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AEROELASTIC TAILORING WITH COMPOSITES APPLIED TO FORWARD SWEPT WINGS

Air Force Wright Aeronautical Laboratories
NASA Langley Research Center
and
Purdue University

November 1981

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The application of aeroelastic tailoring with advanced composites has made forward swept wings a viable configuration option for high performance aircraft. Forward swept wings have an inherent tendency to encounter a static aeroelastic instability called divergence. The extreme weight penalty required to avoid this instability in conventional metallic construction has been the basis for the reluctance of designers to incorporate forward sweep in aircraft.

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Studies performed for the Flight Dynamics Laboratory and by others independently show that, through the use of aeroelastic tailoring (the design process that makes use of the directional properties of fibrous composite materials in wing skins and orients these materials in optimum directions) with advanced composite material, the aeroelastic behavior of a conventional aft swept wing can be controlled and forward swept wings can be constructed with composites that result in an increase in the divergence speed without a prohibitive increase in weight. This report presents the background and evolution of aeroelastic tailoring as applied to forward swept wings together with a summary of work required to establish an aeroelastic data base for forward swept design.

FOREWORD

This report was presented to the 5th DOD/NASA Conference on Fibrous Composites in Structural Design, 27-29 January 1981, New Orleans, Louisiana. The report is a summary of efforts that studied the aeroelastic divergence phenomena in forward swept wings.

Section II, "Anisotropic Aeroelasticity" is a summary of work performed by Virginia Tech under AFOSR Grant 77-3423, DARPA Order 3436, "Aeroelastic Stability and Performance Characteristics of Aircraft with Advanced Composite Swept Forward Wing Structures", and AFWAL contract F33615-79-C-3224, "Aeroelastic Stability of Forward Swept Wings". The work was administered by the Aeroelastic Group, Structures and Dynamics Division, Air Force Wright Aeronautical Laboratories.

Section III, "Aeroelastic Divergence Testing", subsection "Studies Performed by NASA", was performed in-house by the NASA Langley Research Center Aeroelasticity Branch, under Work Unit 505-43-33-01, "Wind-Tunnel Experiments on Divergence of Forward-Swept Wings." The subsection, "Studies Performed by FDL", was performed in-house by the Aeroelastic Group, Structures and Dynamics Division, Air Force Wright Aeronautical Laboratories, under Work Unit 24010226, "Forward Swept Wing Aeroelastic Studies".

Section IV, "Application to Flight Demonstrator", was performed under DARPA Order 3436 by Grumman Aerospace Corporation under Air Force contract F33615-78-C-3223, "Demonstration of Divergence and Flutter Prevention for Forward Swept Wings" and by Rockwell International under an amendment to Air Force contract F33615-77-C-3143, "Forward Swept Wing Concept Validation". This work was technically administered by the Aeroelastic Group, Structures and Dynamics Division, Air Force Wright Aeronautical Laboratories with assistance from the NASA Langley Research Center Aeroelasticity Branch.

The authors wish to acknowledge the valuable contributions of the engineers at Grumman Aerospace Corporation, viz, Messrs. K. Wilkinson and F. Rauch, and at Rockwell International, viz, Messrs. J. Ellis, S. Dobbs and J. Miller for their work on the large scale forward swept wing divergence models.

SUMMARY

The application of aeroelastic tailoring with advanced composites has made forward swept wings a viable configuration option for high performance aircraft. Forward swept wings have an inherent tendency to encounter a static aeroelastic instability called divergence. The extreme weight penalty required to avoid this instability in conventional metallic construction has been the basis for the reluctance of designers to incorporate forward sweep in aircraft.

In studies performed for the Flight Dynamics Laboratory and by others independently, it has been shown that, through the use of aeroelastic tailoring with advanced composite material, the aeroelastic behavior of a conventional aft swept wing can be controlled. Aeroelastic tailoring is the design process that makes use of the directional properties of fibrous composite materials in wing skins and orients these materials in optimum directions. In a paper presented at the 1975 AIAA Aircraft Systems and Technology Meeting, Krone analytically demonstrated, by using the aeroelastic tailoring technology, that forward swept wings could be constructed with composites resulting in an increase in the divergence speed without a prohibitive increase in weight. This report will present the background and evolution of aercelastic tailoring as applied to forward swept wings.

The Flight Dynamics Laboratory has acted as the technical agent for the Defense Advanced Research Projects Agency (DARPA) on three research efforts concerning the application of aeroelastic tailoring to forward swept wings. Under DARPA and Air Force sponsorship, analytical studies comparing aeroelastic divergence and flutter of aft and forward swept wings were conducted at Virginia Tech and are presently continuing at Purdue University. These studies have concentrated on the effects that wing sweep and composite wing skin ply orientation have on flutter and divergence. As part of other contractual efforts, Grumman Aerospace Corporation and Rockwell International have designed, fabricated and tested aeroelastically scaled models of their forward swept wing fighter designs. These models were tested in the NASA Langley Research Center Transonic Dynamics Tunnel to provide correlation with analytical results and provide confidence that divergence can be efficiently eliminated from the flight envelope. NASA Langley performed analyses and tests in preparation for testing the large contractor models. This research included development of divergence test methods and an evaluation of the effects of airfoil shapes on the divergence boundary in the transonic speed regime. In addition, in order to increase technical competence and provide some basic correlation with analytical results, the Flight Dynamics Laboratory performed low speed wind tunnel testing on a variable forward sweep model. Testing was performed on aluminum and composite structures. The results of these forward swept wing efforts are presented together with a summary of work required to establish an aeroelastic data base for forward swept design.

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LIST OF SYMBOLS

AR	aspect ratio
c	root chord (measured perpendicular to reference axis)
CP	center of pressure
DI	divergence index
ℓ	reference axis length
L/D	lift to drag ratio
M	Mach number
psf	pounds per square foot
q_i	ith dynamic pressure
$q_D{}^*$	reference divergence dynamic pressure
t/c	wing thickness to chord ratio
V	velocity
V_D	divergence velocity
V_{DO}	reference divergence velocity
V_F	flutter velocity
V_{FR}	reference flutter velocity
y	span location (perpendicular to streamwise)
$\Delta\bar{y}_{cp}$	change in spanwise center of pressure location
α	angle of attack
Λ	sweep angle
λ	taper ratio
λ_i	ith slope of load versus angle of attack lines
θ	fiber angle (usually angle under study)

SECTION I

INTRODUCTION

"When a weapon system is compared with its predecessor of 10-20 years earlier, its ratio of performance to cost and its meantime to failure typically are greater by factors of 2 to 10" and "no one item (technology development) seems capable of accounting for more than a small fraction of the net change" rather "large changes in performance/cost are the synergistic effect of many innovations, most of them quite modest." Paraphrase of a conclusion from Project Hindsight, circa 1966 [1].

A recent specific example of the synergistic effect referred to by the conclusion from Project Hindsight is the forward swept wing which is made feasible for a high performance fighter by the application of aeroelastically tailored composite structure. The marriage of these technologies has resulted in a potentially significant increase in aircraft design options.

In the 1940's, aerodynamic researchers found that sweeping a wing either forward or aft resulted in a reduction in the transonic drag. However, the aeroelastic characteristics of a flexible wing became the primary deciding factor in selecting the direction of sweep. Diederich and Budiansky [2] published results that showed that the forward swept wing has a strong tendency toward aeroelastic divergence. Their theoretical results were verified by experiments and, consequently, modern high performance aircraft have aft swept wings.

Through the 1960's, advanced filamentary composites were in rapid development and applications were made to both secondary and primary aircraft structures. Accompanying these applications, by either necessity or consequence, structural analysis and design methods were developed based on the mechanics of composites as presented by Tsai [3]. The late 1960's also saw the initial serious development of optimization techniques for structures to satisfy aeroelastic constraints; notably the work of Turner [4] and Ashley, et al [5]. The application of the anisotropic mechanical properties of composites to enhance the aeroelastic response of a wing (aeroelastic tailoring) was first proposed by M. E. Waddoups of General Dynamics and was published in an AFFDL Technical Report in 1971 [6]. Additional work by General Dynamics, under AFFDL contract, resulted in the development of the Wing Aeroelastic Synthesis Procedure, which has come to be known as TSO [7]. It was this procedure that N. J. Krone, Jr. used to perform his study on divergence elimination with advanced composites [8]. Krone showed that by the use of aeroelastic tailoring with composites, aeroelastic divergence of the forward swept wing could be avoided with little or no weight penalty. Consequently, the exploitation of the unique anisotropic characteristics of advanced composites has allowed the once undesirable forward swept wing to become a serious configuration option.

The static aeroelastic divergence instability of lifting surfaces is well known. Bisplinghoff, et al, [9] present the classical trend of divergence speed as a function of wing sweep. In Figure 1, taken from Reference 9, the divergence speed of a wing is seen to decline dramatically with moderate forward sweep, but the divergence speed increases rapidly with moderate aft sweep.

Bending deformation affects the aeroelastic behavior of swept wings. For a slender wing with aft sweep, bending produces a reduction in the local angle of attack known as wash-out. However, for a slender wing with forward sweep, bending produces an increase in the local angle of attack, or wash-in. Wash-in increases both the aerodynamic loading

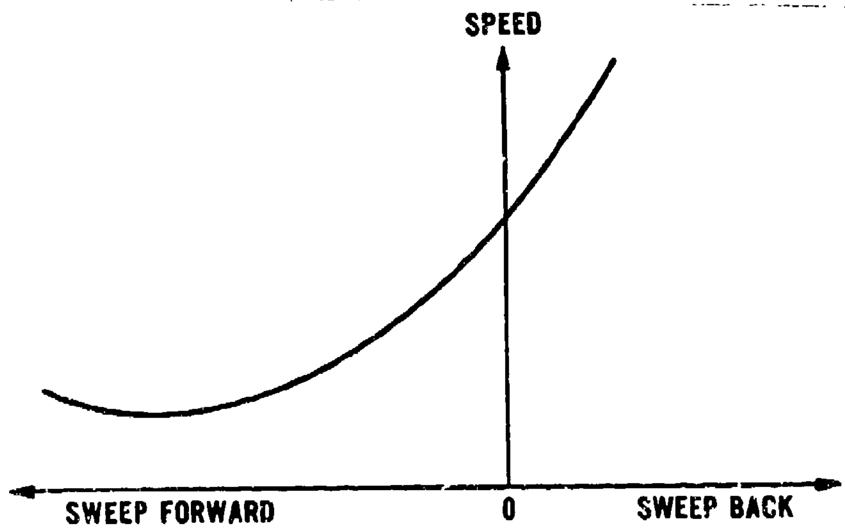


Figure 1. Variation of divergence speed with sweep. (Reference 9)

and flexible total lift-curve slope of the wing reducing the aeroelastic divergence speed. One approach to increasing the divergence speed is to reduce the wing wash-in by reducing the bending deformation. The bending deformation may be reduced by increasing the wing bending stiffness. This normally requires an increase in structural material with an associated increase in weight.

Advanced composites such as graphite-epoxy and boron-epoxy have significantly higher specific stiffness and specific strength characteristics than conventional aircraft metals. A first-order weight savings is thus obvious. Additionally, the stiffness and strength properties of composites are directional. The wash-in or wash-out caused by deformation (twist and bending) of a wing structure can be controlled by proper selection of ply angle and laminate thickness distribution. Since only a reduction in wash-in is required, an alternate approach to increasing divergence speed is possible when advanced composite materials are used. By combining the specific stiffness advantages and directional characteristics, significantly less weight is required for a composite structure than for a conventional metal structure.

Krone [8] showed that the weight of executive transport and lightweight fighter wings with sweeps from 35 degrees aft to 35 degrees forward could be significantly reduced using tailored composites. A weight comparison of a metallic wing and a tailored composite wing for a lightweight fighter is presented in Figure 2, taken from Reference 8. This figure shows that, for increasing forward sweep, the weight required in aluminum (to provide adequate stiffness) increases at a greater rate than the weight required in tailored composites.

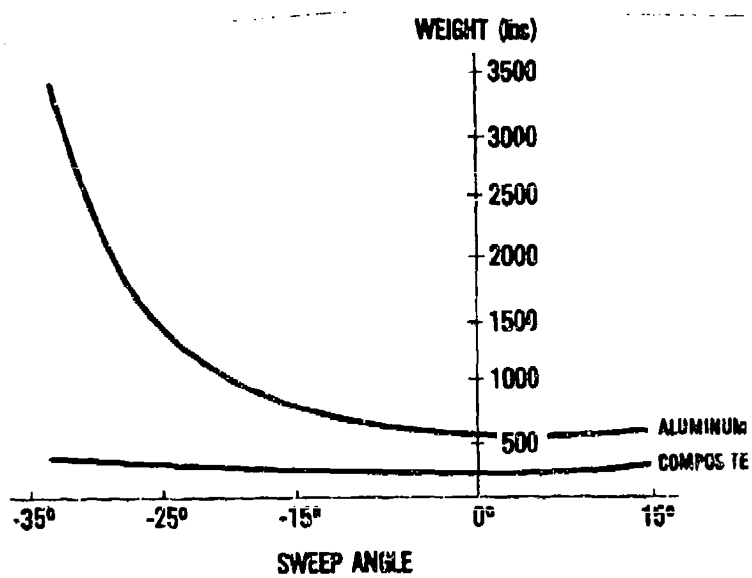


Figure 2. Lightweight fighter wing weight versus sweep. (Reference 8)

The Defense Advanced Research Project Agency (DARPA) funded forward swept wing studies which were technically directed by the Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratories. These studies were performed by General Dynamics, Grumman Aerospace Corporation, and Rockwell International, and identified several potential advantages for a forward swept wing aircraft. A recent paper by Krone [10] summarized these advantages, which include the following:

Configuration Flexibility

Significantly Higher Maneuver L/D

Lower Trim Drag -- Increased Supersonic Range for Variable Sweep

Lower Stall -- Slower Landings

Virtually Spin Proof

Better Low Speed Handling

Volume Benefits -- Lower Wave Drag

Information concerning both the application of aeroelastic tailoring to forward swept wings and aeroelastic wind tunnel testing of forward swept wings has only recently been made available. This paper provides an overview of the recent work performed by Weisshaar, formerly of Virginia Tech and now at Purdue University, the NASA Langley Research Center, and the Flight Dynamics Laboratory (FDL). In addition, this report contains a brief description of the wind tunnel tests performed on the aeroelastic wing models representing both the Grumman and Rockwell full-scale, forward swept wing flight demonstrators.

SECTION II

ANISOTROPIC AEROELASTICITY

Although aeroelastic tailoring expands by many times the design space of aircraft lifting surfaces, there appears to be some hesitancy to use an anisotropic laminate. This hesitancy stems from the relative lack of experience with heavily loaded composite structural components. Attention has been focused upon the use of orthotropic and quasi-isotropic laminates because of their relative simplicity and the ability to characterize, to some degree, failure modes and internal stresses, including interlaminar stresses. In addition, high stiffness, not to mention high strength, along orthotropic material axes may be obtained with these latter designs.

The results presented by Krone left unsettled several questions about the mechanism by which static aeroelastic stability improvements could be achieved through the use of laminated composite materials. To answer these questions, reports by Weisshaar [11-13] (also presented in synoptic form in References 14 and 15) focused upon the elastic coupling between wing bending and torsional deformations introduced by laminated composites. A method of estimating the divergence speed of moderate-to-high aspect ratio wings was developed in Reference 11 and also reported in Reference 14. A method of estimating the influence of other static aeroelastic effects such as wing spanwise center of pressure travel for either forward or aft swept wings was presented in Reference 12 and 13 and later in Reference 15.

The present discussion is limited to an examination of structural laminates that comprise wing cover skins and are themselves constructed of lamina arranged in a symmetrical, but unbalanced, manner. The term symmetrical, as used here, means that, about some middle surface reference line, there is a layer of material lying at some distance above this surface whose ply thickness, angular orientation and material properties are identical to a similar lamina lying at an identical distance below the midsurface. The term "unbalanced" means that, for every material ply lying at some angle Θ to a reference line, there is not an identical ply lying at an angle $-\Theta$ with respect to this line.

A balanced symmetrical laminate will display orthotropic deflection behavior with respect to a given set of axes (one of which is usually oriented along the swept wing structural axis) if there are enough plies in the laminate. An unbalanced symmetrical laminate will display non-orthotropic or anisotropic deflection characteristics about these axes. These anisotropic characteristics have the result that a bending moment causes not only curvature of a wing surface, but twisting of the surface as well. The anisotropy is not, however, due to a general anisotropy of the laminate that might cause warping during the curing of the laminate. (There are several other levels of coupling between the various types of structural deformation of anisotropic structures. The reader is referred to the textbook by Tsai and Hahn [16] for a complete discussion of the various methods of coupling the inplane and out-of-plane deformations of laminated beams and plates.)

Figure 3 presents a plot of wing divergence speed, V_D, normalized with respect to a common reference speed, V_{DO}, for wings at three sweep angles, Λ. Each wing has an identical tapered planform. For each wing, the orientation of the laminate fibers is varied between two extremes. Attention is called to the fact that this particular laminate represents an upper bound to what may be accomplished through tailoring for divergence, in that all of the individual ply layers have a common fiber angle Θ. Strength requirements would preclude the actual utilization of such a laminate in a design. However, the characteristic behavior of this configuration is still found to be typical of the behavior of laminates with adequate strength. The reference speed is the divergence speed for the unswept wing with its fibers oriented at 90°.

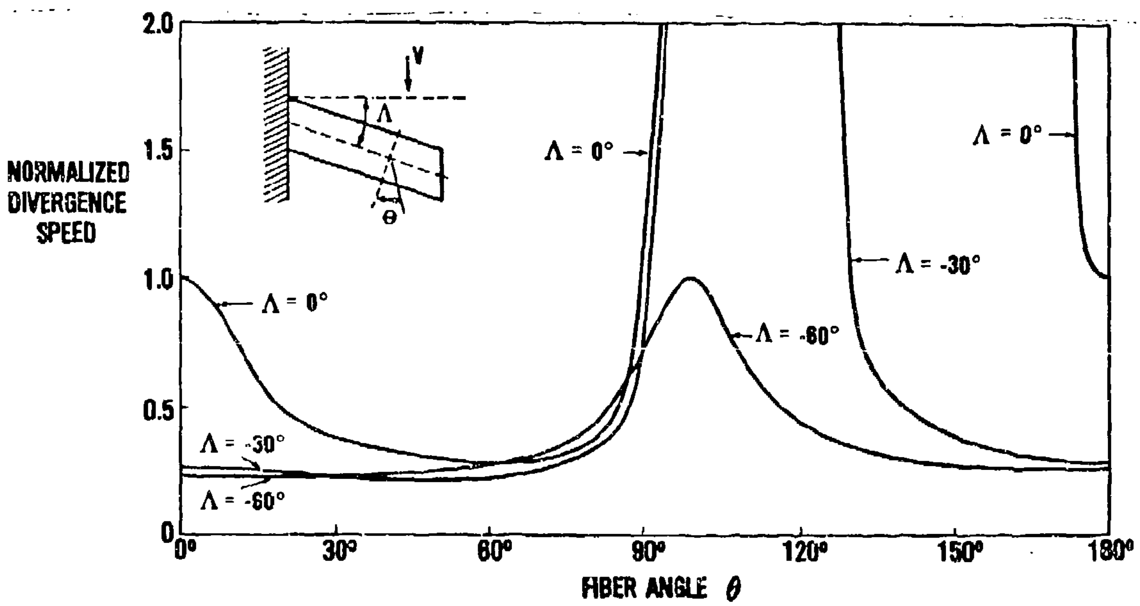


Figure 3. Normalized divergence speed versus fiber angle for a laminate with all fibers oriented at angle Θ. Three different sweep angles; wing taper ratio is $\lambda = 0.20$; wing box to cover sheet thickness is 20:1.

To highlight some general features of Figure 3, the "aft quadrant" of fiber orientation is defined as that for which the fiber angle, Θ, lies between 0° and 90°, and the "forward quadrant" is defined as the region where Θ lies between 90° and 180°. The aft quadrant is undesirable, from the standpoint of aeroelastic divergence, for all wing sweep angles. Laminates with this design feature would have the characteristic that upward bending of the wing, caused by aerodynamic loads, would lead to coupled twist in the nose-up direction. This nose-up twist will develop additional lift. While this characteristic might be desirable from a lift effectiveness viewpoint, it is not desirable for a forward swept wing because it leads to exacerbated divergence difficulties.

A laminate orientation in the forward quadrant causes the wing to twist nose-down with upward bending. This behavior is desirable for a forward swept wing, since it alleviates aeroelastically induced loads. Only a slight off-axis alignment of the fibers ("off-axis" means an orientation with respect to the $\Theta = 90°$ axis, shown in Figure 3) is necessary to drive the divergence speed to large values. In fact, the divergence speed for the unswept and the 30° forward swept wings does not exist for a range of fiber angles in the forward quadrant. Typically, these results show that laminate fiber orientations of 10° to 20° forward of the reference axis lead to maximum divergence speeds. The optimal orientation of fibers for divergence depends upon the overall laminate fiber geometry. For example, if a certain portion of the laminate must be designed with wing strength considerations in mind, only a fraction of the laminate plies are available for divergence tailoring.

The results just reviewed were generated from analytical solutions to idealized problems employing the methods originally suggested by Diederich and Budiansky [2] in their classical study of the divergence of metallic wings. Their results indicated the undesirable static aeroelastic stability characteristics of metallic forward swept wings. The inclusion of composite material bending/torsion coupling demonstrates conclusively the feasibility of greatly reducing or eliminating the importance of divergence in forward swept composite wing design.

Additional insight into the potential for tailoring of forward swept wing laminates is found in Reference 13. This study used more sophisticated methods of analysis to generate several useful parameter studies. The following geometric definitions apply to the wings analyzed in Figures 4-6. The wing reference axis (the semichord line) is swept forward 30°. The structural semispan (measured along the reference axis) is equal to ℓ and the root chord (measured perpendicular to the reference axis) is equal to c. The aspect ratio is $2\ell/c$. The structural laminate is composed of 65% Θ, 25% ±45° and 10% 0° fibers. Two wing taper ratios λ were studied. The reference dynamic pressure q_D^* is the divergence dynamic pressure for a particular wing when $\Theta = 90°$.

Figure 4 shows the effect of laminate design (orientation of the Θ fibers) upon the spanwise center of pressure (CP) movement. Outboard shifts in the CP will increase the root bending moments, since the total lift on the flexible wing remains the same as that on the rigid wing. The movement of the CP of a flexible wing at a constant value of dynamic pressure has been nondimensionalized with respect to the wing semi-span, ℓ. The flexibility of the wing is seen to lead to an outboard shift in the wing center of pressure with respect to its position on a rigid wing. This outboard shift ranges from nearly 6% to less than 0.5% of the semispan depending upon the taper ratio.

Orientation of laminate fibers near the $\Theta = 110°$ position reduces the CP shift, resulting in a flexible wing airload distribution that more closely approximates the rigid wing airload distribution. This result is consistent with the fact that laminate ply orientations in the forward quadrant lead to high divergence speeds. As the flight dynamic pressure is increased, the curves shown in Figure 4 are shifted upward.

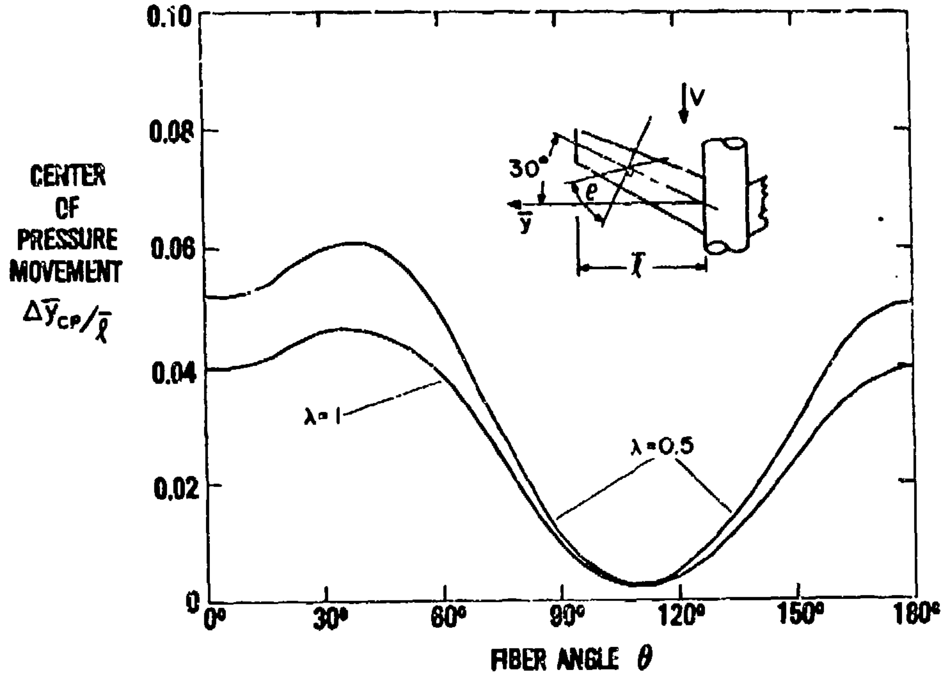


Figure 4. Normalized change in spanwise center of pressure location versus fiber angle for 30° forward swept wing; dynamic pressure is 20% of divergence dynamic pressure for Θ = 90°; aspect ratio is $2\ell/c = 6$ ($\ell = \bar{\ell}/\cos 30°$).

Figure 5 shows the power of aeroelastic tailoring when applied to a wing of extreme high aspect ratio ($2\ell/c = 25$). The figure shows that, at the chosen flight dynamic pressure, divergence can occur if the Θ plies are chosen in the aft fiber region. On the other hand, tailoring the fibers in the forward quadrant very effectively controls the center of pressure, even for extreme aspect ratios.

Lateral control effectiveness is enhanced considerably by judicious tailoring of laminate geometry. Figure 6 illustrates a measure of aileron effectiveness in the form of flexible-to-rigid ratios of a laminated composite, 30° forward swept wing at four values of dynamic pressure. As the dynamic pressure is increased, the control effectiveness declines. However, when the laminate fibers are oriented in the forward quadrant,

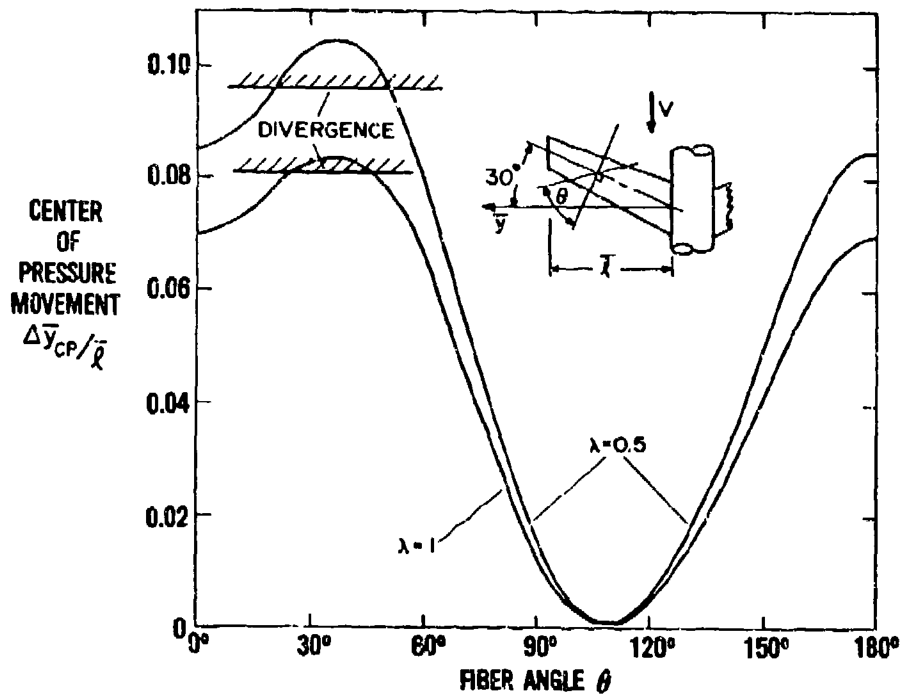


Figure 5. Normalized change in spanwise center of pressure location versus fiber angle for 30° forward swept wing; dynamic pressure is 20% of divergence dynamic pressure for Θ = 90°; aspect ratio is $2\ell/c = 25$ ($\ell = \bar{\ell}/\cos 30°$).

this decline is less rapid. When ply fibers are oriented near Θ = 130°, aileron effectiveness is maximized.

Turning to flutter behavior of the forward swept wing, only one case will be discussed, that of a wing firmly clamped to an immovable support. This type of analysis assumes that flutter does not involve rigid body motion of the freely flying aircraft.

Sweepback has long been known to provide a stabilizing influence on flutter [17], in that sweep of an aircraft wing should, all other things remaining the same, increase the flutter speed. In most cases, divergence is the critical mode of instability of a forward swept wing. However, to study the flutter behavior of a fixed-root forward swept wing, an example was chosen to ensure that divergence was not critical.

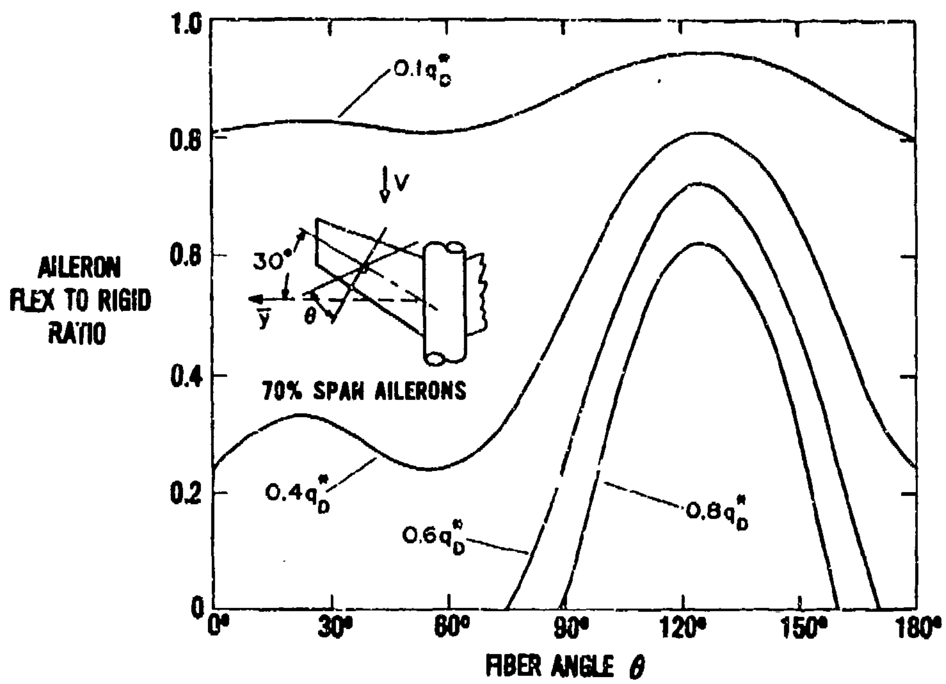


Figure 6. Aileron effectiveness versus fiber angle for 30° forward swept wing; 70% span ailerons; taper ratio is 1; aspect ratio is $2\ell/c = 6$. (q_D is divergence dynamic pressure for $\Theta = 90°$.)

The wing is untapered and has constant stiffness and mass properties. Figure 7 shows the flutter speed behavior of this wing with metallic properties as it is swept fore and aft. The surprising aspect of the results is that, for flutter, forward sweep is slightly more stabilizing than aft sweep. The flutter speed of this wing at 30° forward sweep is about 12% greater than that for 30° aft sweep. Although this wing is not typical of modern wings in its elastic characteristics, this trend of flutter speed versus sweep has been observed in several other cases known to the authors.

The introduction of laminated composites into the structure complicates the picture. Figure 8 presents results of a flutter investigation of a wing similar in planform to that used in Figure 7. The wing structure consists of laminated composite cover-sheets composed of 65% Θ,

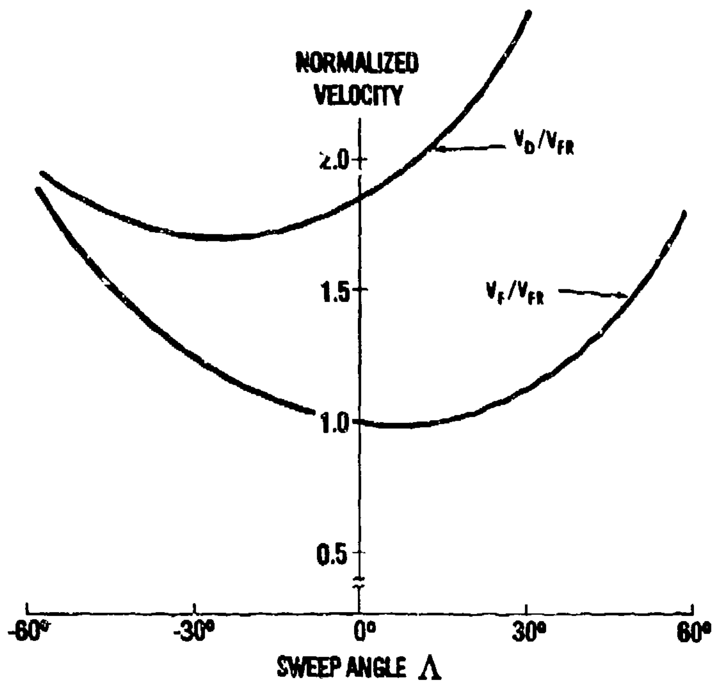


Figure 7. Flutter and divergence velocities versus sweep angle of a flutter-critical forward swept, metallic wing. (Reference velocity is unswept flutter velocity.)

25% ±45° and 10% 0° fibers. Three different sweep angles are considered. For the unswept wing, it is seen that, when the Θ fibers are tailored in the aft quadrant (0° ≤ Θ ≤ 90°), the divergence instability is the primary mode of instability. However, when Θ > 90°, the divergence speed increases rapidly with Θ, and flutter becomes the critical mode of instability. In the forward quadrant, 90° ≤ Θ ≤ 180°, the flutter speed reaches a maximum near Θ = 135°, and then declines after that point.

The Λ = 30°, or aft swept wing, provides a contrast to the unswept wing. In the aft fiber quadrant, three modes of instability are possible. Flutter involving coupling between the first bending and first torsion modes predominates. However, a hump mode (predominately second bending) appears in the range 30° < Θ < 58° and is critical in that region. Divergence becomes critical in the range 58° < Θ < 77°. In the forward

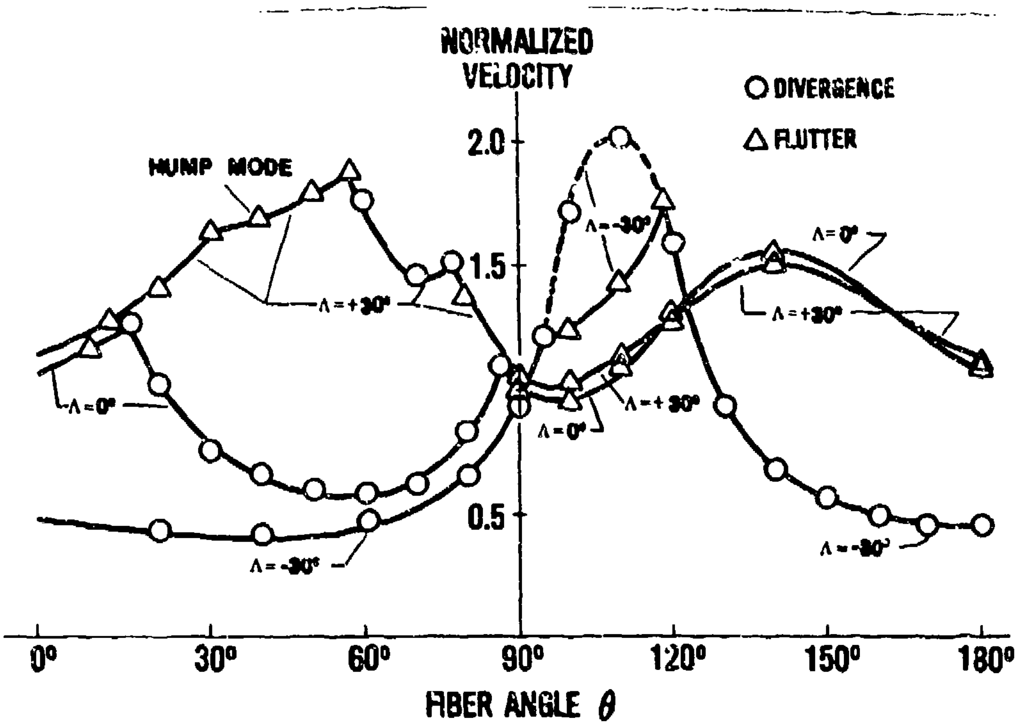


Figure 8. Flutter and divergence velocities versus fiber orientation for unswept, forward and aft swept wings. (Reference velocity is flutter velocity for unswept wing, Θ = 90°.)

fiber quadrant, flutter in the second aeroelastic mode becomes critical once more. A maximum flutter speed is reached in the forward quadrant when Θ = 140° (50° forward of the reference axis). This position is associated with high torsional stiffness.

In the case of the forward swept wing, divergence is critical throughout most of the fiber orientation range. The exception is the range 93° < Θ < 120° where flutter is critical. It is unfortunate that the wing is flutter critical in this region, since the use of fiber tailoring to prevent divergence is very effective there. The reader is reminded, however, that while one may select a "representative wing" for static aeroelastic studies, it is relatively more difficult to select a representative wing for flutter studies, since inertia properties enter into the analysis. For this reason, these studies should not be used to formulate general conclusions.

Aeroelasticity is a multiple parameter problem with variables such as wing sweep, Mach number and wing aspect ratio interacting in combination with structural stiffness and mass in a complex manner. While studies just described confirm the theoretical viability of composite wing tailoring to enhance wing divergence characteristics, an experimental data base to complement analytical studies is necessary. Several of these recent experimental efforts are discussed in the following sections.

SECTION III

AEROELASTIC DIVERGENCE TESTING

1. Studies Performed by NASA

Since aeroelastic divergence had precluded the consideration of forward swept wings in aircraft design, very little experience with divergence testing was available. Therefore, personnel in the NASA Langley Research Center Aeroelasticity Branch developed divergence projection techniques, performed divergence testing on flat aluminum plates [18], and investigated the effects of airfoil shapes on divergence in the transonic speed range [19]. A discussion of the models and results of the tests follows.

A series of flat-plate metallic models was tested at low speeds in the NASA Langley 16 foot Transonic Dynamics Tunnel to determine the effects of wing sweep angle and aspect ratio on divergence and flutter dynamic pressure. Comparisons of experimental results with analytical predictions using subsonic lifting surface theory [20] and a structural finite element model program [21] are shown as stability boundaries in Figures 9 and 10 for the models of aspect ratio 4 and 8, respectively. The AR = 4 results show two distinct boundaries: a flutter instability for aft to low forward sweep and a divergence instability for moderate to high forward sweep. The flutter mode is primarily wing first bending but contains a small amount of coupling with torsion and second bending. These results agree with those of Diederich and Budiansky [2] obtained at NACA in the late 1940's. However, for the AR = 8 wings, three distinct boundaries are shown: two flutter instabilities and a divergence instability. The new flutter mode, which occurs at moderate forward sweep, is primarily wing second bending but has a small amount of coupling with torsion and first bending.

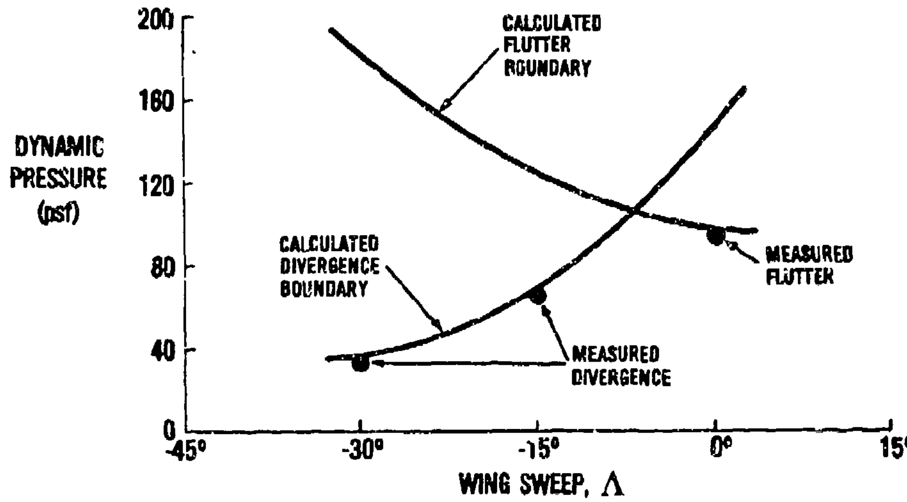


Figure 9. Divergence and flutter dynamic pressures versus wing sweep for NASA aluminum flat plate; constant chord; aspect ratio is 4.

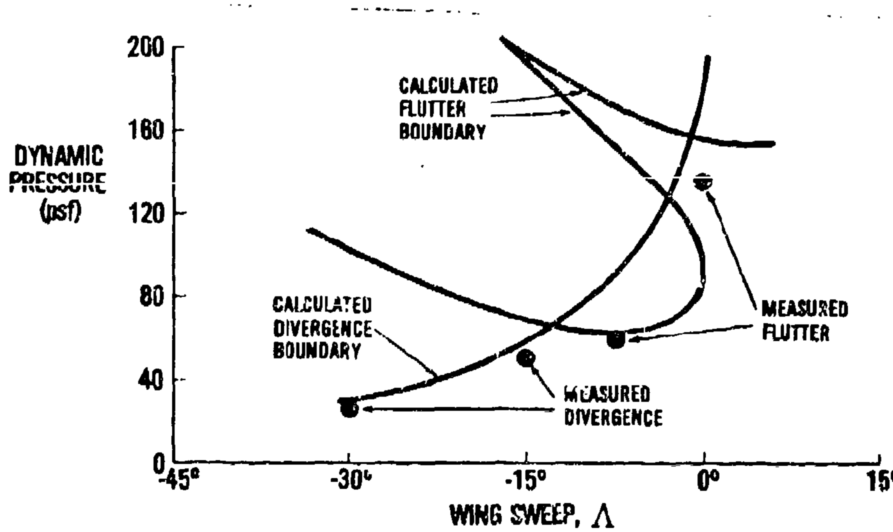


Figure 10. Divergence and flutter dynamic pressures versus wing sweep for NASA aluminum flat plate; constant chord; aspect ratio is 8.

Three additional aspect ratio 4 models with forward sweep angles of 15° were tested at transonic speeds to study the effects of airfoil shape on divergence dynamic pressure. The three model airfoil shapes included a flat-plate, a conventional 64A010, and a symmetric 10-percent-thick supercritical section (developed for vertical tails, horizontal tails and rotorcraft uses). The results of the tests are presented in Figure 11 as divergence boundaries that have been normalized at 0.6 Mach number. These boundaries resemble flutter boundaries in that they are relatively flat in the subsonic region and decrease to a minimum in the transonic region (transonic dip). The dip for the supercritical airfoil occurs at a higher Mach number than does the dip for the conventional airfoil. In analyses using two-dimensional nonlinear aerodynamic theory, Bland [19] determined that the reason for this was that the aft shift in the aerodynamic center occurred at a higher Mach number for the

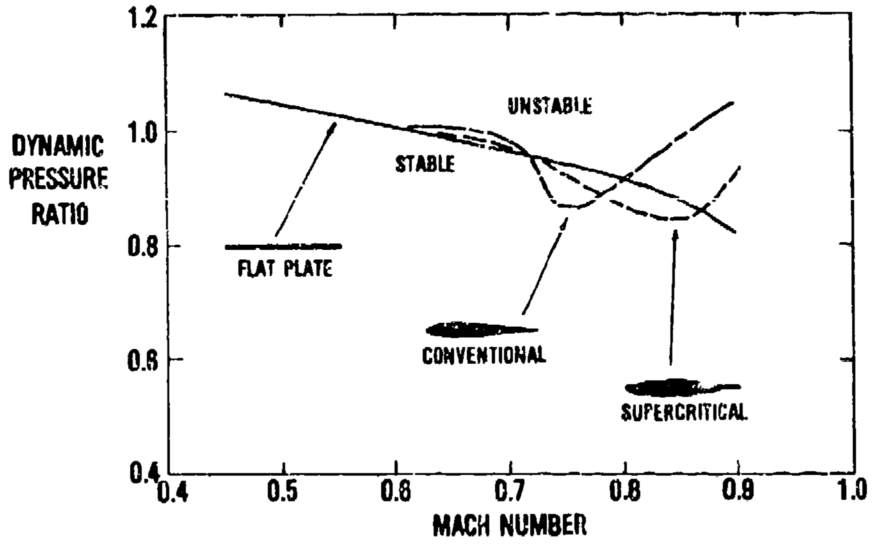


Figure 11. Comparison of divergence boundary transonic dip for forward swept flat plate, conventional and supercritical airfoils.

supercritical airfoil than for the conventional airfoil. Linear theory agrees with the flat plate results.

To prevent destruction of wind tunnel models during testing for aeroelastic divergence, it was necessary to develop subcritical response testing techniques to accurately predict the divergence boundary at dynamic pressures safely lower than the instability point. Therefore, a total of six techniques were developed and evaluated for accuracy [18]. These include four static methods which use static data such as mean root bending moment and two dynamic methods which use dynamic response data such as peak amplitude and frequency.

During wind tunnel testing of the FDL and contractor models, to be discussed subsequently, subcritical divergence projection relied primarily on two of the six methods. One of these methods, called the divergence index, is illustrated in Figure 12b. With this method, as in other static methods, the load/angle-of-attack gradient is measured at an initial dynamic pressure well below the instability point. With Mach number held constant, the gradient is measured at additional higher values of dynamic pressure (Figure 12a). Using the values of the gradient and dynamic pressure in the divergence index parameter, DI, the divergence dynamic pressure can be predicted with a first-order least-squares fit extrapolation. Experience has shown that the prediction is accurate, even when the subcritical data are acquired below 80 percent of the instability dynamic pressure. The second static method, shown in Figure 12c, is an adaptation of the Southwell beam buckling projection method [22]. The load/angle-of-attack gradient is plotted versus this gradient divided by the dynamic pressure. The slope of the least-squares fit of this plot is the projected divergence dynamic pressure.

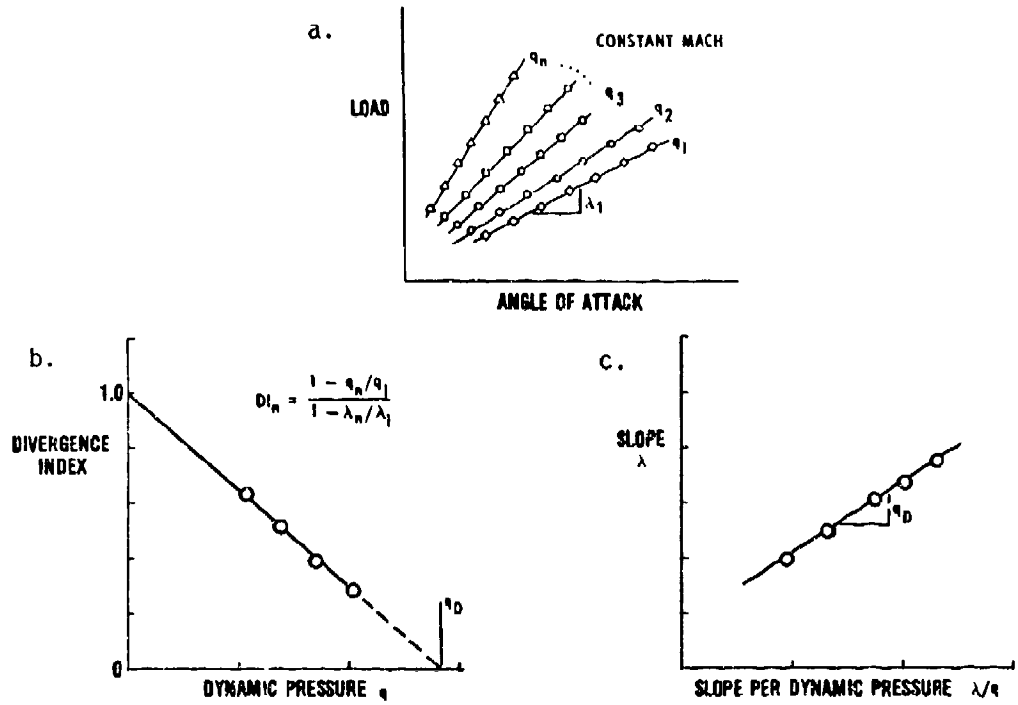


Figure 12. Static methods for subcritical divergence dynamic pressure projection. (a) Load/angle-of-attack gradients. (b) Divergence index projection. (c) Southwell-type projection.

2. Studies Performed by FDL

Until 1979, no wind tunnel demonstration of the principle of aeroelastic tailoring had been performed, though many descriptions of the benefits resulting from the judicious use of tailored composites had been published (References 4-7 and 23-28). In 1979, the Flight Dynamics Laboratory conducted an analysis and wind tunnel test program that successfully demonstrated the principle of aeroelastic tailoring to increase the divergence speed of forward swept wings [29]. The variable sweep model was tested at five leading edge sweeps, 0°, -15°, -30°, -45°, and -60° (Figure 13), in the Air Force Institute of Technology five foot wind tunnel.

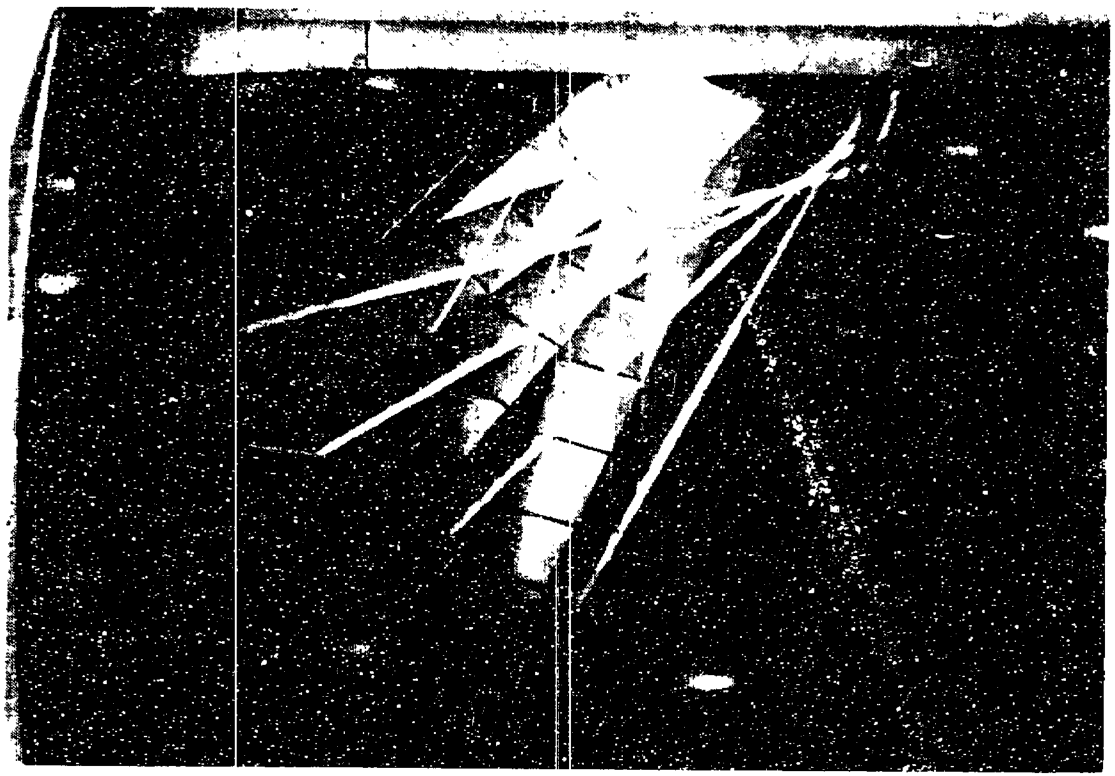


Figure 13. Flight Dynamics Laboratory variable sweep forward swept wing model.

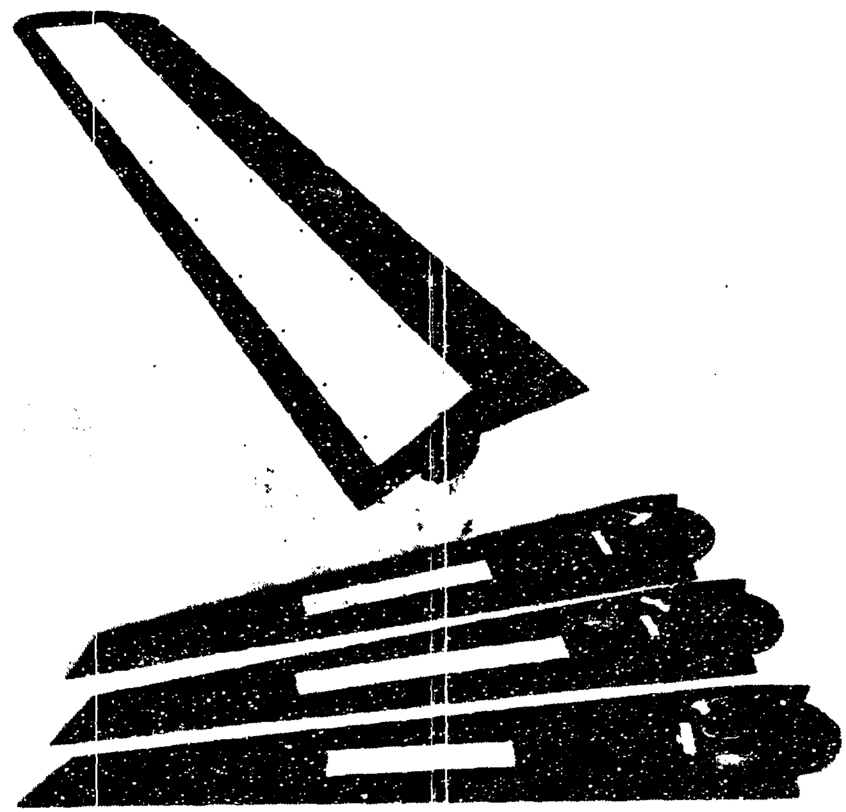


Figure 14. Flight Dynamics Laboratory forward swept wing model and graphite-epoxy structural members.

For 30° forward sweep, the model had a span of 24 inches, a full span aspect ratio of 4, and a taper ratio of 0.4. A foam sleeve provided the aerodynamic shape with a cross-section representing the NACA 0010 airfoil. Four different structural load carrying members were tested: one 0.1 inch thick, 2024-T6 aluminum plate and three 0.08 inch thick graphite-epoxy plates with a $[0_4,(-45,+45)_2]_S$ layup. The leading and trailing edges of the structural plate were the 15 and 65 percent chord, respectively.

To demonstrate a simple form of aeroelastic tailoring, the laminate of one plate was oriented so the spanwise (0°) plies were parallel to the 40% chord line. The other two graphite plates had laminates rotated 7.5° and 15° forward of the 40% chord line. The ability to vary sweep and to change the load carrying structure allowed for testing of twenty configurations. Figure 14 shows the airfoil sleeve mounted on the aluminum plate with the graphite plates in the foreground.

Prior to testing, preliminary analyses were performed using the procedure developed by Weisshaar [13]. More detailed analyses were performed using the aeroelastic tailoring procedure, TSO [23], and NASTRAN [30].

Wind tunnel testing was performed in two stages. During the first stage, tunnel velocities were limited to 80% of the projected divergence speeds. The Southwell-type and divergence index methods previously discussed were used to project the divergence speed of all twenty configurations.

During the second stage, the models were tested to divergence. Fortunately, no damage was sustained during this latter testing; all 15°, 30° and 45° forward sweep configurations were tested to divergence.

The results of the wind tunnel tests are shown in Figure 15. This figure is a graph of the divergence dynamic pressure (nondimensionalized by the plate weight per area) as a function of leading edge sweep. Two benefits of composites are demonstrated in Figure 15. The first is that by replacing the metallic structure with a graphite-epoxy structure of equal weight the divergence speed is increased for all sweeps. This is due to the higher specific stiffness of the graphite-epoxy composite laminate. The second benefit results from rotating the basic laminate forward of the reference axis. Though this benefit is confined to the forward sweeps less than 20°, it demonstrates the effect of this form of aeroelastic tailoring.

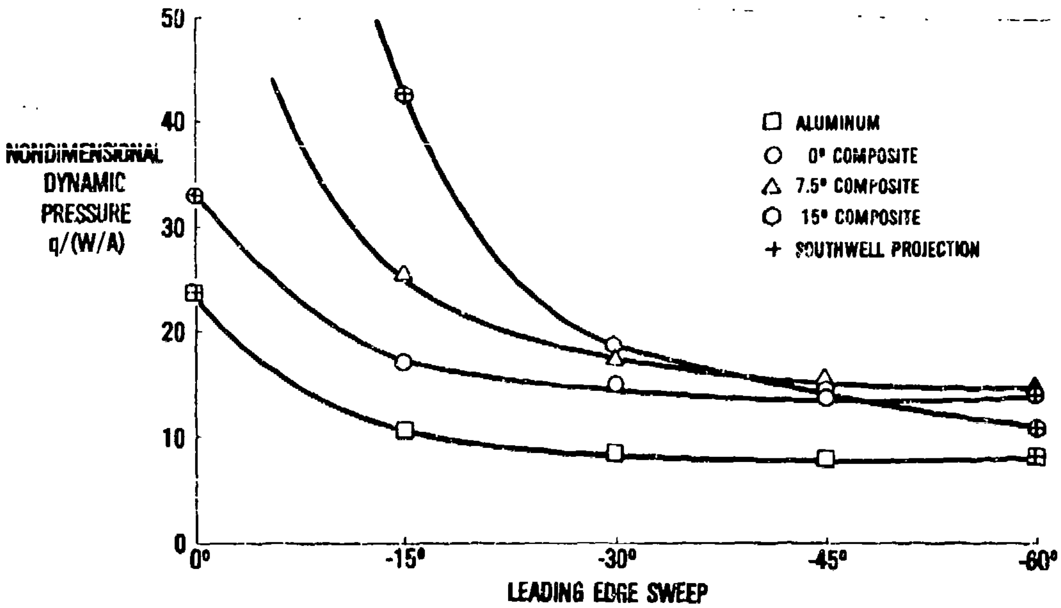


Figure 15. Experimental divergence dynamic pressure (nondimensionalized by plate weight per area) versus leading edge sweep for the FDL forward swept wing model.

The effect of laminate rotation and the reason for its being confined to low forward sweep angles is shown in Figure 16. This figure presents the laminate bending and torsional stiffnesses and a bending/

torsion coupling parameter for each of the composite plates as defined by the method developed by Weisshaar [11]. Torsional stiffness is nearly constant between plus and minus 5° of laminate rotation and increases sharply at higher rotation angles. At 15° rotation, torsional stiffness is about 60% higher than at 0° rotation. The coupling parameter has a nearly constant slope, increasing negatively from 0° rotation to 15° rotation. A negative coupling parameter produces a wash-out, bend-twist characteristic that reduces angle of attack with bending. At the low forward sweeps, the divergence mode is primarily a torsion mode. Therefore, the increased torsional stiffness and wash-out coupling due to 15° laminate rotation have the greatest effect countering the wash-in tendencies and increasing the divergence speed at wing sweeps less than 30° forward.

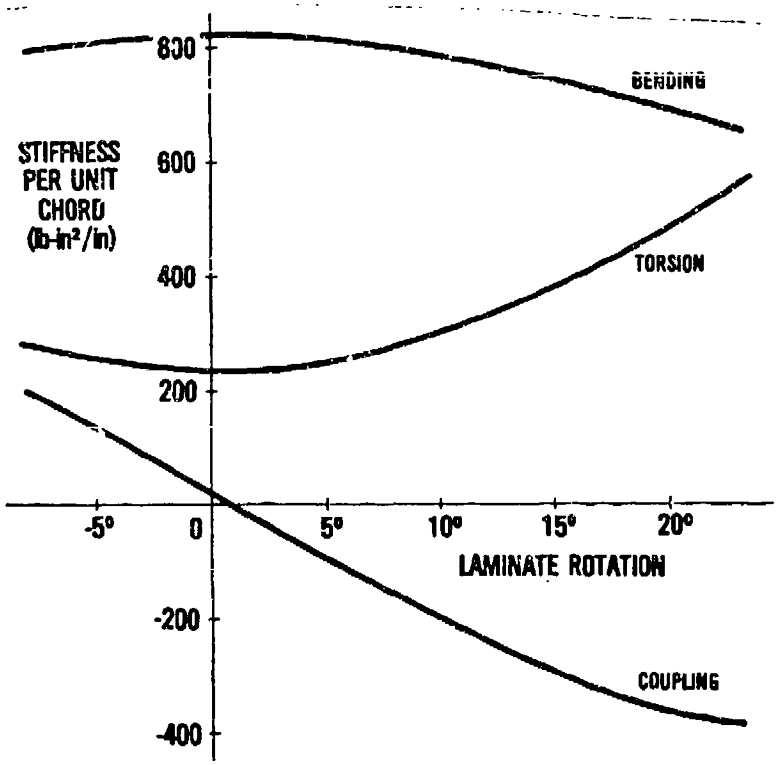


Figure 16. Bending and torsion stiffness and coupling parameter variation due to rotation of the graphite-epoxy $[0_4,(-45,+45)_2]_S$ laminate.

Figure 15 shows that the 15° rotated composite laminate has the lowest divergence dynamic pressure of the three composite plates at -60° sweep. At -45° sweep, the 15° rotated composite laminate has a divergence dynamic pressure that is less than the 7.5° rotated laminate. At sweeps greater than 30° forward, the divergence mode is primarily bending; bending stiffness becomes predominant in determining divergence dynamic pressure. The bending stiffness is nearly constant from 0° to 7.5° rotation, and thus, the increase in torsional stiffness results in only a small increase in divergence speed with laminate rotation. However, the bending stiffness is about 11% less for the 15° rotated laminate than for the nonrotated laminate. Although the torsional stiffness and wash-out coupling are greatest for this laminate, the bending stiffness is lowest resulting in the lowest divergence speeds at the greater forward sweeps.

Rotating the laminate to increase the divergence dynamic pressure also has the effect of decreasing the level of strain under aerodynamic loading. In Figure 17, strain measured at the wing root is plotted against dynamic pressure for the nonrotated and 15° rotated models for -30° sweep and at 3° angle of attack. As the dynamic pressure increases, the strain increases asymptotically to the divergence dynamic pressure. For dynamic pressures greater than 5 psf, the strain level is lower for the 15° rotated model than for the nonrotated model.

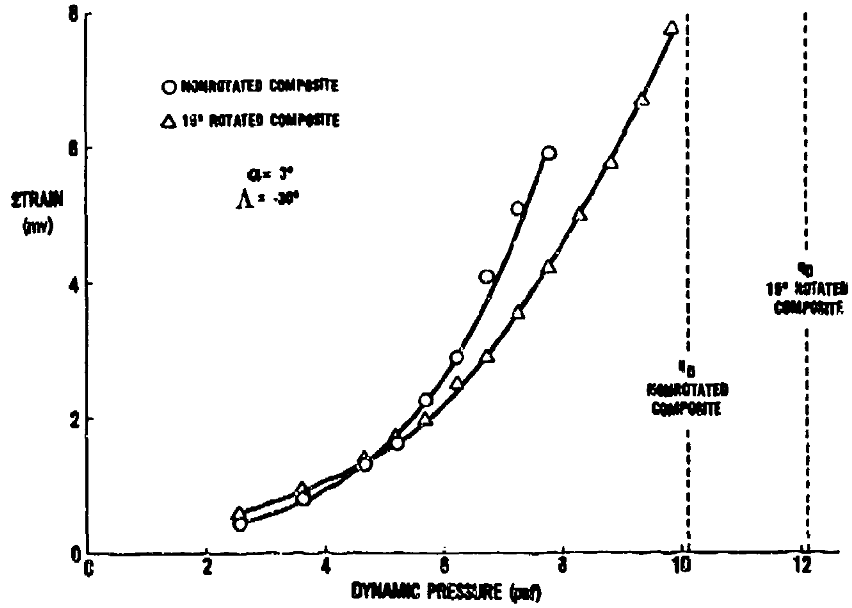


Figure 17. Variation of strain with dynamic pressure for the nonrotated and 15° rotated composite plates.

SECTION IV

APPLICATION OF AEROELASTIC TAILORING TO POTENTIAL FORWARD SWEPT WING FLIGHT DEMONSTRATION

DARPA funded three efforts to study the feasibility of building fighter aircraft with forward swept wings. The three contractors were General Dynamics, Grumman Aerospace Corporation, and Rockwell International. Their designs are shown in Figure 18. The Flight Dynamics Laboratory acted as the technical director for these efforts with support from the NASA Langley Research Center. Grumman and Rockwell were awarded contracts for the design, analysis and testing of dynamically scaled aeroelastic wind tunnel models of their forward swept wing designs. The models were tested in the NASA Langley 16 foot Transonic Dynamics Tunnel.

The objectives of these aeroelastic studies were to assess the accuracy of the analysis procedures for the prediction of wing divergence speed and to develop an understanding of the static aeroelastic behavior of the forward swept wing at speeds near divergence. Additionally, model design and fabrication procedures for accurate simulation of aeroelastic properties of a tailored advanced composite wing were to be developed. These objectives were to be satisfied by the acquisition of wind tunnel data on an aeroelastic model that accurately simulated an optimized (for divergence and strength) full scale wing design and compared to the predicted results using state-of-the-art analytical methods.

A complete description of these studies is contained in Air Force Wright Aeronautical Laboratories technical reports [31,32]. Summaries of these reports are presented in the following subsections.

(a)

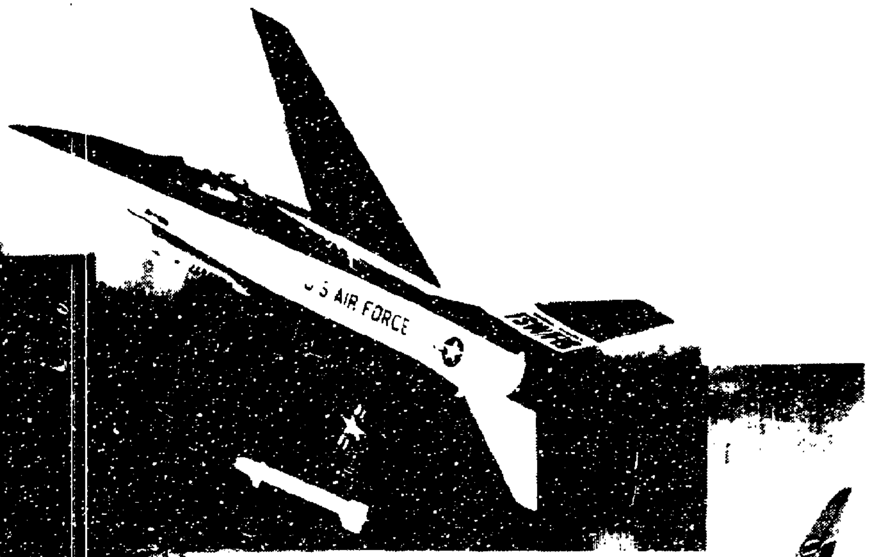
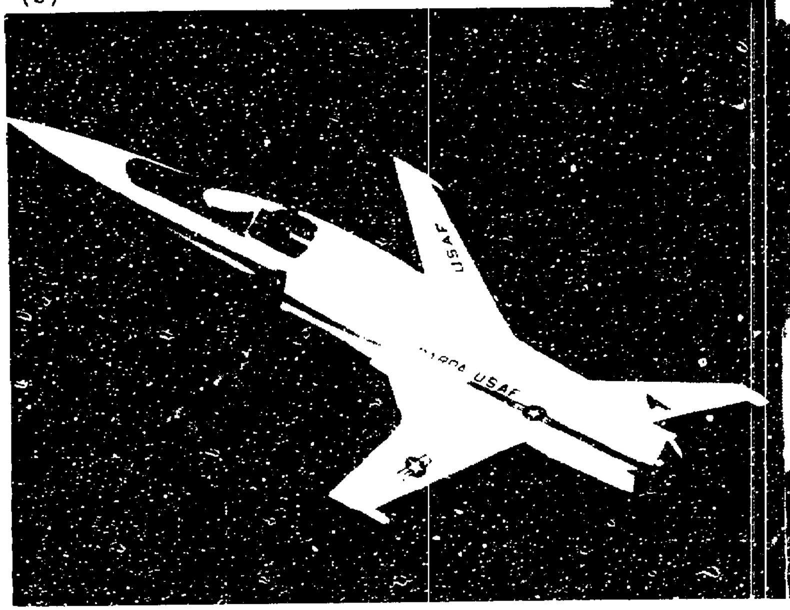
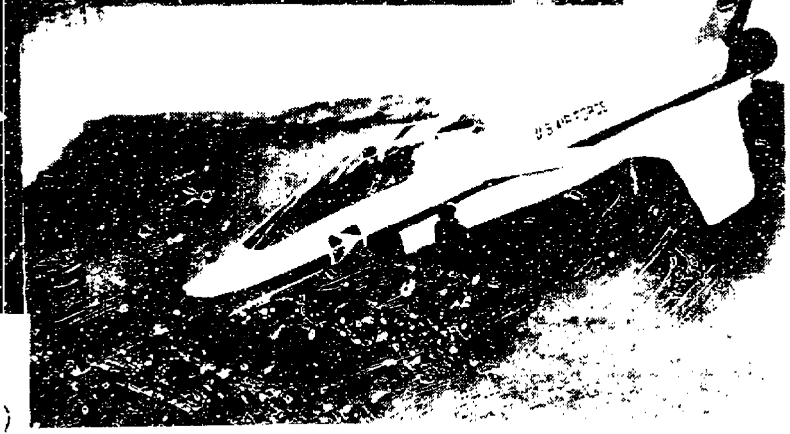


Figure 18. Forward swept wing demonstrator designs.

(a) General Dynamics.
(b) Grumman Aerospace Corporation.
(c) Rockwell International.

(b)





(c)

1. Grumman Aerospace Corporation

The canarded aircraft has a wing with a leading edge forward sweep of 29°, an aspect ratio of 4, and a taper ratio of 0.4. The wing has a 5.1% supercritical airfoil section. The wing structural design concept consisted of a box beam with graphite-epoxy covers and a full-depth aluminum honeycomb substructure. Graphite-epoxy front and rear spars are located along the 15% and 65% chord lines. The cover is a conventional 0°/90°/±45° laminate rotated 9° forward of the 40% chord line to produce favorable bend-twist coupling which reduces the wash-in effect of a forward swept wing and increases its divergence speed. Moreover, this laminate configuration provides plies that are continuous across the airplane centerline, thus enabling the covers to be made in one piece from tip to tip without a centerline splice.

The cover skins were sized for minimum weight using the Automated Strength Optimization Program, ASOP3 [33]. Resizing for the required divergence speed was accomplished using an extended version of the finite element analysis and optimization program FASTOP [34]. Aerodynamics were provided by Woodward and doublet lattice routines.

The aeroelastic model design concept evolved from a requirement to closely simulate the full-scale baseline demonstrator design, particularly in those areas which might influence the wing divergence characteristics. In this way, the resulting correlation between the experimental and predicted data could be applied with confidence to future variants of the baseline configuration. A sketch of the 0.5-scale model is shown in Figure 19. Its span is 81.6 inches.

The correct airfoil shape simulation of the 5.1% thick supercritical K section of the full-scale wing was considered a prime design requirement

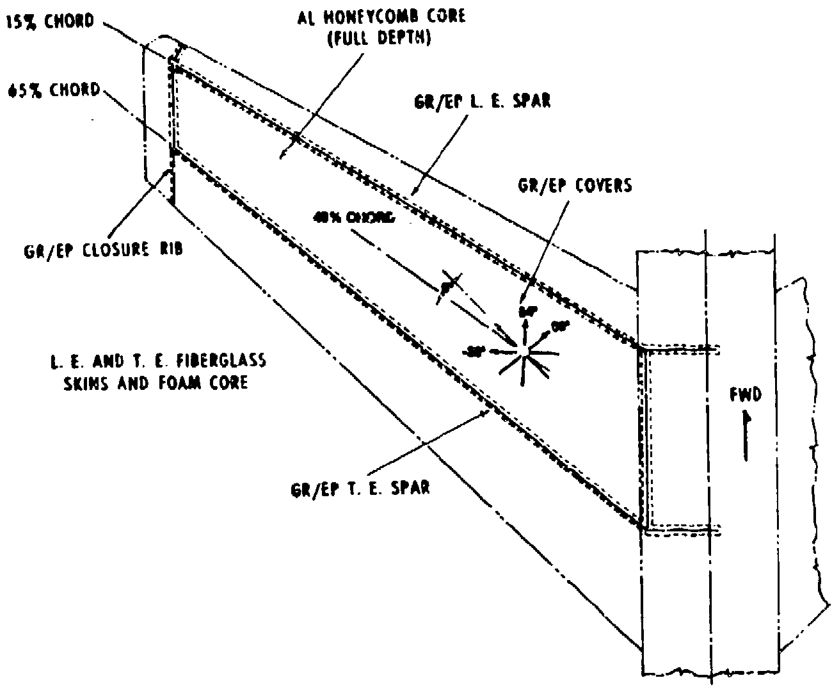


Figure 19. Grumman Aerospace Corporation 0.5-scale aeroelastic wind tunnel model design; leading edge sweep is -29°; aspect ratio is 4.

as it was believed that the chord profile would affect the wing divergence speed characteristics at transonic Mach numbers. This belief was confirmed by NASA Langley in the divergence tests discussed previously in this paper. The model wing box was fabricated from specially developed thin (1.37 mil), unidirectional graphite-epoxy tape which facilitated simulation of both the geometric and stiffness properties of the full-scale design. A coarser than desired skin thickness scale factor resulted from the use of this graphite tape. Although the tape was too stiff to accurately simulate the minimum ply regions in the outer panel of the full-scale wing design, it was considered acceptable. In particular, the stiffness was too high for the 90° and ±45° fiber directions. To minimize error, a non-symmetric model laminate was used in the tip region where there was only one ply in each the +45° and -45° directions.

The original program specified that the wing divergence test be followed by a flutter test in which the wing would be made flutter-critical through the use of adverse mass balance. During design studies, it was shown that the mass balance installation required to make the wing flutter-critical involved significant design changes that tended to compromise the divergence test program. For this reason, the flutter test phase of the program was deleted. However, it was still considered important to achieve dynamic similarity between the model and the full-scale wing design because of the possibility of using the model for future wing-store flutter evaluation.

Prior to the wind tunnel tests, experimental/analytical comparisons for the model were obtained from results of ground vibration, influence coefficient, proof load and mass property testing. Comparison between measured and predicted deflections showed a maximum difference of 12% at the wing tip.

A photograph of the model mounted in the wind tunnel is shown in Figure 20. The wing was mounted to a half-body fuselage with a lifting canard. During the wind tunnel test, data were obtained to project divergence speed by several methods. The Southwell and divergence index methods, discussed previously, were the primary methods used for divergence speed projections. The experimental divergence speed boundary is compared with the calculated boundaries in Figure 21. (Only the results using the Woodward aerodynamics are shown.) The difference between the two lower boundaries (analytical aerodynamics) is attributable to the difference between the predicted and actual structural influence coefficients. The difference between the analytical boundary using measured stiffness data and the experimental boundary indicates the accuracy of

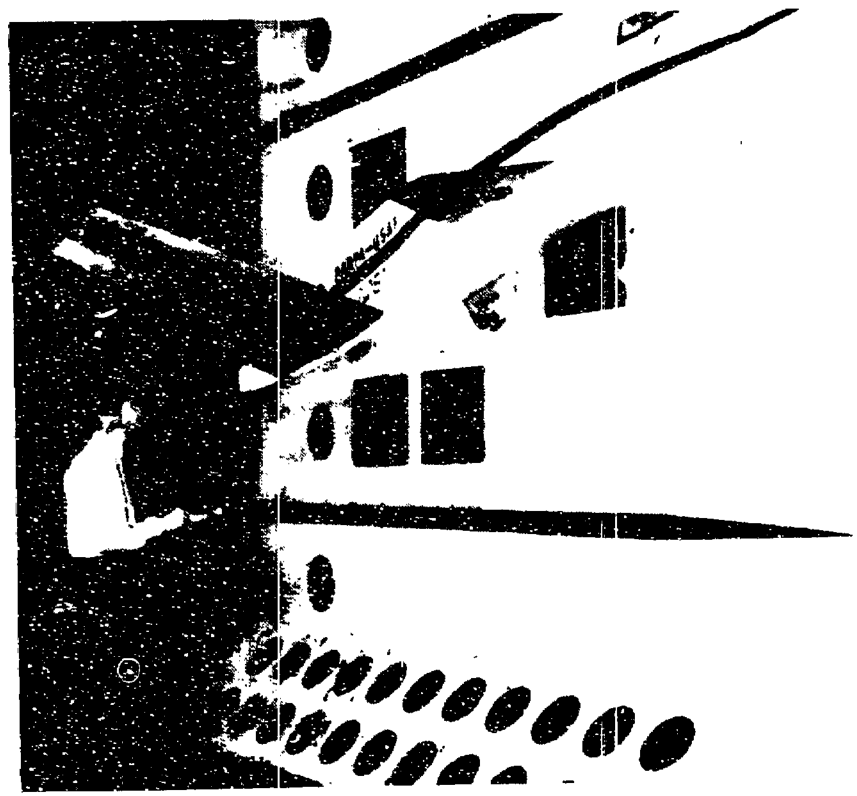


Figure 20. Grumman 0.5-scale aeroelastic wind tunnel model.

the aerodynamic analysis method. It is seen that the divergence speed predictions are conservative at subsonic and supersonic Mach numbers (7% at Mach 0.7 and 12% at Mach 1.15). Although the analytical and experimental boundaries tend to be parallel at lower subsonic Mach numbers (M < 0.7), this is not the case at supersonic Mach numbers. Divergence tests with the canard deflected, and also removed, indicated a negligible effect of the canard flow field on divergence speed. The experimental transonic dip occurs at approximately Mach 0.97.

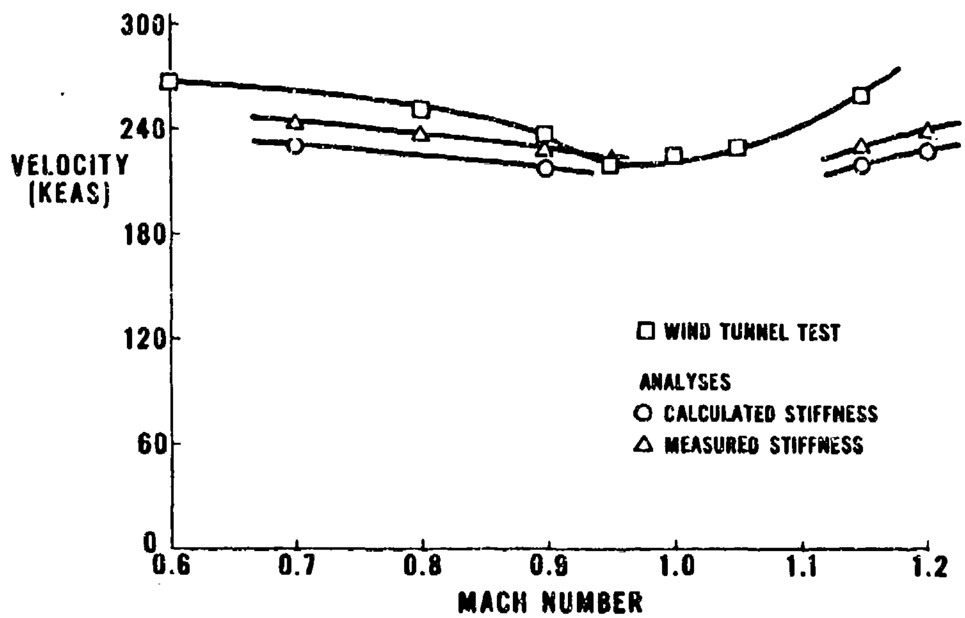


Figure 21. Divergence boundary for the Grumman 0.5-scale aeroelastic wind tunnel model.

2. Rockwell International

The Rockwell forward swept wing fighter aircraft incorporates a canard closely coupled with the wing. The wing has a leading edge forward sweep of 45°, an aspect ratio of 4, and a taper ratio of 0.4. The symmetric airfoil varies from a 4% thick root to a 5.5% thick tip and has moderate twist and camber. The wing box has a conventional rib-spar substructure with graphite-epoxy skin covers. The location of the front spar varies from the 25% chord at the root to the 15% chord at the tip. The aft spar lies along the 65% chord.

The wing skins were sized using TSO; a laminate consisting of 9°, 30° and -51° plies was developed. The reference axis for this laminate is the 40% chord line. The 9° plies in the outer wing are the main bending plies, and the 30° and -51° plies are the diagonals. Plies at 80° were added to the laminate to carry the chordwise loads and to fill the large angular gap between the diagonals. Final wing analysis was performed using the NASTRAN and FASTOP [26] finite element programs. Woodward and doublet lattice programs provided the aerodynamics. The wind tunnel model configuration was a semispan cantilever wing representing only the exposed portion of the demonstrator aircraft wing as shown

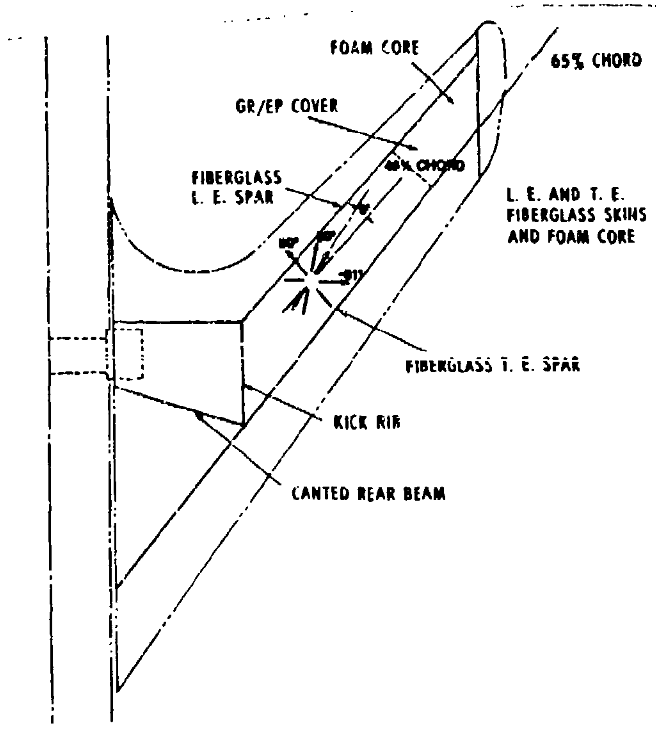


Figure 22. Rockwell International 0.6-scale aeroelastic wind tunnel model design; leading edge sweep is -45°; aspect ratio is 4.

in Figure 22. Model scale is 0.6 giving it a span of 64 inches. The wing panel is a replica in materials and structural arrangement of the aircraft wing, scaled both to model size and test parameters.

From model scaling investigations, it was determined that the required skin gage was thinner than could be produced with the available material. The structural scaling ratios are the result of the requirement for building a replica model. Since the divergence and flutter behavior depend upon the wing bending, torsional and coupling stiffnesses, skin thicknesses could be increased if the thickness ratios (t/c) of the wing section were reduced to keep the scaled stiffnesses unchanged. The model airfoil thickness ratios were reduced to 80% of the aircraft values, permitting 56% greater skin thickness with unchanged elastic properties. Satisfactory ply representation was achieved with the additional skin gages. Instead of the aircraft supercritical wing section, an uncambered 64A000 series airfoil section that varied from 4.4% t/c at the root to 3.2% at the tip was used. No twist was incorporated in the model.

Prior to the wind tunnel tests, the model was evaluated through comparisons of results of ground vibration, influence coefficient, proof load and mass property tests and analyses. Through structural analyses using measured influence coefficients and calculated influence coefficients, it was determined that the model was about 9% stiffer than had been predicted.

A photograph of the model mounted in the wind tunnel is shown in Figure 23. The same wind tunnel testing methods were used for the Rockwell model as had been used for the Grumman model. A nonlinearity in the measured wing bending moment variation with angle of attack data was

Figure 23. Rockwell 0.6-scale aeroelastic wind tunnel model.

observed, producing a slight variation of the experimental projection of divergence as a function of wing load level. The variation was not predicted by the linear analysis and appears to be aerodynamic since the structural characteristics of the model were completely linear.

Comparisons between the analytically predicted divergence boundaries using Woodward aerodynamics and the wind tunnel test results are shown in Figure 24. The analytical results corrected for measured model stiffness correlated well with the experimental divergence boundaries. The maximum difference between the subsonic experimental boundary at zero load and the Woodward analysis occurs at Mach 0.95, where the test boundary is within 3% in velocity of the analytical boundary. In the supersonic region, the analysis compares favorably with the experimental divergence boundary in the small range tested. The transonic dip in the experimental divergence dynamic pressure occurs between Mach 0.9 and 1.0.

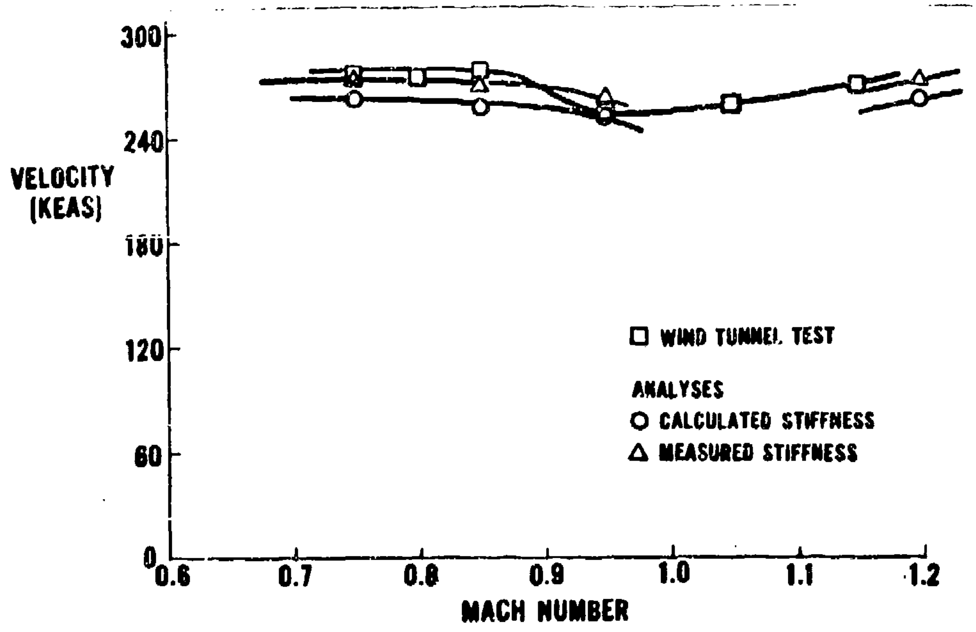


Figure 24. Divergence boundary for the Rockwell 0.6-scale aeroelastic wind tunnel model.

SECTION IV

CONCLUDING REMARKS

This report has presented a short history of aeroelastic tailoring technology applications using advanced filamentary composite materials in the forward swept wing. It has been demonstrated that the aeroelastic phenomenon of divergence, which has prevented the serious consideration of forward sweep on high performance aircraft, can be avoided with an efficient composite structure. Studies also have shown certain advantages of the forward swept wing fighter aircraft. Analytical methods used as design tools have been shown to conservatively predict the divergence speed of advanced composite forward swept wings both subsonically and supersonically. State-of-the-art transonic methods have not yet been applied to the wing divergence problem. A small amount of data has been obtained to illustrate that the airfoil shape affects the divergence speed in the critical transonic speed range.

The analytical and experimental data base for advanced composite, anisotropic laminates tailored for control of aeroelastic phenomena is very small. Each specific application will require a unique laminate that may vary with the location in the structure. Characteristics of the laminate will require definition in each case. Considerations of damage tolerance and durability are important in service application. Much of this work will be done within the design development program if the aeroelastic tailoring technology is applied to a service aircraft or a flight test demonstrator.

Divergence has been the most visible problem for forward swept wings and, hence, most of the emphasis has been placed on cantilevered wing divergence. Little work on other aeroelastic characteristics of forward swept wings has been done. Additional studies are needed to define aeroelastic characteristics of the unrestrained forward swept winged aircraft with either conventional tails or canards. Both the static and dynamic aeroelastic characteristics need to be determined for small, medium and large classes of aircraft, considering parameters such as wing sweep, aspect ratio, mass distribution, and static stability margins.

In addition, the effects of an active flight control system interacting with the airframe dynamics may be unique for the forward swept wing aircraft. Gust response and buffet characteristics should be evaluated. And finally, stores carriage, both from aerodynamic and inertial considerations, needs extensive work to determine both potentially beneficial and detrimental effects.

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