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Swept Composite Wing Aeroelastic Divergence Experiments

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The purpose of this paper is to illustrate by experimentation rather than analysis the potential effects of laminate design on wing divergence speed. Eleven flexible composite wing models have been tested for aeroelastic divergence at a number of fore and aft sweep angles. These fixed-root models incorporate sectioned aerodynamic shells mounted to interchangeable internal graphite-epoxy plates. These plates provide wing structural stiffness and simulate various off-axis composite structural configurations. Test results, obtained from subcritical testing using a modified Southwell method, clearly identify basic relationships between wing sweep, composite fiber orientation, and wing divergence speed. In addition, good agreement is shown between a Southwell prediction and a test actually run to divergence.

Introduction

THE influx of advanced composite materials into the mainstream of aircraft design has led to the study of new aircraft configurations and the revival of others. Fibrous composites, such as graphite-epoxy, have the obvious advantage of significantly higher specific stiffness and specific strength. However, equally important, the stiffness and strength properties of these materials are directional. In effect, laminate design introduces an independent design freedom without a weight penalty. The deformation of a composite lifting surface, and thus its aeroelastic performance, is determined by laminate selection. The concept of using the anisotropic mechanical properties of a structure to enhance aeroelastic response of a lifting surface, commonly referred to as aeroelastic tailoring, was first proposed by Waddoups.[1] Extensive research into the theoretical and practical aspects of this concept has been directed by the U.S. Air Force Wright Aeronautical Laboratories (AFWAL).

One of the more unconventional and interesting outgrowths of the aeroelastic tailoring concept is the proposed forward swept wing (FSW) fighter aircraft. This design has its roots in a study begun at the University of Maryland in 1972.[2] A summary paper by Krone[3] covering the work of Ref. 2 was presented in 1975 and provided the impetus for further design studies directed by the Defense Advanced Research Projects Agency (DARPA). A summary of DARPA aeroelastic efforts, together with those of NASA and AFWAL, is presented in Ref. 4.

Wing divergence appears as a significant design constraint for a forward swept wing constructed of conventional metals such as aluminum.[5] Wing divergence is a classical static structural instability arising from the interaction between aerodynamic loads and the static deformations produced by these loads. As the divergence speed is approached, the wing loading per unit angle of attack increases dramatically. At the theoretical divergence speed, an infinitesimal perturbation in wing root angle of attack will cause an infinitely large static deflection and load.

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Until Krone's study, aeroelastic divergence precluded the FSW from consideration as a serious design option. However, further theoretical studies confirmed Krone's original conclusion that aeroelastic tailoring could effectively control wing divergence, without significant weight penalty, for moderately swept forward wings. While a considerable number of theoretical studies of the effects of laminate tailoring on wing divergence have been performed, only a few experimental studies are available.[6-8]

The effect of laminate design on wing divergence has been demonstrated in a number of numerical studies. The purpose of this paper is to illustrate, by experimentation rather than analysis, the potential effects of laminate design on wing divergence speed. This will be done by testing several structural laminates at different wing sweep angles. The results will indicate clearly the physical reality of aeroelastic tailoring when applied to divergence prevention. However, attempts to correlate the test results with fundamental theoretical predictions were not as successful. The underlying reasons believed to be responsible for this lack of success will be discussed with the objective of alerting future researchers to potential problems in such tests.

Anisotropic Static Aeroelasticity

A classical approach to divergence analysis of high aspect ratio metallic swept wings with bending and torsional flexibility allows one to characterize the wing by an elastic axis or line of shear centers, along which bending and torsion are elastically uncoupled. For this type of wing, bend/twist coupling occurs through the introduction of the aerodynamic loads that interact mutually with the wing structure twisting and bending deformations. The aerodynamic coupling introduced by bending deformation is a function of wing sweep angle. In the case of forward sweep, this coupling is found to be destabilizing, while for aft sweep, the reverse is true.[5]

The inclusion of a laminated fibrous/anisotropic composite structure complicates the understanding of the divergence problem, because it is no longer possible to characterize the wing structure simply with a locus of shear centers. To aid the analytical problem formulation, a reference axis for the structure is usually defined. This axis corresponds to the position of the elastic axis for a geometrically similar, but orthotropic structure. An elastic bend/twist coupling parameter is then introduced and computed with respect to this reference axis. Bending and twisting deformation, coupled by an anisotropic mechanical behavior of the wing structure, can uncouple (or couple) the aerodynamic loads to a certain extent and thus stabilize (or destabilize) the wing.

A wing that deforms with an increasing wingtip angle of attack under a static air load is said to "washin." Most unswept and forward swept metallic wings fall into this category. These wings are characterized by both an outboard center of pressure movement with increasing dynamic pressure and finite divergence speeds. On the other hand, a wing that deforms with a decreasing wingtip angle of attack under static load is said to "washout." Falling into this category is the aft swept metallic wing. Such wings will not diverge.

References 9 and 10 describe the theoretical aspects of passive divergence control with composites. A simplified illustration of the effect of fiber orientation on static aeroelastic behavior is presented in Fig. 1. In Fig. 1a a forward swept wing is shown with all fibers oriented in the spanwise direction. This laminate has no bend/twist structural coupling. As illustrated in the sectional view in Fig. 1a, bending and twisting reinforce each other (upward bending causes an effective noseup twist). This leads to unacceptably low divergence speeds unless additional structure is provided.

Figure 1b shows a swept forward wing with all laminate fibers rotated forward of the reference axis. In this case upward bending causes nosedown twist of each section. Thus a washout condition is created through tailoring and divergence may be eliminated from the design.

Theoretical results indicate that it becomes more difficult to eliminate divergence with tailoring as the forward sweep angle increases. The amount of bend/twist coupling that may be achieved is a function of basic laminate material properties ply orientation and wing structural geometry. Figure 2 presents an illustration of a typical interrelationship between fiber angle θ, sweep angle Λ, and divergence dynamic pressure q_d. This figure was generated from a computer analysis using a method presented in Ref. 11. Contour lines representing constant values of q_d, are plotted as a function of θ and Λ. The angle θ refers to the orientation of a constant fraction of the total number of plies that comprise the composite laminate. Note the inset in Fig. 2 for the θ coordinate. For a constant value of θ, say 10 deg, the stabilizing influence of rearward sweep is seen. For instance, divergence q increases as the wing sweep changes from -30 to -20 deg. For Λ fixed at -20 deg, values of θ in the range -30 deg$<\theta<0$ deg yield lower values of q_d than in the range 0 deg$<\theta<30$ deg. In general, it is seen that the largest changes in q_d with respect to small changes in fiber orientation are between values of θ at -10 and $+10$ deg. It is difficult to appreciate that such a small change in fiber orientation can so drastically affect aeroelastic performance of a physical system. For this reason the test program presented in this paper was conceived.

The present study, although employing a model very similar to that used in Ref. 8, differs in one significant respect. The structural laminates tested are anisotropic rather than orthotropic. To achieve this anisotropy, a core of orthotropic composite plies was overlaid with a group of off-axis plies to form a symmetric, anisotropic, high aspect ratio composite plate. A set of plates was used to demonstrate the effect of varying the orientation of these outer plies. These laminates and the model construction are described next.

Test Model

A primary requirement used to choose the test model configuration was that it clearly demonstrate the effect of laminate design on wing divergence speed. In addition, the model was to be simple enough so that theoretical predictions would be relatively easy. To accomplish this, a set of laminated plates were to be chosen and tested at several wing sweep angles. The design of the model was also subject to constraints such as wind tunnel dimensions, the wind tunnel speed range, and cost considerations. Attention was also directed to the need for a model that could have its sweep angle and laminate structure changed quickly during the testing period.

Essential features of the flexible wing model chosen are illustrated in Figs. 3 and 4. A high aspect ratio, laminated plate with a tapered planform provides structural stiffness and is illustrated in Fig. 3. This plate is housed in a 12% thick aerodynamic shell that is sectioned along the span to minimize

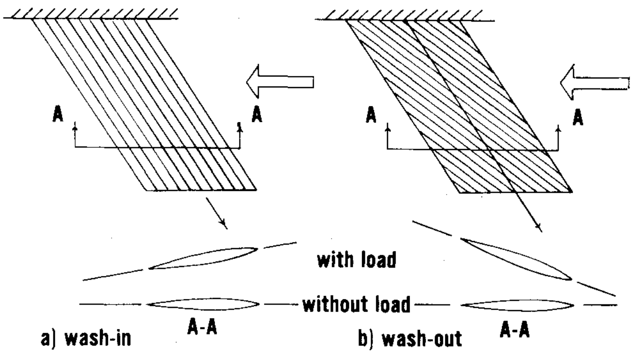

Fig. 1 Aeroelastic deformation of an advanced composite wing.

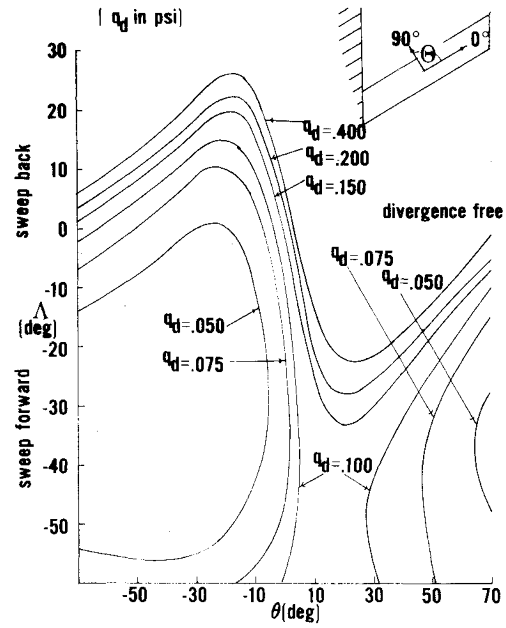

Fig. 2 Divergence critical design contours.

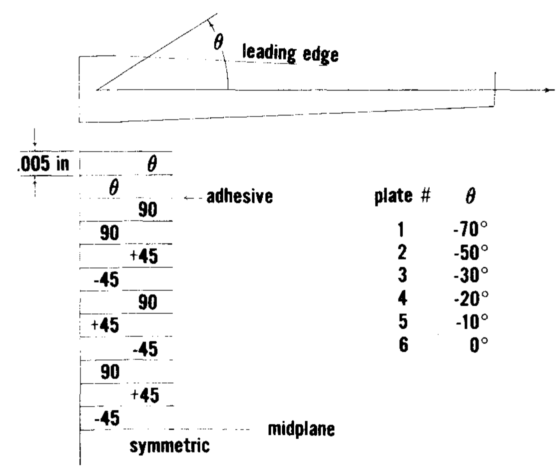

Fig. 3 Plate laminate layup scheme.

its contribution to structural stiffness. This shell is mounted to the plate as shown in Fig. 4. Coordinates of the shell and the plate are given, in inches, with respect to an xy-axis system oriented along the midchord line of the plate.

Six laminated plates were constructed, using layers of 5-mil graphite-epoxy AS5301 prepreg tape. The ply layup, in all cases, was symmetric with respect to the plate midsurface, as illustrated in Fig. 3. A central core of 20 plies, oriented along the spanwise reference axis, was covered, top and bottom, by an additional layer of material. For each of the six plates, these outer layers, or coversheets, are oriented at a unique angle θ (see Fig. 3) with respect to the spanwise reference axis to introduce bend/twist coupling into the plate. The six cases of outer ply orientations that were chosen for fabrication were $\theta=0$, $+10$, $+20$, $+30$, $+50$, and $+70$ deg. By simply inverting the plates, five additional cases of outer ply orientations are created, namely, $\theta=-10$, -20, -30, -50, and -70 deg.

During testing, the composite plate was clamped to a heavy steel stand attached to a turntable on the floor of the 6×6 ft wind tunnel at Virginia Polytechnic Institute and State University. This arrangement is shown in Fig. 5. The turntable allows remote adjustment of the wing root angle of attack. Wing sweep is measured as the angle between the wing structure reference axis and a vertical axis. Because the floor mounting protruded above the floor, an aerodynamic fairing to cover the internal mounting apparatus had to be constructed. Its purpose was to smooth the flow around the root section of the wing.

A strain gage was attached to each plate near the wing root and oriented along the spanwise structural reference axis ($\theta=0$ deg). This strain gage provided the necessary wing bending moment measurements for divergence speed prediction. An automatic data acquisition and computer system was used during testing to acquire and store the strain

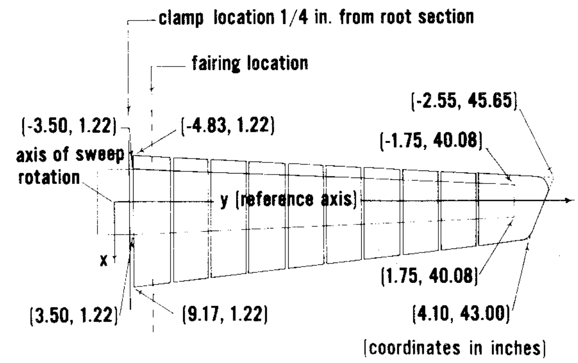

Fig. 4 Aeroelastic model for wind tunnel testing.

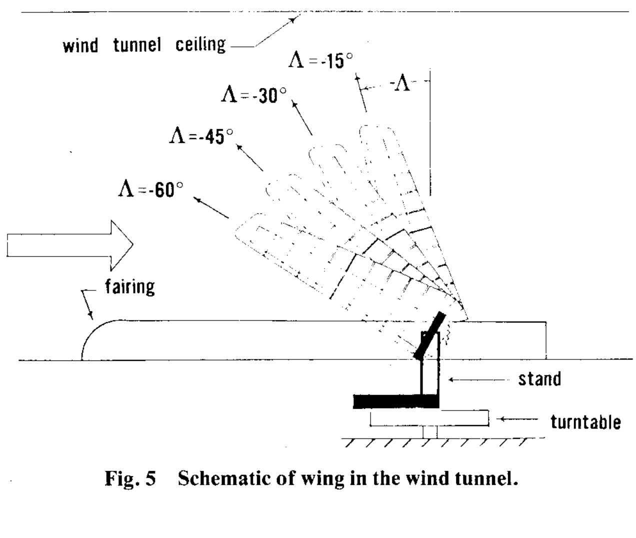

Fig. 5 Schematic of wing in the wind tunnel.

gage measurements (using a time averaged sampling technique), read and store the wind tunnel dynamic pressure data, and to compute divergence dynamic pressure. The system was linked to an automatic plotter so that data could be displayed as it was generated. The divergence prediction technique used during the experiment was a modified Southwell method, discussed in the following section.

Wing Divergence and Subcritical Projection Methods

Divergence can be characterized as flutter at zero oscillatory frequency. As such, it will arise naturally from a conventional flutter analysis. Ziegler[12] has observed that stability boundaries for nonconservative systems are best determined from a study of the time dependent behavior of the free motion of the system. When this time dependent analysis is conducted for a cantilevered lifting surface, such as is the case for a wing securely anchored to a wind tunnel wall, the static aeroelastic analysis and the dynamic analysis yield identical results for divergence speed. There is some controversy as to how the static instability of a wing structure manifests itself when it is attached to an unfixed fuselage.[13,14] However, to establish a clear basis for the present experiment, only cantilevered wing divergence was considered.

Until recently, divergence of conventional metallic wings, whether unswept or sweptback, was not regarded as a design constraint. As such, no reliable experimental methods to predict divergence were developed. Since wing divergence is a structural instability, characterized by a large change in deformation for a small change in flight speed, a nondestructive test technique is desirable, if not essential.

Flax[15] described one possible method of determining divergence from subcritical static tests and observed a similarity between the equation for two-dimensional airfoil divergence and Southwell's equation[16] for static buckling. In addition, Fung[17] also suggests a similar divergence prediction technique. Blair,[18] following the suggestion of Hallauer of Virginia Polytechnic Institute and State University, investigated the use of a modified Southwell's method to experimentally predict the value of the divergence speed for an unswept wing. Independent of this latter effort, Ricketts and Doggett[19] conducted a definitive study in which they developed several divergence projection methods, including a modified Southwell technique similar to Hallauer's. They examined the application of these methods with numerous experiments on metallic wings at the NASA Langley Research Center.

When a two-dimensional airfoil is attached to a flexible support, in this case a torsion spring of constant k (see Fig. 6), and given an initial angle of attack, α_0, the value of the final angle of attack, α, is found to be

$$\alpha=\frac{\alpha_0}{1-q/q_d} \tag{1}$$

where

$$q_d=k/SeC_{L_\alpha} \tag{2}$$

This equation gives the classical value of the divergence dynamic pressure of the two-dimensional airfoil.

To subcritically project the divergence speed, α_0 is fixed. Then, tunnel speed is increased slowly. Measured values of α and (α/q) are plotted as ordinate and abscissa, respectively. When several ordinate/abscissa values have been plotted a straight line is generated using a least squares method. The slope of this straight line is q_d. Since strain varies linearly with α, a Southwell plot can be generated using strain instead of α.[19]

The validity of the Southwell technique is readily demonstrated for a problem with a single degree of freedom such as the one described. However, the authors are unaware of any rigorous mathematical examination of the validity of the extension of this subcritical projection technique for finite

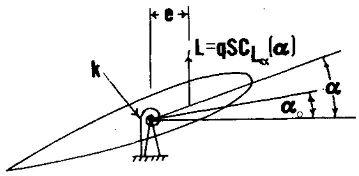

Fig. 6 Two-dimensional aeroelastic airfoil.

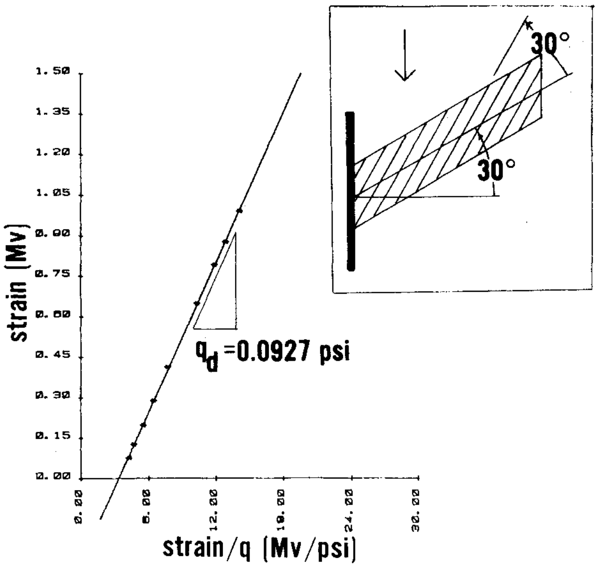

Fig. 7 Southwell plot for 30-deg forward sweep with 30-deg plate.

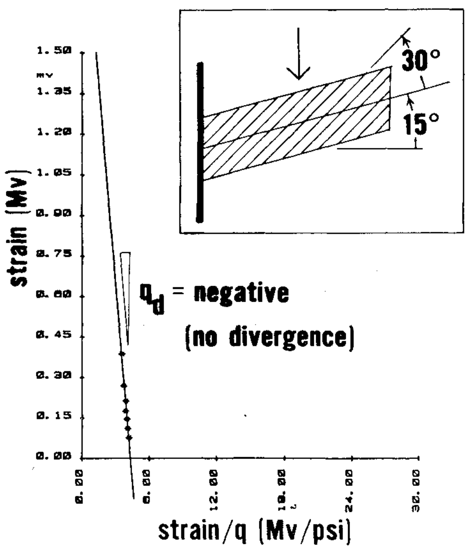

Fig. 8 Southwell plot for 15-deg forward sweep with 30-deg plate.

swept and unswept wings with many degrees of freedom. The theoretical determination of wing divergence speed usually takes the form of an eigenvalue problem, with the dynamic pressure, or a nondimensional counterpart, as the eigenvalue. More than one eigenvalue solution exists, but only that eigenvalue associated with the lowest dynamic pressure has physical importance. In theory, the solution for static deflection of the wing with a prescribed loading could be obtained as a series solution using the eigenvalues and eigenvectors found from the divergence analysis. For low values of dynamic pressure, one would expect this expansion to be dominated by the lowest eigenvalue/eigenvector combination. However, the wide separation of forward swept wing divergence eigenvalues (see, for instance, Flax's

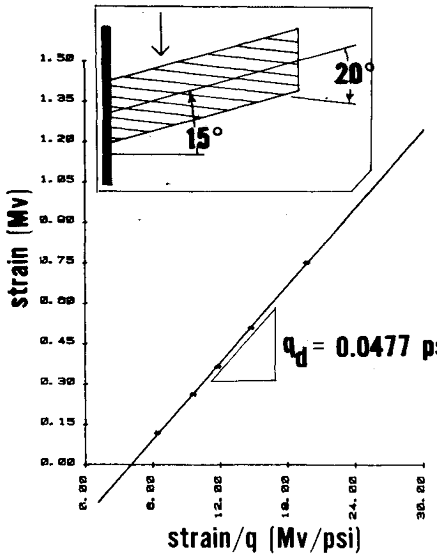

Fig. 9 Southwell plot for 15-deg forward sweep with −20-deg plate.

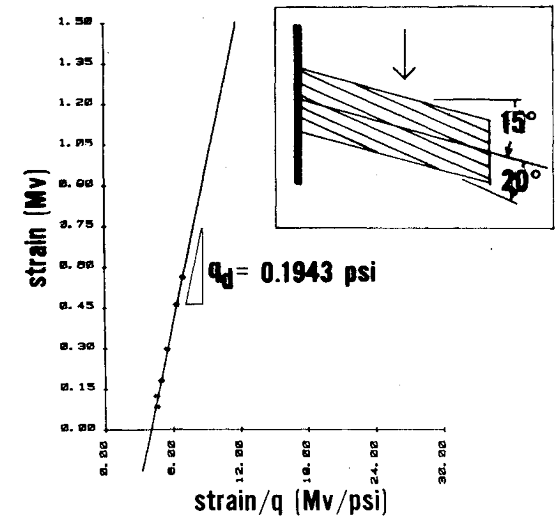

Fig. 10 Southwell plot for 15-deg aft sweep with −20-deg plate.

discussion in Ref. 15) and recent numerical and mechanical experiments have given a high degree of confidence to the Southwell method of projection.

Discussion of Results

A Southwell plot, typical of those generated from the tests, is shown in Fig. 7. These data were taken for a 30-deg forward swept wing containing a $\theta = 30$-deg laminated plate. The slope of the straight line, fitted through the data points, is 0.0927 psi, corresponding to a speed of 106 ft/s at sea level. The Southwell plot usually has a positive slope for forward swept wings, indicating a finite divergence speed. However, Fig. 8 shows a Southwell plot for a 15-deg forward swept wing with a laminate constructed with $\theta = 30$-deg cover plies. This plot has a negative slope, indicating that q_d is negative. Therefore the wing will not diverge, even though it is swept forward. Here the laminate provides enough bend/twist coupling to create a washout condition that eliminates divergence.

Figure 9 presents a Southwell plot for a 15-deg forward swept configuration with a $\theta = -20$-deg laminate. The washin characteristics of this laminate are evident, since the divergence dynamic pressure is only 0.0477 psi (76 ft/s). In fact, the washin tendencies of this laminate are so strong that even the 15-deg swept back wing has a finite divergence dynamic pressure, an unusual feature for a moderately swept back wing. The Southwell plot in Fig. 10 shows this dynamic pressure to be 0.1943 psi (153 ft/s).

Important test results are summarized in Figs. 11 and 12. The cover ply angle, θ, is shown on the abscissa, while the divergence dynamic pressure is plotted as the ordinate. Figure 11 shows data obtained for the 15-deg swept forward wing. The $\theta = 20$- and 30-deg laminates were found to be divergence free. From Fig. 11, it is seen that ply angles outside the range 0 deg$<\theta<$50 deg are relatively ineffective in increasing divergence speeds.

Figure 12 shows a similar plot for the 30-, 45-, and 60-deg swept forward wing cases. From this figure, it is seen that cover ply sweep angles between 0 and 30 deg forward of the spanwise reference axis lead to the maximum divergence dynamic pressures. At a wing forward sweep angle of 45 deg, the maximum divergence dynamic pressure is lower than for $\Lambda = -30$ or -60 deg. This implies that, at $\Lambda = -45$ deg, more bend/twist coupling is required for the structure to achieve the same divergence boundaries associated with either the 30- or a 60-deg swept forward wing.

The maximum divergence dynamic pressure for the 60-deg swept forward wing is slightly higher than for the $\Lambda = -45$-deg wing. In addition, this maximum occurs when the θ fibers are nearly spanwise. This indicates that bend/twist coupling becomes less important than spanwise bending stiffness to achieve maximum washout for wings highly swept forward.

One divergence "hard point," a test where the wing actually diverged, was obtained after a Southwell projection was made. The 30-deg swept forward wing with a $\theta = -70$-deg plate was chosen for this test. This divergence hard point was approached by unloading the wing as the dynamic pressure was increased. The dynamic pressure at which the clamped wing diverged was 0.0394 psi. The Southwell technique projected a divergence dynamic pressure of 0.0379 psi, a difference of 4%.

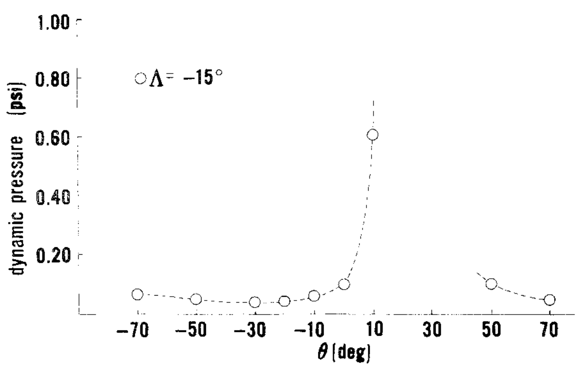

Fig. 11 Test results for 15-deg forward sweep.

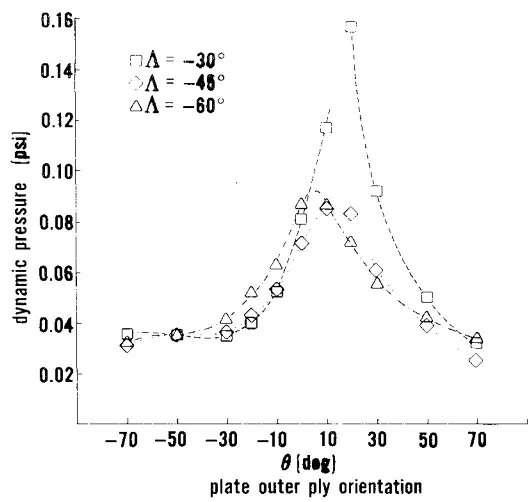

Fig. 12 Test results for 30-, 45-, and 60-deg forward sweep.

Comparison of Test Results with Theoretical Predictions

While the trends seen both in the experimental results and the predicted results are identical, exact comparisons between the two studies are not good. To compare theory and experiment, the bending and torsional stiffnesses of a wing with the orthotropic 0-deg plate were measured and checked against plate theory predictions. Measured bending stiffness was approximately 9% over the predictions. However torsional stiffness was approximately 66% over the analytically determined values. Much of this difference in the latter case was due to the shell. Without the shell, measured bending and torsion stiffness exceeded theoretical predictions by 9% and 26%, respectively. Divergence dynamic pressures based upon the measured stiffnesses were then calculated. The results are shown in Fig. 13. In this figure, wing sweep is plotted on the horizontal axis and divergence dynamic pressure is plotted on the vertical axis. The four plotted points are divergence dynamic pressures experimentally determined by the Southwell method. Reasonable correlation between theory and experiment is indicated between wing sweeps of -15 and -45 deg.

Correlation between the original predictions and experimental results was even less satisfactory for the anisotropic plates. Two factors are thought to be responsible. Close inspection of the laminates showed that thickness tolerances along the span had been exceeded. As a result, the theoretical values of bending stiffness, torsional stiffness, and bend/twist coupling are in error. Because the actual measurement of the bending stiffness, torsional stiffness, and stiffness coupling parameter is a major project, extensive checking of these values was not conducted. In addition, a major goal of the tests had been achieved, namely, the illustration of the major effect of lamina orientation on divergence.

During the test tufting of the model revealed that the root fairing used to cover the wing support mechanism was substantially modifying the flow over the wing. Short of reconstructing the models and repeating the test program, nothing further could be accomplished in the way of correlating theory with experiment.

A comparison of experiment and theory shows remarkably similar trends as far as lamina orientation is concerned. A

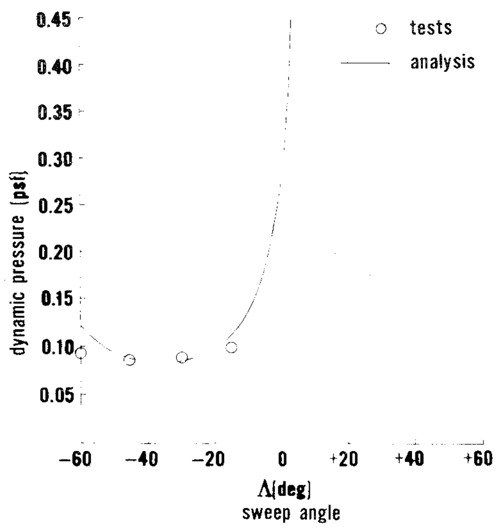

Fig. 13 Correlation of experimental results and numerical calculations without interference effects.

change in lamina orientation of only a few degrees can result in a sizable increase in divergence speed. In particular, the divergence speed is most sensitive to designs with outer fiber orientations between −10 and +10 deg with respect to the reference axis (see Fig. 11).

Conclusions

The primary purpose of this presentation has been to illustrate how anisotropic composite fiber orientation can affect divergence of a clamped swept wing structure. Maximum divergence speeds are found in wings with cover ply fibers swept between 0 and 30 deg forward of a structural reference axis. These orientations minimize washin of the wing due to deflection. The converse is true for fibers swept aft, since washin is then maximized, causing divergence speed to decline. As predicted by elementary theory, a moderate forward sweeping of lamina fibers causes a dramatic increase in the divergence speed. Fibers oriented to enhance bending stiffness are most effective in maintaining high divergence speeds for configurations with high forward sweep. Finally it was learned that fuselage interference effects may play a significant role in determining the divergence speed of wing structures. For this reason, a test with the primary objective of comparing divergence theory with experiment should probably remove this flow disturbance. In addition, close attention must be given to determining the actual bend/twist coupling caused by the anisotropic laminate. In this regard, only a limited amount of data has been published that compares predicted anisotropic stiffness characteristics with measured data, even for relatively simple structures such as those described in this paper. The results and lack of acceptable results given in this paper clearly indicate pitfalls and areas for further research.

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