Aeroelastic Considerations in the Design of Variable Sweep Aeroplanes

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ABSTRACT

Theoretical analyses and experimental results on variable geometry aircraft models are presented to identify the important parameters affecting flutter characteristics. Effects of wing and tail sweep, pivot free play, pivot stiffness, and possible wing-empennage coupling are discussed. The possibility of an unexpected antisymmetrical flutter mode with the wing aft is discussed in the light of experimental data illustrating the reality of the problem. Unsuccessful attempts to provide theoretical prediction of the unexpected phenomenon are also discussed. Results of wind tunnel flutter model tests are presented to evaluate the effects of the critical parameter variations. Comparison of the test data with the theoretical analyses are presented.

1. INTRODUCTION

Since man first thought of flying, variable geometry has been known to offer advantages. In fact, some of man's early unsuccessful attempts to fly used variable geometry surfaces. In 1903, the Wright brothers flew a machine that incorporated certain elements of variable geometry in terms of warping of the wing and variation in control surfaces. Hinged control surfaces, retractable landing gear and leading and trailing edge high-lift devices are examples of variable geometry used in aircraft design. Supersonic flight requires low aspect ratio and highly swept wings. The desire to retain the subsonic efficiency of lower sweeps and higher aspect ratios suggest the in-flight variable sweeping wing. However, the inherent complexities of variable sweep have, until recently, prevented the successful development of such an aircraft.

The F.111, presently in production in the United States, has demonstrated the feasibility of the variable sweep concept. Further studies evaluating variable sweep applications for fighters, bombers, and transport aircraft are in progress. The primary reason for variable sweep surfaces is versatility of performance. Lower sweep angles provide the high lift required for take-off, landing and long range. High sweep angles reduce drag for high speed flight. The higher flutter speeds resulting from increased sweep angles complement the intended use of the variable sweep aeroplanes. However, aeroelastic problems do exist and flutter considerations can influence the design.

An obvious problem in defining flutter characteristics is the large number of combinations of wing sweep, fuel loadings, store locations, etc. A major concern is the development of an adequate pivot and bearing system to withstand the large concentrated structural loads produced by the main lifting surface. The effect of the pivot and bearing flexibility on the flutter speed is a problem unique to variable sweep surfaces. Also, free play in the pivot and bearings must be considered in the flutter investigations.

Variable sweep generally results in improved flutter characteristics. However, the flutter speed can be seriously degraded by coupling between the wing and empennage for some planform, frequency and mode shape combinations. Unsteady aerodynamic interaction exists with the wing in the aft sweep position in close proximity to the horizontal tail. The airframe frequencies and mode shapes continually change from the forward to the aft sweep position. This increases the probability of a detrimental elastic coupling.

The following discussion presents some results of investigations covering the above problems, and possible solutions for minimising flutter penalties for variable sweep aeroplanes are suggested.

SYMBOLS

$b/2$ exposed horizontal tail semispan

k reduced frequency

$L_i^{h_i}$ unsteady lift coefficient due to surface translation

$L_i^{\alpha_i}$ unsteady lift coefficient due to surface pitching

$M_i^{h_i}$ unsteady moment coefficient due to surface translation

$M_i^{\alpha_i}$ unsteady moment coefficient due to surface pitching

V_F flutter speed

V_R flutter speed at forward sweep angle

Subscripts

W wing

T horizontal tail

2. Flutter Trends

The flutter trends presented were obtained from both analytical and experimental studies. To allow easy comparison, all flutter speeds are normalised on the flutter speed of the most forward sweep angle (V_R).

Analytical methods

All theoretical analyses were accomplished using a high speed digital computer. Between 7 and 15 of the most significant modes of vibration were used in the theoretical calculations. Vibration analyses utilised the elastic axis-lumped mass concept. Three unsteady aerodynamic theories were used in the analyses: (i) the well-known incompressible strip theory[(1)] was extensively used for trend studies; (ii) the accurate compressible flow finite span theory[(2)] provided unsteady aerodynamic theory where strip theory was not applicable; and (iii) finite span theory[(3)] was used to predict the flutter speed in the supersonic regions. The flutter determinant was solved for both eigenvalues and eigenvectors.

Experimental methods

Experimental work was accomplished in a low speed, continuous flow wind tunnel. A complete, dynamically scaled flutter model was designed and fabricated simulating flexible wing, fuselage, and empennage geometry, stiffness and inertias. The model was mounted in the tunnel on a flexible rod allowing freedom in vertical translation, pitch, roll and yaw, as shown in Fig. 1. The model was flown in the tunnel by pitch control of the horizontal stabilisers. The speed of the wind tunnel was increased until flutter was encountered. At the onset of flutter, accelerometer data were recorded and high speed movies were taken.

Effects of sweep and compressibility

The first task was to determine the effect on flutter speed due to different sweep angles of the wing. A well organised plan and computer programmes permit rapid completion of the large number of analyses required of a variable sweep wing. Also, flutter models can be designed such that rapid sweep changes can be made in the wind tunnel. A sketch showing a typical variable sweep configuration is shown in Fig. 2.

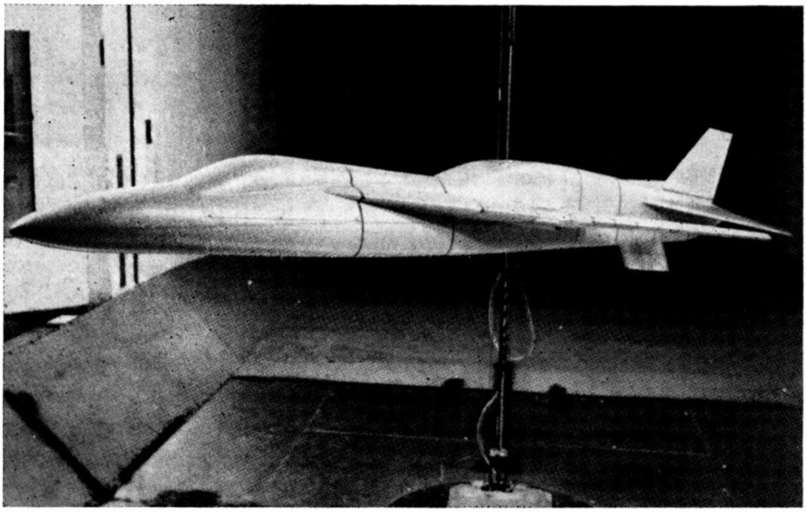

FIG. 1 — Low-speed flutter model

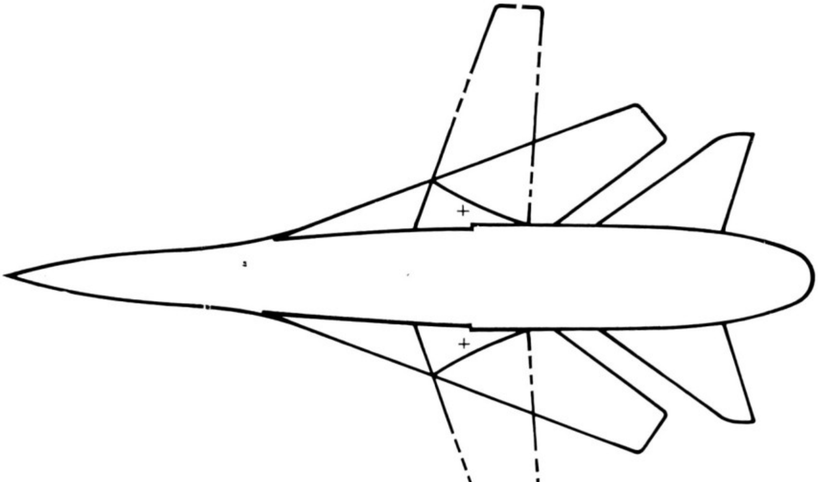

FIG. 2 — Variable sweep aircraft planform

As mentioned previously, past experience with swept-back fixed wings indicates that larger sweep angles are beneficial to the flutter speed. The theoretical trends of Fig. 3 show that indeed this is the case for variable

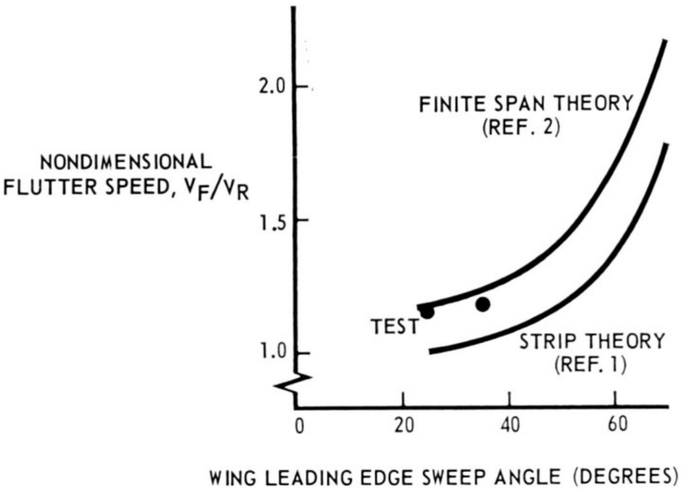

FIG. 3 — Effect of sweepback

sweep wings. Dynamically scaled model wind tunnel test data produce the same trends if a coupling between the wing and empennage does not exist. It can be seen that a relatively rapid increase in flutter speed is obtained by sweeping the wing from the forward to the aft position. The flutter speed for the aft position is almost double that for the forward position, complementing the intended aeroplane use.

Figure 3 presents the wing stability boundaries based on oscillating aerodynamics, using both incompressible strip theory and compressible lifting surface theory. These trends are generally the same, indicating that sweepback is the predominant aerodynamic parameter affecting the flutter speed. The wind tunnel test points show good agreement between the finite span theory and experimental values. In all cases the flutter mode was predominantly bending-torsion motion of the section outboard of the pivot.

Additionally, the trends due to varying stiffness and mass of a variable sweep wing exhibit the same characteristics as a fixed sweep wing. Centre of gravity location has virtually no effect on the flutter speed at 70° sweep. However, at the more forward positions, moving the centre of gravity aft lowers the flutter speed.

The effect of compressibility on flutter speed is shown in Fig. 4. The forward sweep position is intended for subsonic flight only and approximately

10% compressibility effect was found. Throughout the subsonic region the aft position flutter speed is nearly double the speed of the forward position. The rate of increase of supersonic flutter speed is strongly dependent on Mach number, a characteristic of highly swept surfaces.

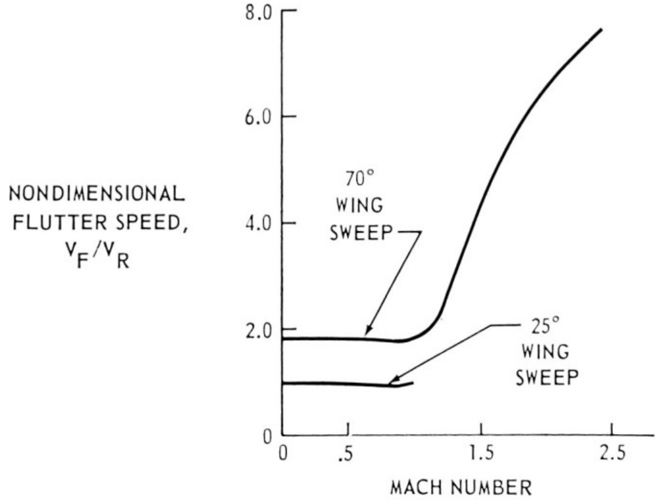

FIG. 4 — Effect of compressibility

Effects of pivot stiffness and free play

Successful performance of a variable sweep aeroplane depends heavily on the design of the wing pivot and bearing system. It is necessary for the pivot to have the ability to carry the structural loading efficiently through a confined space. The salient features of typical pivot and bearing systems are shown in the sketch of Fig. 5. Thrust and shear loads on the outer wing are reacted by spherical bearings at the pivot. This arrangement results in additional flexibility in the local area about the pivot. Rotational deflections can occur about any axis in the plane of the bearing.

Rotational deflections are treated as two additional degrees of freedom in the equations of wing motion, namely pitch and roll. Effects of these two degrees of freedom are determined separately, as well as in combination. Pivot stiffness values include the contributions of the lugs, the support structure and carry-through structure. Roll stiffness does not have a significant effect on flutter speeds for any of the three sweep angles shown in Fig. 6, but the data of Fig. 7 show the flutter speed to be quite dependent upon pitch stiffness. As the stiffness is reduced below the design value, the flutter speed is significantly reduced; however, as the stiffness is increased above the design

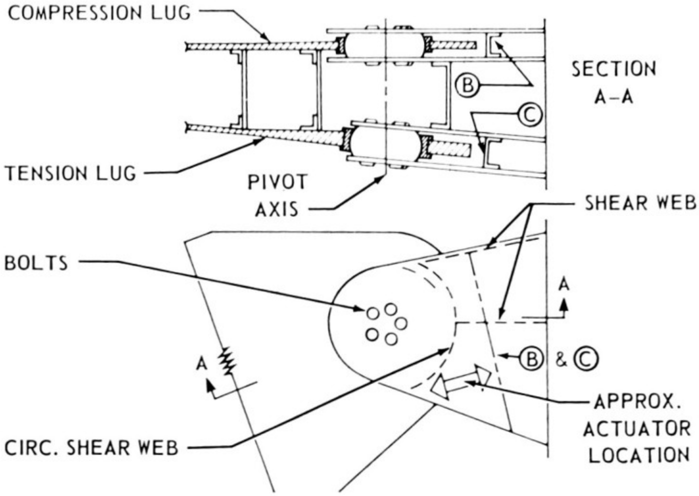

FIG. 5 — Typical pivot detail

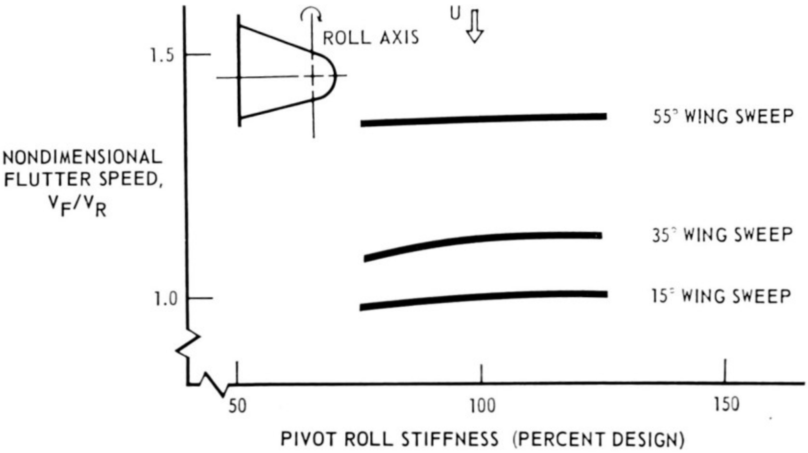

FIG. 6 — Effect of pivot roll stiffness

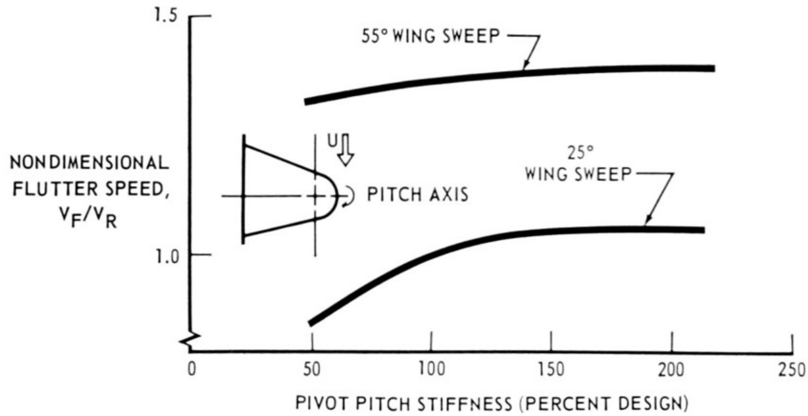

FIG. 7 — Effect of pitch stiffness

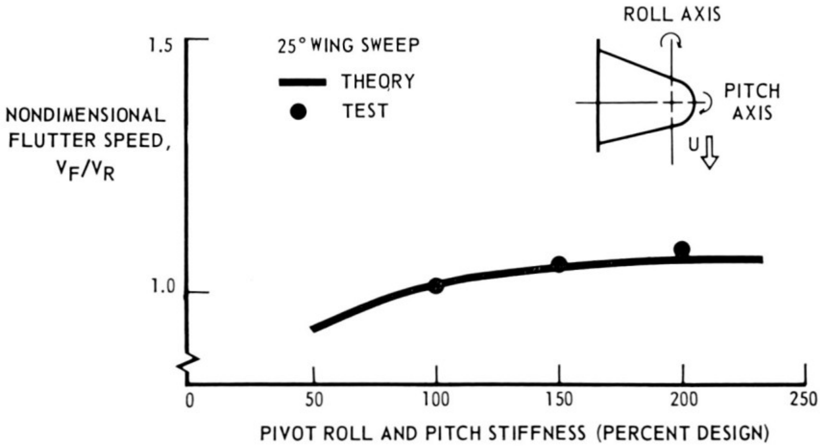

FIG. 8 — Effect of pivot roll and pitch stiffness

value, the flutter speed levels off, since the flexibility of the outboard wing becomes dominant. Simultaneous variations in roll and pitch stiffness are shown in Fig. 8 and have an effect similar to the pitch stiffness alone. Thus it is apparent that care must be taken in the pivot and bearing design to ensure that adequate stiffness is provided.

A potential problem with any moving part is free play that may develop between bearing surfaces caused by wear, manufacturing tolerance, temperature gradients, etc. For considerations other than flutter, design care is taken to keep the free play to a minimum. However, experimental flutter studies were conducted to evaluate the effect of ± 1 degree free play about the pitch and roll axes. Data of Fig. 9 show that the flutter speed was lowered

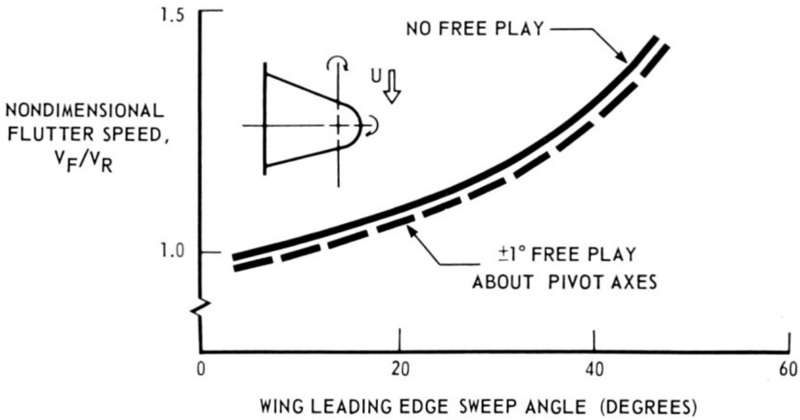

FIG. 9 — Effect of pivot free play

less than 2% by the free play. This amount of free play would never be allowed to exist on an actual flight vehicle having normal inspection necessary to minimise any bearing spalling effects. Since the reduction in flutter speed is negligible, it is not considered to be a critical problem area in defining the stability boundaries.

Effect of wing-empennage coupling

An area of concern with variable sweep aeroplanes is the effect on flutter speeds due to aerodynamic interaction and elastic coupling between the wing and empennage.

Digital computing programmes defining the theoretical unsteady aerodynamic interaction between two separate surfaces are not yet complete. Some assumptions, such as relative location of surfaces, have been required to obtain a theoretical aerodynamic solution. Theory for determining the elastic coupling between the wing and empennage is well developed. However, collecting the large amount of input data and performing the large number of calculations required to define adequately the dynamic characteristics of the wing, fuselage and empennage are time consuming. Therefore, most of the studies conducted up to the present time have been experimental, utilising wind tunnel models.

Aerodynamic interaction is important when the motion of one surface causes significant unsteady forces on the other surface. This can be illustrated in the matrix of Fig. 10. The principal terms for the wing are the four coefficients in the upper left-hand corner and, for the horizontal tail, are the four coefficients in the lower right-hand corner. The interaction terms are the remaining eight coefficients, which give the unsteady forces on one surface

	WING TRANSLATION	WING PITCHING	HORIZONTAL TAIL TRANSLATION	HORIZONTAL TAIL PITCHING
WING LIFT COEFFICIENT	$L_W^{h_W}$	$L_W^{\alpha_W}$	$L_W^{h_T}$	$L_W^{\alpha_T}$ — $L_W^{\alpha_T} \stackrel{?}{=} 0$
WING MOMENT COEFFICIENT	$M_W^{h_W}$	$M_W^{\alpha_W}$	$M_W^{h_T}$	$M_W^{\alpha_T}$
HORIZONTAL TAIL LIFT COEFFICIENT	$L_T^{h_W}$	$L_T^{\alpha_W}$	$L_T^{h_T}$	$L_T^{\alpha_T}$
HORIZONTAL TAIL MOMENT COEFFICIENT	$M_T^{h_W}$	$M_T^{\alpha_W}$	$M_T^{h_T}$	$M_T^{\alpha_T}$

FIG. 10 — Total air force coefficient matrix

caused by the vibratory motion of the other surface. Past practice has been to assume the interaction unsteady forces to be zero. The question to be answered, then, is 'Is this aerodynamic interaction sufficiently small to be considered zero for all positions of a variable sweep wing?' For example, from Fig. 10, is $L_W^{\alpha T} = 0$?

Theoretical and experimental studies were undertaken to answer this question. Dual two-dimensional surfaces were tested in the wind-tunnel as shown in Fig. 11. One surface was driven sinusoidally in either pure pitching or pure plunging motion, while the unsteady forces and moments of the other surface were recorded. Wind velocity, frequency of motion and the location of one surface with respect to the other were varied during the study.

The interaction for unsteady lift on the wing due to pitching motion of the horizontal tail, $L_W^{\alpha T}$, is shown in Fig. 12 for the wing trailing edge located very near the horizontal tail leading edge. For comparison, the dashed line represents the corresponding principal term, $L_W^{\alpha W}$, for the unsteady lift on the wind due to pitching motion of the wing. Both theory and test show that the unsteady lift on the wing due to horizontal tail pitching motion is approximately the same magnitude as the lift due to wing pitching motion, rather than being negligible as has been assumed in the past. This is generally true for the other combinations of surface forces and motion. As the gap between the two surfaces is increased, the interaction decreases rapidly.

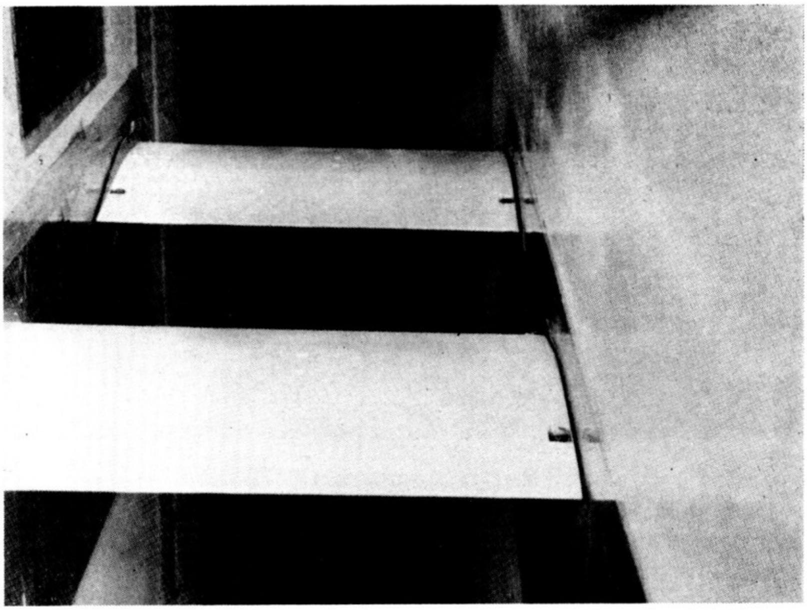

FIG. 11 — Two-dimensional wind tunnel test configuration

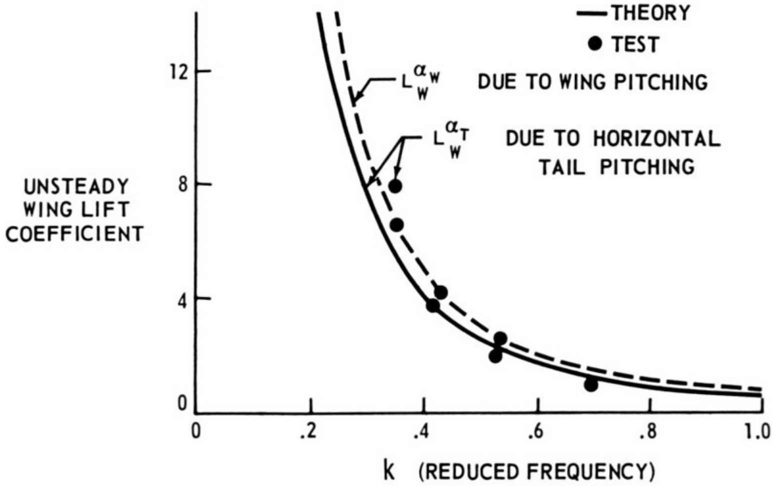

FIG. 12 — Effect of aerodynamic interaction

Detrimental elastic coupling has been known to exist on some fixed-wing aircraft, but the possibility of this type of coupling increases with variable sweep aircraft since the wing frequencies and mode shapes continually change with sweep angle.

Investigation of aerodynamic interaction and elastic coupling between wing and empennage requires a complete dynamic simulation of the aeroplane. Complete, dynamically scaled flutter models were tested and for certain wing-fuselage-empennage relationships detrimental coupling was shown to exist. We have seen the effect of sweep, considering only the primary or wing surface, in Fig. 3. Figure 13 shows the results of coupling on one configuration

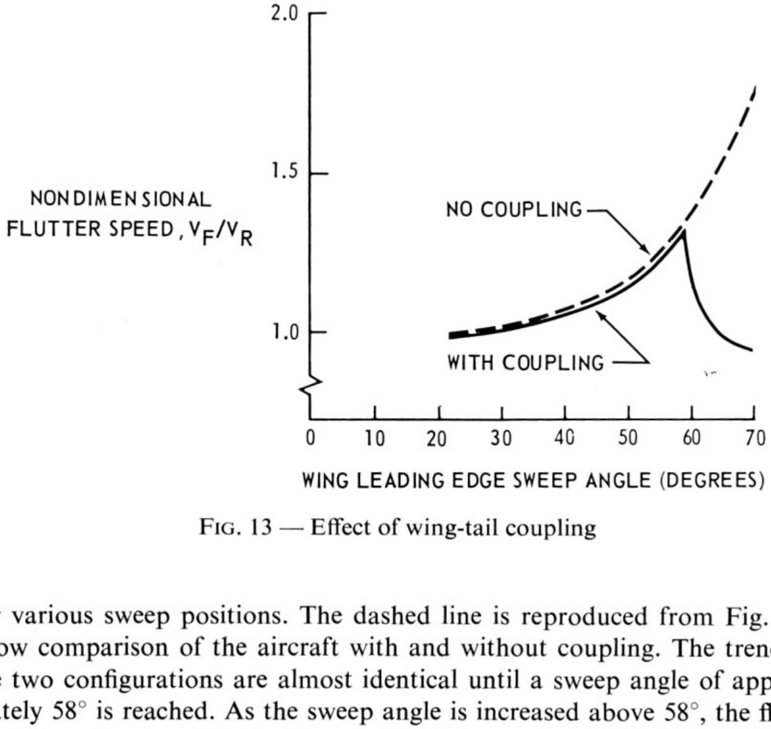

FIG. 13 — Effect of wing-tail coupling

for various sweep positions. The dashed line is reproduced from Fig. 3 to allow comparison of the aircraft with and without coupling. The trends of the two configurations are almost identical until a sweep angle of approximately 58° is reached. As the sweep angle is increased above 58°, the flutter speed is reduced rapidly by the coupling between the wing, aft fuselage and horizontal tail modes. The photograph of Fig. 14 shows the large anti-symmetric deflection of the wing tips and the vertical tail during a wind tunnel run. The horizontal tail amplitude is also large but is somewhat difficult to see in this picture, since one side of the horizontal tail is directly behind the wing.

The effect of detrimental coupling or tuning is illustrated in Fig. 15. The single surface flutter could be considered to be the classical flutter of the wing. As the frequency of the coupling surface, say the horizontal tail, is increased,

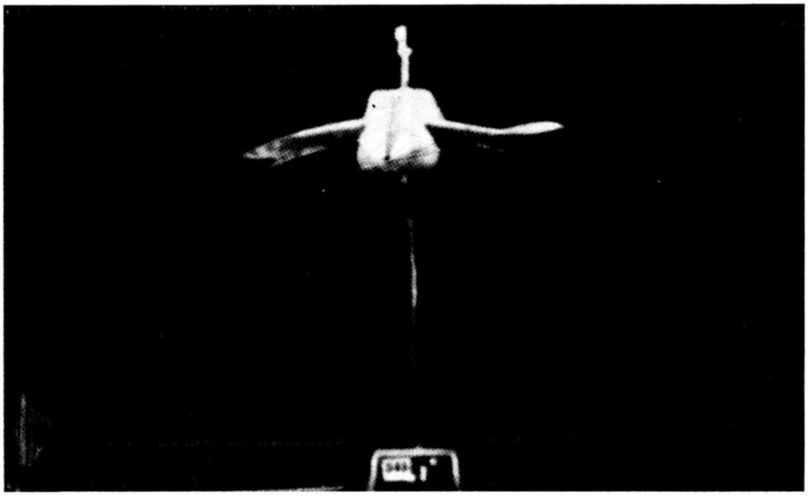

FIG. 14 — Flutter model coupled mode

the coupled flutter condition is encountered. A sharp drop in flutter speed is found as the frequency of the coupling surface is increased until the maximum coupling exists between the two surfaces. A further frequency increase detunes the system until finally the single surface flutter is again attained. This is quite similar to the effect of frequency variation of strut mounted engines on the flutter speed of flexible wings. If this detrimental coupling exists between the wing and empennage, various methods of changing frequencies on both surfaces must be investigated to determine the least penalty.

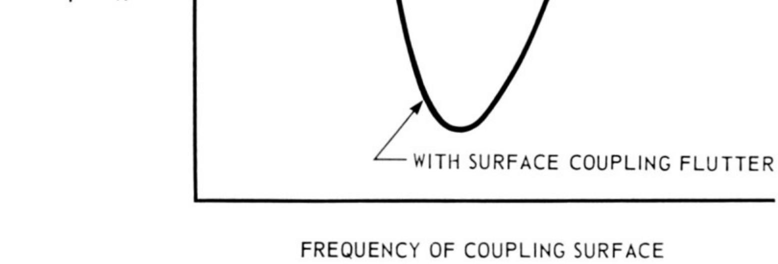

FIG. 15 — Effect of system coupling

Varying the stiffness and mass properties of wing and fuselage was investigated to determine their effectiveness in detuning this coupled flutter mode.

Increasing wing pivot stiffness to double design strength gave no appreciable change in flutter speed. Changing the outboard wing stiffness moderately affects the flutter speed; however, this imposes a large weight increment that is not required at the lower sweep positions. Mass balance in the region of the wing tip had little effect when the wing was in the aft sweep position. Referring to Fig. 16, adding 240 pounds aeroplane mass balance raised the

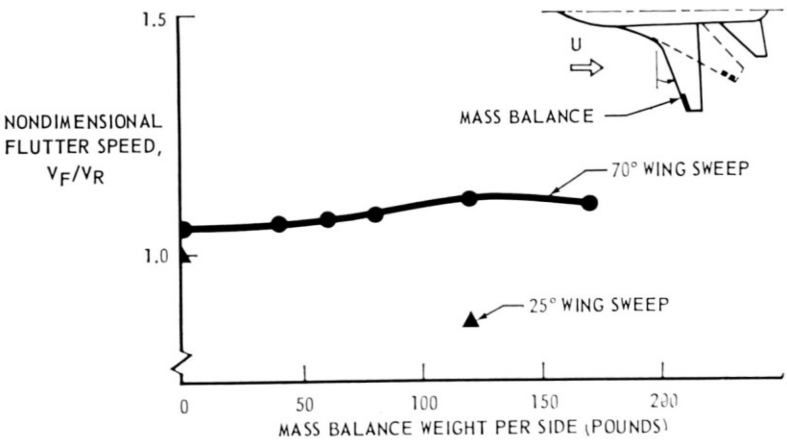

FIG. 16 — Effect of mass balance on coupling

flutter speed 5% in the 70° sweep position and lowered the flutter speed 15% in the 25° sweep position. Fuselage stiffness changes were effective in detuning the coupled flutter mode; however, relatively large fuselage stiffness changes were required. Thus it appears evident that changing the wing or fuselage characteristics to eliminate the coupling flutter mode would impose a severe weight penalty.

A potential means of detuning this system is to change the geometry. It is likely that reducing the horizontal tail area or span would be beneficial. This was accomplished by clipping the tip streamwise and obtaining a simultaneous reduction in area and span. Variations in area and span were combined in the single parameter aspect ratio for the data of Fig. 17. It can be seen that reduction of aspect ratio in this manner is extremely beneficial.

An increase of sweep angle of the horizontal tail is another potential means of detuning the system. Data of Fig. 18 show the benefit that is gained by incorporating a variable sweep horizontal tail as well as the variable sweep wing. Thus, a powerful means of detuning the coupled system is available through changing the horizontal tail geometry as suggested in Figs. 17 and 18.

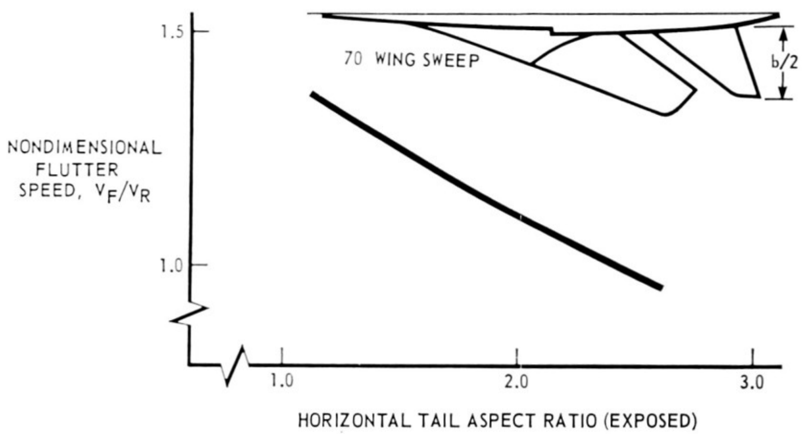

FIG. 17 — Effect of horizontal tail aspect ratio on coupling

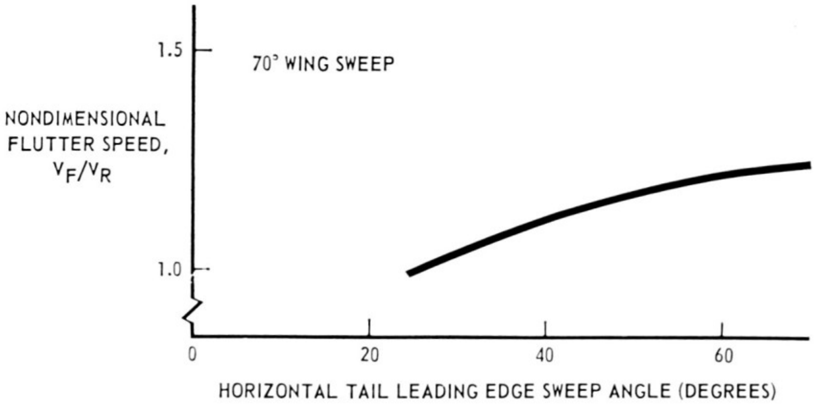

FIG. 18—Effect of horizontal tail sweep on coupling

It has been shown that there exist unique flutter characteristics for certain wing-fuselage-empennage relationships. However, the flutter characteristics can be evaluated with modern theoretical analyses and wind tunnel testing techniques. It should be emphasised that not all variable sweep configurations exhibit the detrimental coupling. However, all configurations should be examined for this phenomenon.

3. THEORETICAL AND EXPERIMENTAL COMPARISON

A correlation study was undertaken to determine the extent to which theory could be used in predicting the stability boundaries of variable sweep aircraft. The mathematical model used in the analysis simulated an early test configuration having a completely elastic model. The horizontal tail reflects a variable geometry surface in the 25° sweep position. Modal analysis technique was used to derive the equations of motion, using the normal modes as generalised co-ordinates. Extreme care was taken to formulate the coupled modes and generalised mass expressions necessary to simulate the total wing-fuselage-empennage structural description. The generalised forces were obtained using both the two-dimensional theory of ref. 1 and the lifting surface theory of ref. 2.

These generalised forces were computed for each surface using the assumption that no aerodynamic interaction forces existed between the lifting surfaces. This is not a valid assumption for close proximity lifting surfaces, as was previously pointed out, nor is it a valid assumption in the present model case where the lifting surfaces are only one chord length apart with the trailing surface submerged in the wake of the leading surface.

The results of the correlation study, Fig. 19, show that the stability

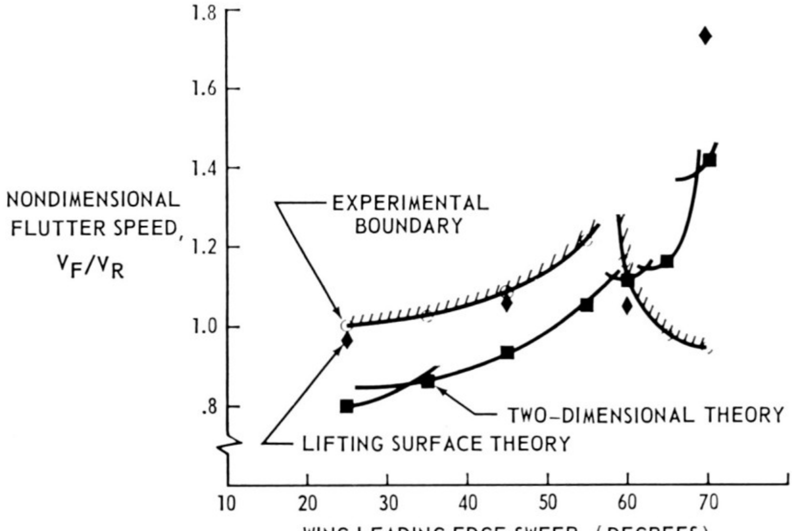

FIG. 19 — Correlation results

boundary is composed of both symmetrical and anti-symmetrical branches that dominate portions of the sweep range. These branches are obtainable only by considering the motion of the entire system. Analysis of a single surface would not reveal the degradation in flutter speed with sweep angle, nor would a single surface analysis predict the change in modal characteristics shown in Fig. 19. For sweep angles less than 58°, the two-dimensional theory is very conservative in predicting the flutter speeds; however, the trends are properly defined. The lifting surface theory predicts the stability boundary within 5 per cent of the actual values over the same sweep range. Both theories indicate that the flutter mode is changing rapidly with sweep angle; however, both theories show a general increase in flutter speed throughout the sweep range. However, the experimental flutter speeds diminish rapidly for sweep angles greater than 58° and the figure shows that the lowest flutter speed exists for the wing in the full aft position of 70°. Neither theoretical method indicated that the flutter speed would be so adversely affected.

Two conditions are necessary to have any appreciable aerodynamic interaction: (i) both surfaces are oscillating at nearly the same frequency, and (ii) the surfaces are closely spaced. Both conditions are met in the model test in that the surfaces are moving at the same frequency for each of the natural modes and the trailing vortex off the wing, at high sweep angles, fully engulfed the outboard portion of the stabiliser.

Figure 20 presents a schematic of the relative position of the wing-tail test

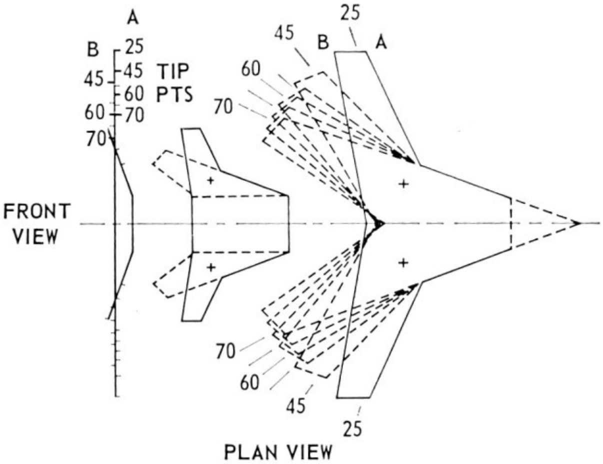

FIG. 20 — Relative location between wing and horizontal tail

combination. The observed wing motions taking place during flutter for the high sweep angles were composed mostly of tip motion with very little inboard wing motion. Consequently, the portion of the wing vortices shed into the wake near the wing tip would contain the highest vortex strength and would affect the trailing surface whenever the wing tip station approached the stabiliser spanwise tip station. Figure 20 shows that the trailing vortex off the wing tip would be located well outboard of the tail surfaces for wing sweep positions less than 58°. However, for wing sweep positions greater than

58° the wing tip vortices would gradually engulf the tail surface until, at 70-degree wing sweep, a large portion of the tail surface would be submerged in the oscillating wing wake. The resulting aerodynamic forces on the horizontal tail could then take on values having the same order of magnitude as the wing forces, which would certainly produce a change in the flutter mode, as well as the flutter speed.

Further aerodynamic interaction effects were experimentally investigated, with the variable geometry horizontal tail having a 70° leading edge sweep. The pitch and roll stiffness were the same as used in the 25° position. The semispan was such that the horizontal tail tip was not engulfed in the wing tip vortices. The experimental value given in Fig. 21 shows that an appreciable

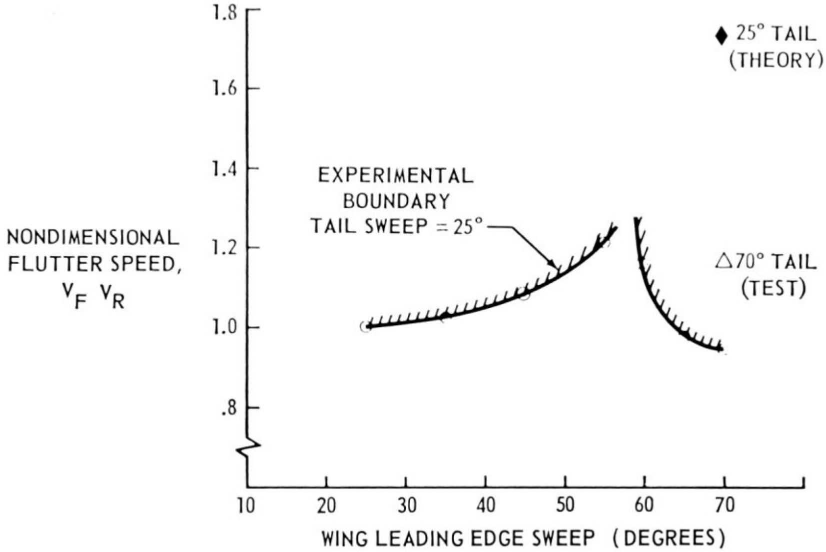

FIG. 21 — Aerodynamic interaction comparison

gain in flutter speed is achieved over the 25° test values. Since the wing-tip shed vortices are passing near the horizontal tail it is expected that some aerodynamic interaction would exist and this is the case as demonstrated in the comparison of the no-interaction theoretical value and the 70-degree wing–70-degree tail test point.

4. CONCLUSIONS

Dynamic problems associated with a variable sweep aircraft are complex, but are not insurmountable. Close proximity lifting surfaces, as well as the frequencies and mode shapes, may create problems that were not previously evident in fixed-wing aircraft; however, the gain in performance using variable sweep configuration more than offsets the additional investigations necessary to evaluate the aeroelastic coupling effects. Flutter model testing in the early design stage will identify the parameters affecting the stability boundaries and will establish the values of the stabiliser planform parameters such as aspect ratio, span length and surface separation necessary to clear the required flight envelope. The effect on flutter speed due to aerodynamic interaction and elastic coupling between the wing and empennage must be determined. Even though many variable sweep configurations do not exhibit this coupling, enough cases have been found experimentally to emphasise this problem. Neglecting the aerodynamic interaction forces between closely spaced lifting surfaces could result in unconservative theoretical prediction of the high sweep flutter speeds. However, new theoretical aerodynamic programmes now in development include the interaction effects and should extend the accuracy of the theoretical prediction methods in establishing the high sweep stability boundaries.

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Discussion

Joseph Taub (Department of Aeronautics, Technological University Delft): Could the adverse effect of coupling of wing and horizontal tail at high wing sweep angles not be improved by changing the position of the tail relative to the wing in the vertical sense (in the direction of the Z-axis)?

Authors: It is expected that changing the position of the horizontal tail in the vertical sense would significantly change the coupling effect. This position change would affect both the aerodynamic interaction and the elastic coupling.

B. W. Payne (British Aircraft Corporation (Operating) Ltd., Weybridge, U.K.): From studies which we have made, we would confirm the findings with regard to pivot stiffness and backlash. I would add that the wing would exhibit a fixed amplitude flutter within the backlash.

It is the results, on the effect of wing-empennage coupling, which surprise me, however. All the test results are at subsonic speeds. At supersonic speeds, when I would have expected the wing to be in the highly swept condition, half of the cross terms (tail effect on wing) will have disappeared.

Would delaying full sweep until supersonic speed has been reached remove this problem? Also, if any transonic-supersonic model testing is planned, I am sure we would welcome the opportunity to hear of the results.

Authors: The wing-empennage coupling, as observed in the wind tunnel, requires both aerodynamic interaction and elastic coupling. It is believed that this type of coupling can exist in the supersonic regime, however, it is quite likely the tuning effect may change. Both transonic and supersonic testing are planned in the future.

In an attempt to gain maximum mission versatility, it is desirable to have the capability to use the aft sweep position in the subsonic regime. This, of course, has to be considered for each individual aeroplane and the requirements of the associated mission.