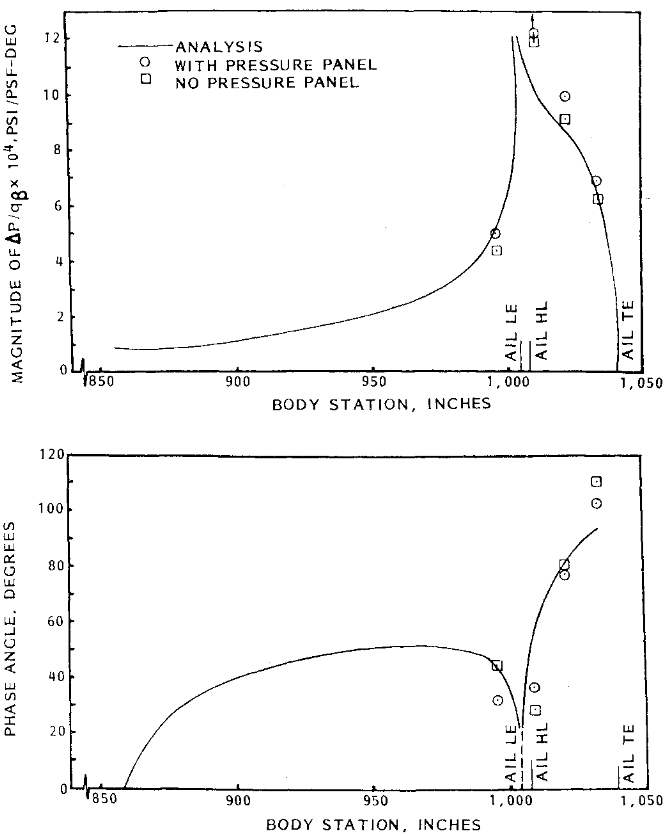

Fig. 13 Pressure loading at wing station 267.3 due to aileron rotation, $k = 0.508$.

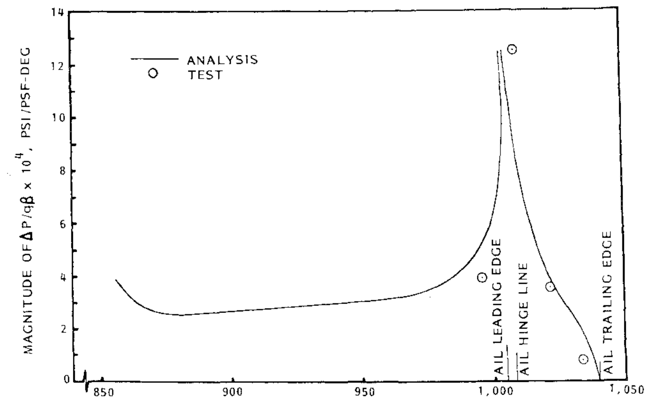

Fig. 12 Pressure loading at wing station 267.3 due to aileron rotation, $k = 0.0$.

Hz. The reduction in frequency was due to the added inertia of the simulated control system. In the modified analysis, zero airspeed frequency was tuned in addition to the modification of the aerodynamics.

Test and analytical results for the overbalanced tab configuration presented in Fig. 10 do not show the existence of flutter even in the absence of structural damping. The analytical curve shows the presence of a loop, indicating the nonuniqueness of the v-g type solution, which is not uncommon in flutter analyses.

The hinge moments measured during the aileron oscillation tests are shown in Fig. 11, along with the analytical results. The theoretical aileron hinge moment was adjusted to match the $k = 0$ value obtained from an earlier scaled wind-tunnel static pressure test. The data presented are for frequencies between 1 and 5 Hz. The test data for higher frequencies (10-18 Hz) seemed to exhibit a nonlinear behavior of the system and the results are not presented. The test data show a fair amount of scatter and the hinge moment for low reduced frequencies does not appear to approach the previous static test value. The data presented show that the magnitude of the hinge moment increases with increases in k value. Overall, there is a good qualitative agreement of both magnitude and phase between the test and analysis for $k > 0.5$. The test data do not show significant differences in hinge moment between the configurations with and without the internal balance panel except at higher values of k.

Analytical and experimental chordwise pressure distributions across the control surface are shown in Figs. 12 and 13 for $k = 0$ and 0.508. The distributions are along wing buttock line station 267.3. The results show a reasonable agreement between theory and test, except in the region close to the hinge line, where a large pressure gradient exists.

The doublet-lattice method used in the analysis did not represent the internal pressure panel. In order to provide test data in support of development of an algorithm which accounts for the balance panel characteristics, the oscillatory pressure on the panel was measured and compared with the external control surface pressure. The measured pressure loadings on the panel, P_8, and at control surface point, P_3, are shown in Fig. 14. The pressure magnitude on the panel is slightly less than at P_3 for values of $k < 0.5$ and slightly greater for $k > 0.5$. Within the range of data scatter, the phase is about the same at both points for all values of k. The data indicate that it is not unreasonable to assume for flutter analysis computations that the pressure loading on the panel is equal to the pressure at a point, P_3, on the control surface. Based on this assumption, a computer code is under development to include internal balance panel effects in the doublet-lattice program.

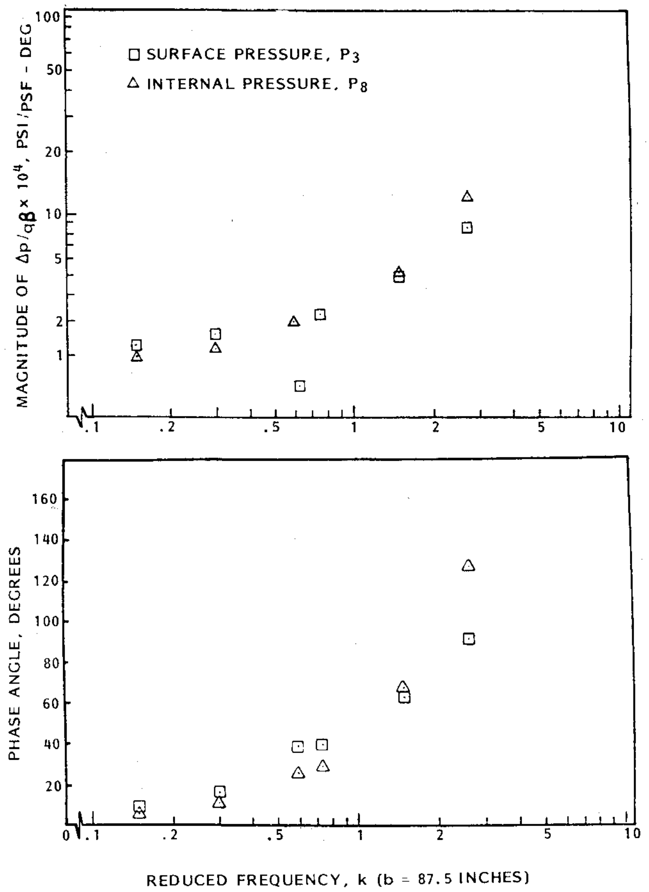

Fig. 14 Effect of reduced frequency on pressure loading at P_3 and P_8.

Summary

1) The aileron and tab with failed tab-rod was found to be free from flutter with or without balance weights on the aileron.

2) There was a significant effect of tab mass balance on the flutter stability of the aileron-tab system.

3) The flutter speed was sensitive to the control system stiffness and, to a lesser degree, the removal of the internal pressure balance panel.

4) General agreement was found between the theoretical and experimental aileron hinge moments and pressure distributions. However, there was poor correlation between the test and predicted flutter speeds using modified aerodynamics. The source of the disagreement appears to be in modifying the aileron and tab aerodynamic derivatives.

5) The measured pressure loading magnitude on the internal pressure balance panel increased with reduced frequency and was found to be approximately equal to that measured at a control point on the external surface of the aileron.

References

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