Aeroelastic Tailoring—Theory, Practice, and Promise

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Introduction

THE minimum-weight aspect of aircraft structural design is well known. Shanley[1] writes, the "primary function of the [aircraft] structure is to transmit forces through space...the objective is to do this with the minimum possible weight and at a minimum cost...the optimum structure is the one that does the best overall job of minimizing the undesirable quantities (weight, air resistance, cost, service troubles, production time, etc.)." From the standpoint of simplicity it is difficult to find fault with this time-honored view of *structural* optimization. Nevertheless, this narrow view may be increasingly difficult to defend as systems become more complex.

While weight is undeniably a measure of premier importance to the structural designer, the real objective is performance, which may involve weight as a constraint, but also includes, among others, range, payload, and turn rate. This philosophical point is raised at the outset, not to generate heated debate with those more knowledgable in the art of structural optimization than ourselves, but instead to anticipate conclusions about aeroelastic tailoring that involve only the high stiffness and lightweight aspects of composites. Rather than accentuating the minimization of undesirable quantities, this paper concentrates on depicting aeroelastic tailoring as a way of maximizing measures of performance.

Aeroelastic tailoring, as used herein, refers to a design process in which minimum weight is an ever-present objective. In addition, and equally important, aeroelastic tailoring involves the use of structural deformation of a lifting surface to achieve aircraft performance objectives not usually associated with structural design. These include, but are not limited to, maximizing the lift-to-drag ratio of a flexible surface, expanding the flight envelope, and improving ride quality and aircraft controllability. The effectiveness of aeroelastic tailoring relies upon the creation of external aerodynamic loads through controlled deformation.

The definition of *aeroelastic tailoring* has been somewhat illusive and confusing. Therefore, we would like to present a definition and suggest that it become the standard.

Aeroelastic tailoring is the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way.

Similarities exist between aeroelastic tailoring and active control methodology. For instance, with active control, the aeroelastic "plant" may be modified to allow existing control surfaces and a system of sensors to control the dynamic response. While passive in the sense that no external energy source is used directly, aeroelastic tailoring uses a form of preprogrammed control law to modify the behavior of a structural system. In this analogy, the aeroelastically tailored structure is both sensor and actuator; the "control law" is embedded within the structure in the form of material constitutive relations.

This article presents the historical background of aero-

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Presented as Paper 84-0982 at the AIAA/ASME/ASCE/AHS 25th Structures, Structural Dynamics and Materials Conference, Palm Springs, CA, May 14-16, 1984; submitted July 1984; revision received July 29, 1985.

elastic tailoring and the theory underlying the technology. A summary of trend studies that have been performed and a discussion of more specific applications are also presented. This paper concludes with an outlook of the future of the technology.

Historical Background

The design concepts intrinsic in aeroelastic tailoring are not entirely new, but were applied by Munk[2] in a wooden propeller design (Fig. 1) invented in 1949: "Propellers Containing Diagonally Disposed Fibrous Material." Munk described: "the purpose of the present invention [is] to provide a fixed pitch propeller the blades of which twist elastically and favorably as the thrust changes." This was accomplished by orienting the grain (fibers) of the wood in such a manner as to cause the blades of the propeller to deform favorably as the load increases.

The concept of elastic coupling between bending and torsional degrees of freedom in materials was probably well known to Munk since it can be found in the published literature of that time.[3-5] Such coupling was recognized to occur in crystalline substances and plywood. It is interesting that this coupling was most often regarded as a nuisance since it complicated accurate determination of material properties in both static and dynamic tests.

Four years after the issuance of the Munk patent, a novel wing design, known as the aero-isoclinic wing, was incorporated into the design of the Short S.B.4 or Sherpa prototype (Fig. 2, Ref. 6). Invented by Prof. G.T.R. Hill, this wing was designed so that its incidence, or inclination to the airflow, remained constant along the span despite flexural distortion. The importance of this invention was described as follows: "For air safety, and air combat, Professor Hill's aero-isoclinic wing, as exemplified in the Short Sherpa, is one of the most important design developments of recent years."[7] The aeroelastic characteristics of the aero-isoclinic wing are "achieved, in part, by placing the torsion-box well back in the wing." Hill's design was prompted by the desire to improve the aeroelastic performance of the wing, mostly concerned with airplane longitudinal and lateral stability as well as aileron reversal. The aero-isoclinic wing is an excellent example of aeroelastic tailoring. It satisfies the definition presented in the Introduction wherein aircraft performance is the driving goal.

Almost 20 years elapsed before the idea to passively control the wing incidence due to flexural distortion was again proposed. Interestingly, this was done without prior knowledge of the work of Munk or Hill. In 1969, as part of a program to improve transonic performance, General Dynamics submitted a proposal to the Air Force Flight Dynamics Laboratory (AFFDL) to apply advanced filamentary composite materials to the design of a supercritical wing.[8] The objective of the program was to provide the best wing "shape" (primarily twist distribution) at both cruise and a design maneuver condition. At General Dynamics, Waddoups, McCullers,and Naberhaus[9] had been pursuing the application of advanced composites for design improvements other than the obvious weight savings. With the encouragement of E.B. Maske,[9] they showed that the directional properties of composites could be used to provide a significant level of anisotropy to create coupling between bending and twisting deformation. This coupling produced the desired "shape" control for the supercritical wing. At this time the name *aeroelastic tailoring* was coined.[9]

Early in the same year (1969), unaware of General Dynamics' proprietary transonic improvement work, AFFDL prepared a request for proposals for the development of a pilot computer program for the aeroelastic and strength optimization of aircraft lifting surfaces using the unique properties of advanced filamentary composite materials. General Dynamics was selected for the subsequent contract.[10] The most significant development and product of this contract was the Wing Aeroelastic Synthesis Procedure, later simply called TSO.[11] Developed by Waddoups, McCullers, Ashton, and Naberhaus,[11] this computer program was made available to the United States aerospace community in 1972 and soon became synonymous with aeroelastic tailoring. References 12-18 provided the theoretical basis for the development of the TSO program.

Shortly after the initial release of TSO several American aerospace companies visited AFFDL seeking further information on aeroelastic tailoring and the TSO program. Among these were the North American Aircraft Division of Rockwell International and Grumman Aerospace Corporation. In 1975, Rockwell was selected to design and fabricate a 0.5-scale remotely piloted research vehicle of a highly maneuverable advanced technology (HiMAT) aircraft under contract to NASA. In February 1978, the first HiMAT test aircraft (Fig. 3) with aeroelastically tailored wings was rolled out in preparation for ground and flight tests.[19] The design approach was to satisfy the cruise goal by designing the wing with a jig shape and aeroelastically tailoring the canard and wing skins to deform to satisfy the desired 8-*g* maneuver goal. The flight-test program, begun in 1979, successfully demonstrated the benefits of aeroelastic shape control.

The most recent application of aeroelastic tailoring is on the X-29 forward-swept wing demonstrator aircraft (Fig. 4). This application was the result of applying a relatively new

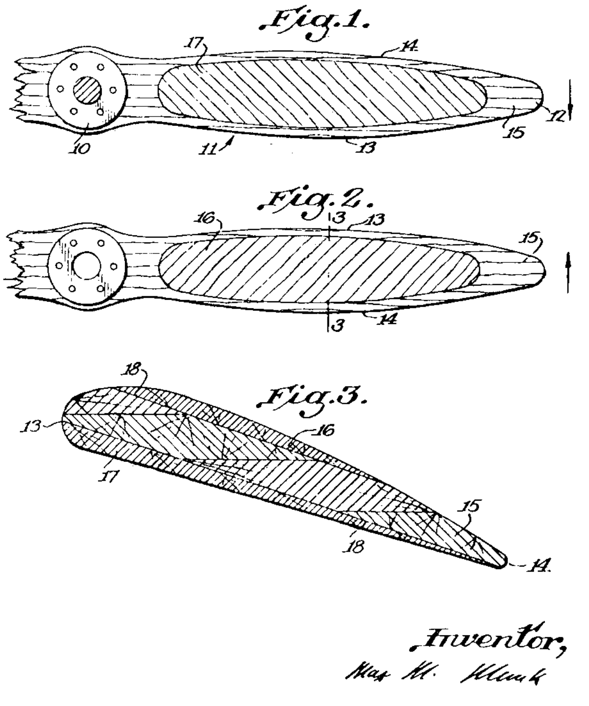


Fig. 1 Monk's wooden propeller design.[2]

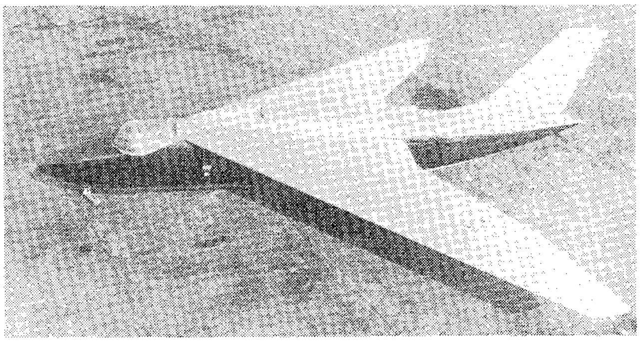


Fig. 2 Short S.B.4 Sherpa.[6]

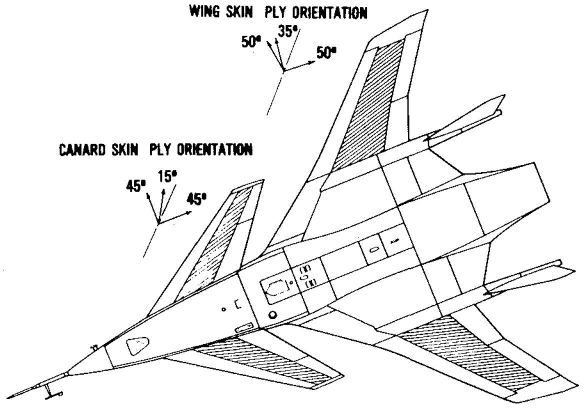


Fig. 3 HiMAT remotely piloted research vehicle.[19]

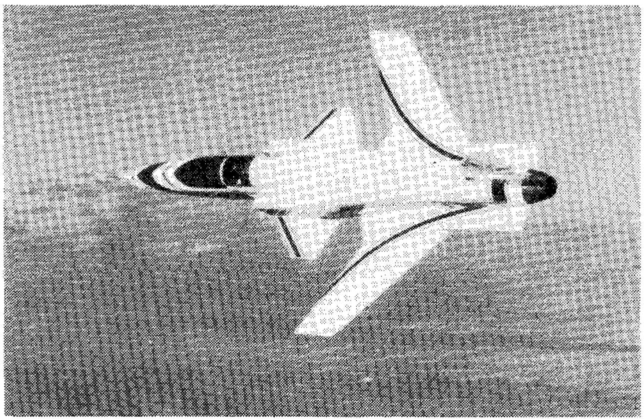


Fig. 4 X-29 forward-swept wing demonstrator.

technology, advanced composites, to take advantage of an old idea, sweeping the wings forward. Although the benefit of wing sweep had been proposed in 1935,[20] it was not until the 1940s that aircraft designers seriously considered sweeping a wing either forward or aft to reduce transonic drag. The aeroelastic characteristics of flexible wings, in particular the likelihood of aeroelastic divergence of the forward-swept wing, became the deciding factor in selecting aft-swept wings for virtually all high-performance aircraft.

The reintroduction of the forward-swept concept is due in large part to the doctoral dissertation of N.J. Krone.[21] In early 1973, Krone visited AFFDL to discuss a thesis topic in the area of aeroelastic optimization. Mutual discussions among Krone, M.H. Shirk, and T.A. Weisshaar led to the examination of the optimization of a forward-swept wing for aeroelastic dirvergence avoidance using advanced composite materials. In 1974, Krone showed that, with little or no weight penalty, tailored composites could be used to avoid divergence of a forward-swept wing. Grumman investigated forward sweep for improved transonic maneuvering performance, and used Krone's data on aeroelastic characteristics.[22] In 1977, mutual interest in forward-swept wings resulted in the Defense Advanced Research Projects Agency (DARPA) initiating studies to verify divergence avoidance with aeroelastically tailored composites, and to evaluate aerodynamic performance of forward-swept wing designs.[23] These studies, technically directed by AFFDL, were performed by General Dynamics, Grumman, and Rockwell. Following more in-depth research and wind tunnel testing, DARPA selected Grumman to design and build the forward-swept wing flight demonstrator, the X-29. The first flight of the X-29 occurred in December 1984. (Hill's aero-isoclinic wing concept is, in principle, the concept required to solve the divergence problem of the forward-swept wing.)

Over the past 15 years, numerous research studies in the aeroelastic tailoring area have proceeded in two distinct directions: 1) general studies of the mechanics to gain an understanding of the phenomenon, to evaluate theory, and to conduct trend studies to identify important parameters; and 2) the more specific application of the technology to particular designs. It is to these studies that our attention now turns.

Theoretical Foundation and Trend Studies

Aeroelastic tailoring has matured as the result of the developments in two technologies: fibrous composite materials and mathematical programming methods. The material characteristics of fibrous composites significantly increased aircraft structural design options. Equally important are the advances in mathematical programming methods that allow the designer to efficiently consider and use the multitude of design variables.

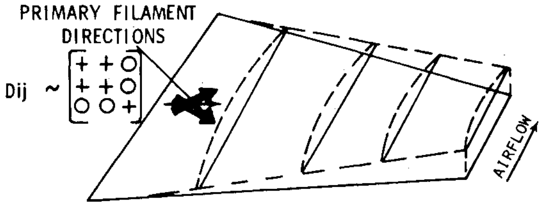
Advanced Composites

The orthotropic characteristics of composites, in particular their directional stiffness and strength properties and high stiffness-to-weight ratio, allow a latitude in design of a load-carrying structure that is not available with conventional metallic materials. There is a direct relationship between the directional stiffness characteristics designed into the structure, such as the skin covers, and the resulting deformation of the lifting surface under load. This directional stiffness is determined through the assembly or stacking sequence of the orthotropic lamina and can be calculated by laminate theory, such as presented in Tsai and Hahn[24] or any of the other excellent texts on composites.

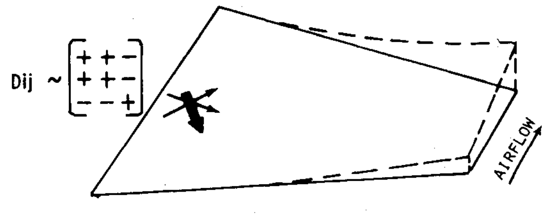
Most studies of composite fixed-wing aircraft are concerned only with structural laminates that are constructed of lamina arranged in a symmetrical but possibly unbalanced manner. Symmetrical means that a layer of material at some distance above the midsurface has identical ply thickness, angular orientation, and material properties as a lamina at an identical distance below the midsurface. Unbalanced means that, for every material ply in a laminate oriented at angle θ to a reference line, there is not an identical ply lying at an angle $-\theta$ with respect to this line.

A simple example of the deformation control possible through laminate design is presented in Fig. 5, from Ref. 25. The large arrows indicate the directions in which the highest percentage of the lamina is oriented for each example shown. A balanced symmetrical laminate such as shown in Fig. 5a will display orthotropic deflection with respect to a given set of axes (one axis is usually oriented along the wing structural axis) if there are enough plies in the laminate. An unbalanced symmetrical laminate such as shown in Figs. 5b and 5c will display nonorthotropic, or anisotropic, deflections about these axes; a bending moment causes not only curvature of a wing surface, but twisting of the surface as well. When positive bending causes nose-down twist, as shown in Fig. 5b, the deformation is defined as *washout*. If positive bending results in nose-up twist, Fig. 5a, the deformation is defined as *washin*. Washout and washin are also used herein to refer to the streamwise incidence of a swept lifting surface. An aft swept surface usually exhibits washout with positive bending, while a forward swept surface would exhibit washin.

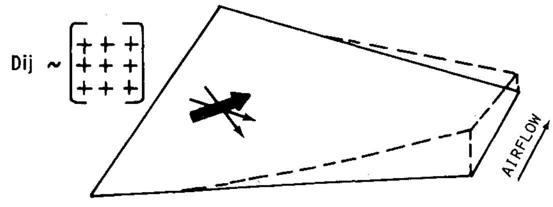
Notice the character of the plate bending stiffness matrices D_{ij}, also shown in Fig. 5. For an orthotropic laminate, D_{ij} has zeros in the third row and column indicating that bending and torsion are elastically uncoupled. However, for the anisotropic laminates, D_{ij} is fully populated. The magnitude and signs of the D_{13} and D_{23} elements govern the directional coupling between spanwise and chordwise flexure and twist



a. ORTHOTROPIC CHORD - SPAN BENDING COUPLING



b. ANISOTROPIC - BENDING - TWIST COUPLING (WASH-OUT)



c. ANISOTROPIC - BENDING - TWIST COUPLING (WASH-IN)

Fig. 5 Coupled deflection shapes.[25]

of the plate. The reader is referred to Ref. 24 for a complete discussion of the various methods of coupling the in-plane and out-of-plane deformations of laminated beams and plates.

Mathematical Programming (Optimization)

While there is significant latitude of structural design with fibrous composites, the number of design variables significantly increases the complexity of the design problem. For this reason, mathematical programming technology has played a key role in the development and application of aeroelastic tailoring. McCullers[26] states: "Advantageous utilization of the anisotropic properties of composites requires consideration of additional design variables and use of complex behavior and failure mode analysis techniques. Many metal design problems can be reduced to the determination of a single thickness for each member. A composite laminate, however, requires the determination of the number of plies and the orientation of each ply for the material(s) selected, which increases the magnitude and complexity of the design problem. Therefore, although optimization techniques are very useful in metal design problems, they are almost essential for the efficient design of composite structures."

In the last few years, excellent papers and articles have been published that summarize the structural and aeronautical optimization area. Among the more notable are papers by Schmit,[27] Ashley,[28] and Lansing et al.[29] The reader is referred to these articles and their extensive references for the background in the optimization area. Some of the references mentioned in Refs. 27-29 will be repeated herein since they are directly related to aeroelastic tailoring.

Methods and Trend Studies

In any research endeavor, activity usually proceeds at two levels. The first level involves the sophisticated application of numerical methods to support the design mission. Among the numerical methods used for aeroelastic tailoring, two have received widespread use: the Wing Aeroelastic Synthesis Procedure (TSO)[11] and the Flutter and Strength Optimization Procedure (FASTOP).[30] TSO is a preliminary design tool that employs a Ritz equivalent plate model structural idealization of the wing to minimize the degrees of freedom in the design. Nonlinear programming techniques are used to calculate minimum weight skin thickness and composite ply orientations to satisfy many constraints, including strength, minimum gage, weight, lift-curve, flexible-to-rigid lift ratios, deflected shape, and flutter and divergence speeds. On the other hand, FASTOP is a finite element based, two-step design procedure. In the first step, FASTOP redesigns the strength critical elements using the fully stressed design criterion. The flutter critical elements are redesigned in the second step using a uniform-flutter velocity derivative optimality criterion. The two steps are repeated as necessary to converge on a minimum weight design. The objective function (minimum weight) and constraints (minimum gage, flutter, and deflection) are not as varied as those found in TSO, but the procedure provides better structural detail by allowing many more degrees of freedom and design variables.

The second level of research endeavor referred to earlier attempts to unravel the mysteries and consequences of a new technology, to assess its limitations, and to anticipate problems associated with its application. This second level is primarily an educational endeavor; often the tools used are purposely not as sophisticated as they could be so that principles may be examined, uncluttered by a myriad of details. The authors must point out, however, that among this myriad of excluded details may lie the reasons why a theoretically sound idea cannot be brought to practical maturity.

In varying degrees of complexity, several theoretical studies have examined the various aspects and benefits of aeroelastic tailoring. In many studies, the structural deformation model used is that of a beam-like wing, since tailoring focuses on bend-twist deformation coupling. A number of references propose structural idealizations for use in aeroelastic analyses. In others, more complex models, including the effects of camber, are used to examine aspects of aeroelastic tailoring. The studies include the effects of variation of laminate parameters, usually ply orientation or some other measure of bend/twist coupling. In general, these studies have concentrated on three types of aeroelastic effects for a variety of unswept, swept-back, and swept-forward wings: 1) stability (divergence and flutter) 2) lateral control effectiveness, and 3) load redistribution.

In an early series of experiments, Ashton and Love[31] demonstrated the effect of laminated composite design on the natural frequencies, ultimate strength, and critical buckng loads of rectangular boron-epoxy plates. This work was performed to check the anisotropic plate analysis theory developed by Ashton,[32] which eventually led to the development of TSO. This study showed that symmetric angle ply laminates are most resistant to buckling. The experiments also showed that [0°, 90°] laminates were more resistant to buckling when the load was applied parallel to the outer ply than when it was perpendicular to the outer ply, thus demonstrating an effect of the laminate stacking sequence.

Housner and Stein[33] examined the effect of ply orientation for a symmetrical, cross-ply laminate upon flutter of a beam-like wing. Because the study was limited to symmetrical cross-ply laminates, bend/twist coupling was not present. Changes in flutter speed were shown to be dependent solely on changes in bending and torsional stiffness as plies were reoriented.

Bakthavatsalam[34] demonstrated the effect on flutter speed of aeroelastically tailoring wing and tail surfaces of a closely coupled wing-tail flutter model. Although tailoring the wing surface to washin produced the largest increase in flutter speed over the baseline aluminum design, it was shown that tailoring the closely coupled tail to washout and reducing its stiffness could also produce an increase in flutter speed. This passive technique of controlling flutter speed by tail deformation is directly comparable to results of active flutter suppression testing of this model using a rotating tail surface.[35] The washout tail surface design results in a wing deflection and tail rotation that have the same phasing as the active system. Although higher speeds were obtained using the active system, applying the passive technique may allow a cost and weight reduction.

In the course of TSO development at General Dynamics, McCullers et al.[36] performed an extensive series of experiments to provide a data base for the evaluation of static and dynamic response prediction methods specifically dealing with anisotropic plates. Stiffness and vibration characteristics were predicted, measured, and compared in detail. The parameters examined included: anisotropy, planform shape (leading-edge angle, taper ratio, and aspect ratio), curvature, boundary conditions, thickness distribution, skin thickness, shear modulus, and tapered cores.

To demonstrate the design latitude available for desired aeroelastic effects, Shirk and Griffin[25] used TSO to design three wing structures with the same planform to meet different objectives with flutter and control reversal constraints. Designing for minimum weight, maximum washin, and maximum washout, they demonstrated the ability to aeroelastically tailor a wing for center-of-pressure control either from a load relief standpoint or for increased flexible lift.

A series of studies by Weisshaar[37-41] focused on the use of laminated composites to increase divergence speeds of swept-forward wings. Although influenced by the work of Housner and Stein,[33] Weisshaar included bend/twist cross-coupling. A result of including this cross-coupling was the definition of a stiffness parameter that described the amount of interaction between bending curvature and twist rate. This stiffness cross-coupling parameter is a function of the orientation and stacking sequence of symmetrical laminate plies with respect to a reference axis along the wing.

Krone's[21] analyses of forward-swept wings used TSO to demonstrate that the divergence speed of forward-swept, lightweight fighter or transport wings could be increased through aeroelastic tailoring (Fig. 6). Krone's work prompted the studies of Weisshaar as well as Lerner and Markowitz,[42] Sherrer et al.[43] and Schneider et al.[44] Lerner and Markowitz[43] applied a modified version of FASTOP to perform initial design studies of the X-29. In a series of simple wind tunnel tests, AFFDL demonstrated the effect laminate rotation has on divergence speed. Sherrer et al.[43] showed that a simple rotation of a 0±45 family of orthotropic graphite-epoxy laminates would increase the divergence speed of a wing at various leading-edge sweeps (Fig. 7). In another study, FASTOP was incorporated in a routine developed by Schneider et al.[44] They used this routine to examine the variation of divergence speed with ply angle and the variation of optimized wing weight and divergence speed with wing-box sweep.

Weisshaar[40] also discussed the potential effects of bend/twist cross-coupling upon spanwise center-of-pressure position and lateral control effectiveness of swept-back and swept-forward wings. Results indicate that laminate design can be used effectively to increase the aileron reversal dynamic pressures. Reference 45 summarizes many of the results of Refs. 37-41.

Austin et al.[46] and Gimmestad[47] have investigated the effects of tailoring upon aircraft designs subject to a combination of realistic constraints. Austin discussed, in detail, a stiffness model that may be used to describe a laminated box-beam with spars. Gimmestad used a nearly identical model to examine the effects of laminate design upon load redistribution, flutter speed, and structural weight.

As evidenced by the discussion of Hill's aero-isoclinic wing, aeroelastic tailoring principles are not limited to composite materials. Gimmestad,[47] Williams,[48] and Gratke and Williams[49] have shown that the arrangement of stiffeners (spars and ribs) can be used to control directional stiffness and bend/twist cross-coupling. Gimmestad[47] concluded that, because standard design practice often results in the orientation of stringers nearly parallel to the wing rear spar, the direction of maximum stiffness is actually swept forward of the assumed elastic axis. This accentuates the wash-out condition already present on swept-back wings and may lead to smaller flutter margins than predicted by isotropic theory.

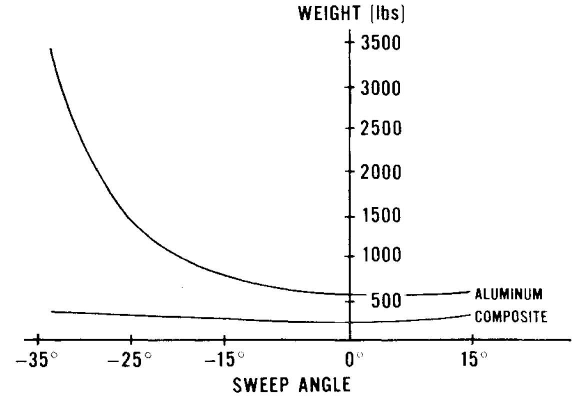


Fig. 6 Lightweight fighter wing weight vs sweep.[21]

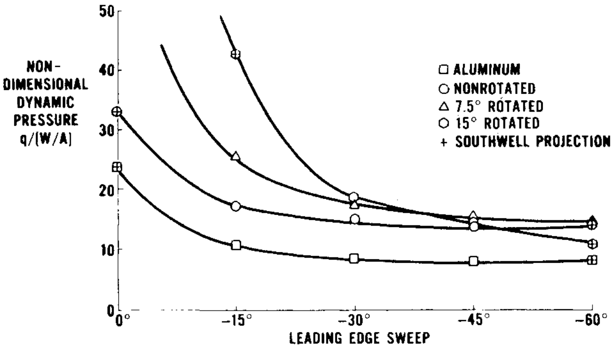


Fig. 7 Forward-swept wing aeroelastic studies.[43]

In work performed at the University of Texas, aeroelastic tailoring was applied by Dwyer and Rogers[50] and Rogers[51] to propeller design. Since the efficiency of propellers depends upon the angel between the blade mean chord line and the plane of rotation, Dwyer and Rogers used composites to provide coupling between the centrifugal force applied to the blades and the shearing strain in the plane of the blade cross section to passively control the angle of attack. They used an idealized thin-wall tube model to examine the variation of stress-strain coupling and allowable stress with property axis and composite fiber orientation. Their resulting design was a compromise between laminates with high allowable stress and laminates with large axial-strain/shear-strain coupling.

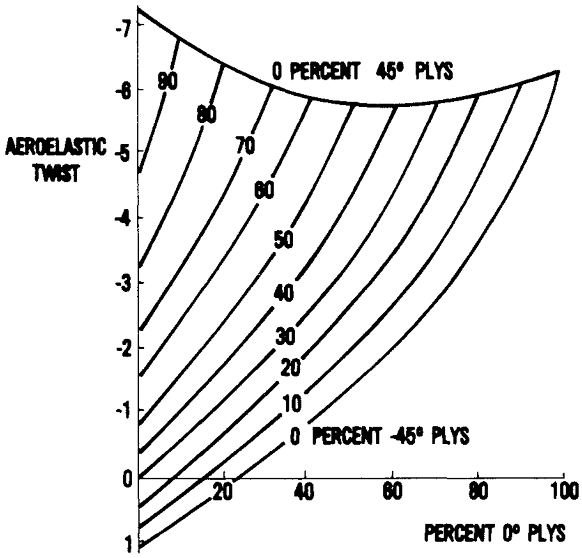
Studies conducted at the Royal Aeronautical Establishment (RAE) by Mansfield and Sobey[52] and Niblett[53,54] are significant in several aspects. Reference 52 outlines an analytical model of an anisotropic, single cell tube that may be used for tailoring studies. In addition, this study also focuses attention upon tension/twist coupling such as might be beneficial to rotor blade design. The likely effects of laminate design upon structural dynamic (as opposed to aeroelastic) characteristics of beam-like structures were also discussed.

Niblett[53] has also examined flutter and divergence of laminated swept-forward wings. In addition, he introduced the concept of bend/twist "cross-flexibility" and defined a nondimensional parameter so that tailoring studies can be separated from the problem of laminate definition. An earlier study by Austin et al.[46] also recognized the presence of a nondimensional parameter in the tailoring process as did Weisshaar.[37] Unlike Austin, Niblett[53] and Weisshaar[37] use nondimensionalization to define a bounded cross-flexibility parameter.

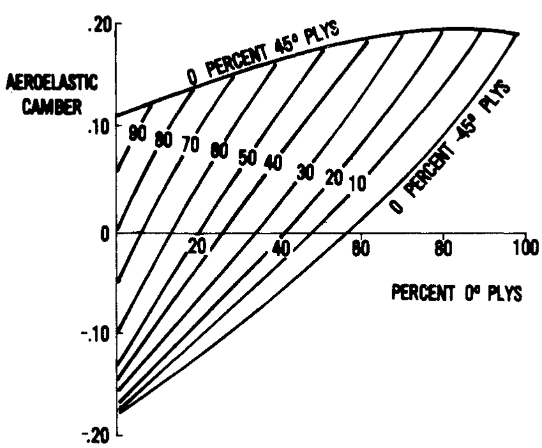
Studies by Weisshaar[55] and Weisshaar and Foist,[56] and similar studies by Hollowell and Dugundji,[57] Crawley and Dugundji,[58] and Jensen et al.,[59] concluded that restraint of the freedom of the chordwise bending mode can result in substantially different natural frequencies and mode shapes of highly coupled laminates. More importantly, the correlation between theoretical and experimental flutter velocities may be poor if the assumption of chordwise rigidity is not valid. A comparison of the algebraic expressions developed by Weisshaar, that results from the assumption of chordwise rigidity of the beam model, to those obtained from the Mansfield-Sobey tube model[52] and from a plate model, such as in Ref. 24, reveals some rather outstanding differences in stiffness predictions.[60] The differences resulting from these assumptions are of small consequence for slender metallic plates, but are important when advanced composite plate-like structures with a substantial proportion of off-axis plies are used. While this is perhaps not surprising to those well versed in the mechanics of composite materials, it is an important signal to the aeroelastician that conventional assumptions regarding unconventional materials must be carefully examined in light of modern developments.

The goal of studies by Lynch et al.,[61] using an improved version of TSO, was to determine the potential performance benefits available from aeroelastic shape control. Since aeroelastic twist and camber affect performance, Lynch et al. undertook an analytical study to determine the amount of camber and twist achievable by aeroelastic tailoring. A 0 ± 45 family was examined in which the laminate contained varying percentages of plies in each of the three orientations. Figure 8 demonstrates the latitude of twist and camber available on a lightweight fighter wing at a given design condition. Rotating the laminate ± 10 deg also resulted in significant camber variations and tip twist angles. In addition, Ref. 61 examines the effect of these orientations on roll effectiveness, flutter speed, flex-to-rigid ratio, and tip deflection. Also demonstrated is the ability to achieve performance benefits by increasing span or decreasing wing depth due to the strength and stiffness characteristics of composites.

Foist[62] and Weisshaar and Foist[56,63] examined the potential effects of wing root boundary conditions on the flutter and divergence of laminated composite lifting surfaces. One interesting effect uncovered during these studies was that laminate designs that yield high flutter speeds when the wing is cantilevered at the root may suffer from body-freedom flutter when the wing root is allowed freedom to move with the vehicle. This possibility was illustrated for the case of a 30-deg sweptback laminated composite wing in Ref. 62. Results appear to call for caution during structural optimization studies where flutter and divergence are design constraints for a washin-type wing (such as would be desirable for control effectiveness or lift effectiveness). It may be prudent to include rigid-body modes in the flutter analysis during the design iterations. At the very least, in the final design the cantilever wing flutter speed should be compared with the flutter speed of the freely flying aircraft.



a) Twist control.



b) Camber control.

Fig. 8 Twist and camber control by ply distribution.[61]

Until recently, most aeroelastic tailoring parameter studies have used laminate ply orientation as the design parameter; the notable exceptions are the previously mentioned RAE studies.[52-54] The advantage of defining a baseline design, complete with ply thicknesses and stacking sequence, is that the physical nature of the problem is easily understood. However, uncovering, understanding, and applying basic principles is difficult because of the multitude of possible laminates that might be examined. Following the lead of Niblett,[53] Weisshaar and Foist[56] developed a stiffness cross-coupling parameter ψ in terms of the bending and torsional stiffness and stiffness cross-coupling parameters Weisshaar developed in Ref. 37 (*EI, GJ,* and *K,* respectively). This stiffness cross-coupling parameter for beam analysis is

$$\psi^2 = \frac{K^2}{EIGJ} < 1 \tag{1}$$

or

$$\psi = K/\sqrt{EIGJ} \tag{2}$$

The advantage of this particular cross-coupling parameter is that tailoring studies can be conducted without a detailed definition of the laminate geometry, yet the parameter is bounded between ± 1. In the case of plates, three parameters are present that are dependent on the elements of the plate flexural modulus matrix. These parameters are:

$$\psi_1 = D_{16}/\sqrt{D_{11}D_{66}} \tag{3}$$

$$\psi_2 = D_{26}/\sqrt{D_{22}D_{66}} \tag{4}$$

$$\bar{\nu} = D_{12}/\sqrt{D_{11}D_{22}} \tag{5}$$

and must satisfy the requirement

$$1 - \psi_1^2 - \psi_2^2 - \bar{\nu}(\bar{\nu} - 2\psi_1\psi_2) > 0 \tag{6}$$

The parameter $\bar{\nu}$ reduces to Poisson's ratio for isotropic structures. The ψ_1 and ψ_2 parameters can be regarded as primary aeroelastic tailoring parameters, since they control coupling between "bending" and "twisting" curvatures. The approach of using a stiffness cross-coupling parameter to examine aeroelastic stability of beam-like structures was used in Refs. 63-65.

In the area of structural dynamic response and flutter, control through tailoring is achieved largely through the changes in normal mode shapes brought about by stiffness cross-coupling. Figure 9 illustrates the effect of rotating a percentage of plies forward of a spanwise reference axis upon the second normal mode of a beam-like surface. This mode shape begins as a pure torsion mode when plies are oriented parallel to the reference axis and ends as a mode resembling second bending when plies are oriented perpendicular to the reference axis. For intermediate orientations, the node lines for this mode curve aft of the reference axis.

Conventional wisdom suggests that such node-line behavior will cause a decrease in flutter speed as the node line lies closer to the ¾-chord position. This is found to be true, as shown in Fig. 10. This figure shows the variation of flutter speed and divergence speed when only laminate cross-coupling is allowed to change while *EI* and *GJ* parameters are held fixed. Positive β-ply orientations cause negative stiffness cross-coupling; that is, upward bending is accompanied by nose-down twist or washout. From Fig. 10, it is seen that the requirements for maximizing flutter speed (washin) are in conflict with those for maximizing the divergence speed (washout). An additional interesting feature of Fig. 10 is that it is possible to preclude flutter (at the expense of a low divergence speed) for certain ranges of stiffness cross-coupling. These results are similar to those found by Austin et al.,[46] although their nondimensional parameter is different than that used for Fig. 10.

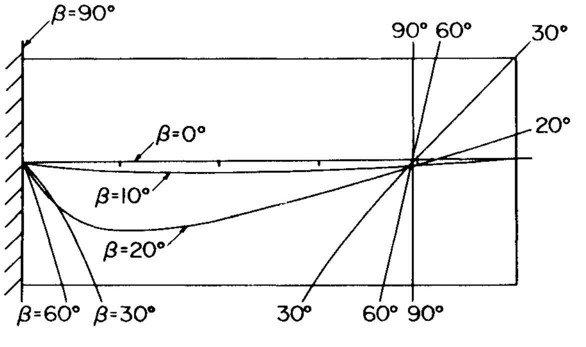


Fig. 9 Free-vibration node lines, second normal mode.[64] β measured relative to the spanwise axis, positive counterclockwise.

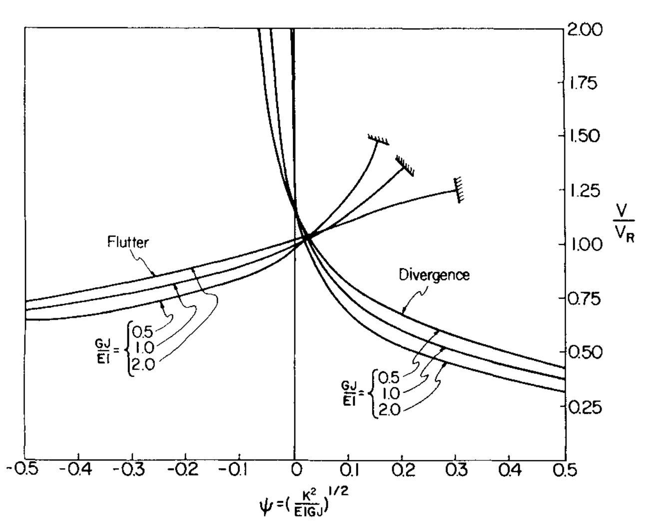


Fig. 10 Flutter and divergence speeds vs cross-coupling parameter.[65]

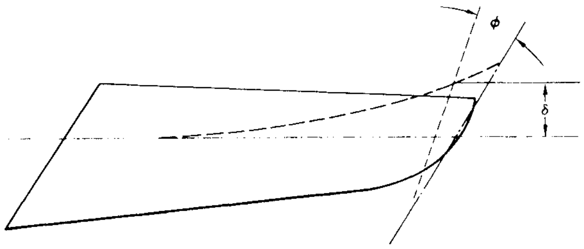
The results in Fig. 10 appear similar to those found by sweeping the wing while maintaining constant aspect ratio. Positive stiffness cross-coupling is analogous to forward sweep while negative stiffness cross-coupling resembles aft sweep. Many conclusions about the aeroelastic effect due to wing sweep may be applied, albeit cautiously, to the aeroelastic effects due to composite ply orientation.

Design Studies and Specific Applications

Modern application of aeroelastic tailoring technology has occurred during the past 15 years, from the beginning of the transonic improvement program in 1969 to the X-29 today. A sample of the results of design studies performed during this time period is presented to illustrate the performance benefits possible from application of the technology.

Transonic Aircraft Technology Program

The Transonic Aircraft Technology (TACT) program provided the first opportunity to apply aeroelastic tailoring with advanced filamentary composite meterials.[66,67] The objective of this program was to obtain efficient aerodynamic performance at both cruise and 7.33-*g* maneuver conditions. To obtain this performance, the wing was designed with a jig shape for the cruise condition and to wash out at the 7.33-*g* maneuver condition. Additional constraints on the design included pivot loads, wing loads, flutter speed, and panel buckling. Anisotropy was provided by composite cover skins to maximize wing aeroelastic twist from 1 to 7.33*g* while maintaining weight savings. Some of the results from a parametric study[66] examining the effect of lamina orientation and wing-box geometry variation on wing twist are summarized in Fig. 11. Demonstrating that shape control could be achieved, this analysis showed that material bend/twist coupling variations have a greater effect than variations in box chord dimension. These studies also indicated that the twist of the composite wing is twice that of an aluminum wing, and pivot loads may be reduced by 4%. Also, flutter speed requirements were satisfied without a weight penalty.



- CONSTANT WEIGHT
- 35° SWEEP
- RIGID AIRLOADS
- GRAPHITE-EPOXY
- 1/24 SCALE MODEL
- 20,000FT 7.33G

ORIENTATIONS	THICKNESS RATIOS	DEFLECTION (δ- in.)	TWIST (ϕ- Deg.)
0/ 45/-45	2-2-1	0.82	1.64
0/ 60/-60	1-1-1	1.12	-2.77
-10/-45/ 67	3-5-1	1.18	-5.26
0/-30/-60	1-4-1	1.12	-5.60
-15/-45/-75	1-2-1	1.40	-6.23
-38/-73	1-1	1.97	-8.20

Fig. 11 TACT model Rayleigh-Ritz twist study results.[66]

A 1/24-scale aeroelastic wind tunnel model of the TACT design was tested to evaluate transonic aerodynamic performance at cruise and maneuver conditions. This model had the desired twist distribution at the 1-*g* cruise condition and also had the maximum possible wash-out twist at the simulated 7.33-*g* maneuver condition. The drag polar in Fig. 12 illustrates the reduced drag due to lift of the wash-out design compared to rigid built-in twist designs and illustrates that weight need not be the only objective in the design of an efficient lifting-surface structure.

Advanced Design Composite Aircraft

In 1975, AFFDL contracted Grumman to define the benefits and results of the unrestrained application of advanced composite materials to an Advanced Design Composite Aircraft (ADCA).[68] The primary objective of the ADCA program was the definition of a smaller, lighter, and less costly aircraft, capable of performing a supersonic penetration interdiction fighter mission at lower life-cycle costs than a metallic counterpart. One of the technologies evaluated in the ADCA program was aeroelastic tailoring of the wing and vertical stabilizer.

Since it had direct impact on mission performance and takeoff gross weight, wing shape at supersonic cruise was an overriding requirement. However, the transonic maneuver condition was also important. Tailored and nontailored aeroelastic wing twist characteristics were determined, subject to the constraint of minimum structural weight and strength at ultimate load. The tailored design met supersonic cruise requirements, but showed negligible improvements in transonic maneuverability. This was not too surprising since no significant center-of-pressure variation was found between the supersonic cruise and the transonic maneuver conditions investigated.

Tailoring of the vertical tail, which included rotating the spanwise plies 15 deg aft of the main load-carrying axis, demonstrated a significant flutter speed improvement, as well as increased effectiveness in generating yawing moments. The increased effectiveness of the tail may be exploited in one of two ways. First, by maintaining tail size, lateral directional stability and rolling performance are increased and lateral maneuver loads are decreased. Also the response requirements of the control system may be relaxed. Second, without changing stability of the aircraft, tail size may be reduced, thereby decreasing drag and tail weight.

AFFDL Aeroelastic Tailoring Contracts

Under three contracts with AFFDL, General Dynamics conducted studies examining the benefits of aeroelastic tailoring. The first study[69] resulted in the test of a demonstration component, a 3/8 scale of a conceptual fighter wing, as well as the development of TSO. The wing design goal was to increase aerodynamic effectiveness through elastic camber and twist. To choose the design goal, a parametric study involving ten candidate minimum-weight graphite-epoxy skin designs was conducted. Two different objectives were explored: 1) maximum static aeroelastic lift, and 2) maximum load relief.

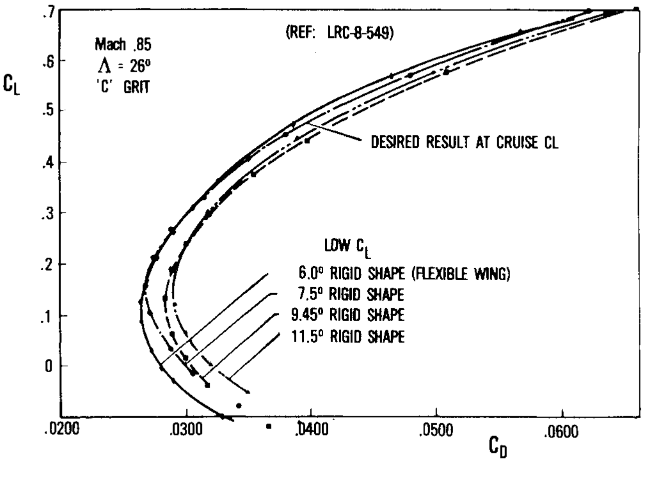
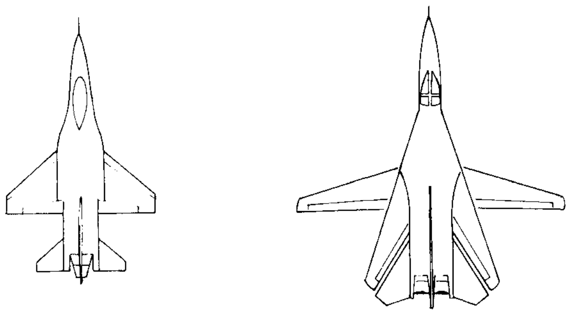


Fig. 12 Drag polars for the TACT composite aerolastic compared to rigid models.[66]

The design objective chosen was to maximize the flex-to-rigid lift ratio through camber and twist control, yet maintain an uninterrupted tip-to-tip spanwise ply orientation. Graphite-epoxy skins, full-depth aluminum honeycomb core, and fiberglass spars were used. Both finite element and TSO analyses were compared with influence-coefficient and vibration tests. Analyses agreed with test results to within 5% for both deflection and frequency. Although some compromises were required in the component design, the results of this program provided confidence that analytical and design methods were adequate to proceed with further aeroelastic tailoring studies.

In the second aeroelastic tailoring study,[70] the TSO computer code was updated, improved, and used to study performance benefits through shape control. Two wing configurations, shown in Fig. 13, were aeroelastically tailored: a low aspect ratio fighter wing and a high aspect ratio bomber wing. The results of this study were: 1) a wing that is to be fabricated of composites should be aeroelastically tailored to provide acceptable aerodynamic characteristics, otherwise a low drag



F-16 FIGHTER		FB-111 BOMBER
3	ASPECT RATIO	8.91 to 2.10
280 FT^2	AREA	550 FT^2
40°	Λ_{LE}	16° to 72°
.04	t/c	.10
.2275	λ	.250
16,900 LB	DESIGN GROSS WT	109,000 LB

Fig. 13 Baseline design study for low and high aspect ratio wings.[70]

● Wing	Full Scale
Area	338.29Ft^2
Span	399.726 in.
The 0 Root Chord	200.738 in.
Mac, ξ	138.882 in.
Aspect Ratio	3.28
Taper Ratio	0.2142
Sweep	40.0°
Airfoil	NACA 64A004 @ Tip NACA 64A003.5 @Root
Incidence	0°
Twist	0°
● Fuselage	
Overall Length	547.000 in.
Max Body Diam	55.400 in.

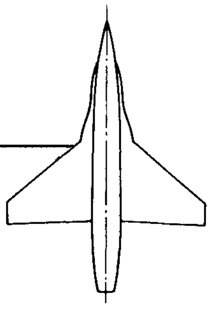


Fig. 14 Selected wing/body/strake configuration.[72]

polar break lift coefficient or an undesirable aerodynamic center shift could completely negate the benefit of reduced weight; 2) the dual design objectives of maximizing camber while achieving high negative twist should be used to obtain the best drag polar; 3) the weight savings from composites provide the possibility of improved planform geometry (analyses indicated that an extended span wing provides a 5.8% greater sustained turn rate than a wing with a scheduled leading-edge flap at Mach 0.9, and a 2.3% increase at Mach 1.2); and 4) a 13.6% increase in ferrying range and 15.6% increase in refuel altitude were predicted by extending the span of the bomber wing configuration.

The objectives of the third contract with General Dynamics[71-73] were to obtain wind tunnel data for tailored wing designs and to demonstrate the range of beneficial aeroelastic response attainable. The wing/body-of-revolution/strake configuration illustrated in Fig. 14 was selected for this study. The wing planform was the outgrowth of an independent R&D program concerned with providing good transonic maneuverability without sacrificing supersonic performance. The model planform was similar to the extended-span fighter wing mentioned previously.

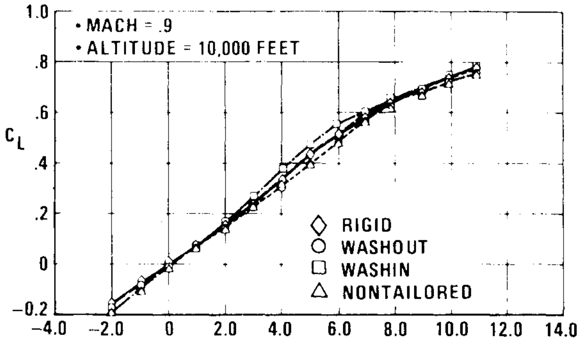
Three sets of aeroelastic wings and a set of "rigid" steel wings were designed. The aeroelastic wings designs represented three different tailoring objectives. The first wing was designed for reduced drag at transonic maneuver conditions through achievement of aeroelastic camber and negative twist (washout). The aerodynamic benefit of the second was increased lift-curve slope through positive twist (washin) and camber. Such a design is applicable to vertical tail surfaces, where conventional designs often lose effectiveness due to aeroelastic effects. The wash-out and wash-in wing designs provided two significantly different concepts for the evaluation of analysis and design methods while illustrating the wide range of deformation control available with composites. The third aeroelastic wing, a nontailored design, simulated a balanced composite wing laminate with equal amounts of crossplies. The steel wing established a conventional model data base. The baseline aeroelastic shape was provided by the nontailored design and compared to the data from the tailored models to determine the benefits of aeroelastic tailoring.

A unique feature of this test was the simultaneous acquisition of all data (force, pressure, aeroelastic shape, and steady-state and dynamic bending moment), which provided an excellent data base for evaluation of design methods. This program demonstrated that aeroelastic tailoring of a wing can produce a significant reduction in transonic drag due to lift (at the design point, a 23% reduction compared to the rigid wing), or for a different design approach, a significant increase in lift-curve slope (16% increase compared to the rigid wing). Figure 15 presents these results. The program also demonstrated the effectiveness of the analysis/design procedures in preliminary design.

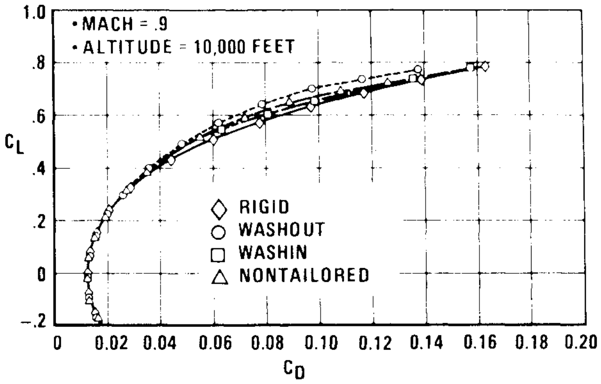
Flutter models of the two aeroelastically tailored wings were also wind-tunnel-tested. Comparisons of flutter analysis results with test results for the wash-in wing verified that state-of-the-art analysis methods are satisfactory. No test data were obtained for the wash-out wing. However, analysis indicated that the flutter speed for the wash-out wing is higher than for the F-16 metal wing. This was an unexpected result since the aeroelastically tailored wings have greater areas and aspect ratios and thinner airfoil sections than the F-16 wing.

Wing/Inlet Composite Advanced Development Program

During preliminary design activity in the Wing/Inlet Composite Advanced Development (WICAD) program,[74] General Dynamics performed a small aeroelastic tailoring study. The objectives of the WICAD program were to provide a flightworthy wing and inlet for the F-16, and develop and demonstrate advanced composite conceptual design technology that could be used to manufacture low-cost, lightweight, and durable fighter wing and inlet structures.



a) Lift characteristics.



b) Drag characteristics.

Fig. 15 Lift and drag characteristics at design condition.[72]

Wing skin trade studies using TSO, defined a wing skin with a laminate weighing 67.5% of an aluminum skin, a flexible-to-rigid lift ratio of 1.116, and a flutter speed 12.7% greater than the aluminum skin design. The program was terminated after only seven months preventing validation of the aeroelastically tailored design through ground or flight testing.

Highly Maneuverable Advanced Technology

The first modern aircraft to fly with aeroelastically tailored lifting surfaces was the HiMAT remotely piloted research vehicle, designed and built by Rockwell for the NASA Dryden Flight Research Center.[75-78] The outboard wing and the canard were aeroelastically tailored to provide additional performance in transonic maneuverability (a sustained 9-*g* turn at Mach 0.9 and 25,000 ft) while maintaining subsonic cruise performance. Flight testing began in 1979 to validate the performance objectives. The aeroelastically tailored surfaces of the HiMAT aircraft are shown in Fig. 3.

The HiMAT wing and canard were aeroelastically tailored using a two-phase iterative process: preliminary sizing using the advanced composite beam theory of two Rockwell computer codes, AC87 and AC89,[76] followed by a detailed design verification with NASTRAN. This process was repeated until twist and strength requirements were met. The resulting outboard wing ply orientation and distribution are also shown in Fig. 3.

Results of a 110% limit load (8-*g*) test conducted on the wing and canard did not correlate well with analytical results. Detailed investigations revealed that the analysis input data included inaccurate material properties. The investigations also revealed that the laminate behaved nonlinearly, especially in the transverse property direction. Aside from these difficulties, the HiMAT program demonstrated the feasibility of unconventional, unbalanced, graphite-epoxy laminates in controlling aeroelastic twist.

Forward-Swept Wing

In previously discussed application studies, aeroelastic tailoring has been applied primarily to improve a performance parameter. In the case of the forward-swept wing on a high-performance aircraft, aeroelastic tailoring was applied for divergence avoidance and feasibility of the design. DARPA funded feasibility studies to show that aeroelastic tailoring could be successfully applied to a flight demonstrator. General Dynamics, Grumman, and Rockwell performed these studies. Reference 79 presents an excellent summary of the aeroelastic development work leading to the flight demonstration of a small, fighter-class aircraft, the X-29.

Following the feasibility studies, two aeroelastic wind tunnel programs, conducted by Grumman[80] and Rockwell,[81] assessed the accuracy of predicting wing divergence speed. The wind tunnel tests were significant in that an understanding was obtained of the static aeroelastic behavior of a fixed-root forward-swept wing at speeds near divergence. In addition, and of no less importance, model design and fabrication procedures for simulation of aeroelastic properties of tailored, advanced composite wings were developed, as were subcritical divergence test techniques.

Although Grumman and Rockwell used different aircraft design philosophies and aeroelastic tailoring computer procedures, the laminates designed to raise the divergence speed were similar. Grumman used FASTOP and found that rotating a conventional [0, ±45, 90] laminate, so that the primary bending plies are 9 deg forward of the reference structural axis, added the desirable bend-twist coupling necessary to minimize the wing wash-in tendencies. Rockwell used TSO to design a laminate with cross plies oriented 30 deg forward and 51 deg aft of the reference axis, but with the primary bending plies also oriented 9 deg forward of the reference axis.

The models (Figs. 16 and 17) were tested in the NASA Langley Research Center 16 ft transonic dynamics tunnel. Experimental results (compared with analyses in Figs. 16 and 17) demonstrated that wing divergence could be efficiently avoided through application of advanced composites tailored for aeroelastic shape control.

Other Application Studies

Gimmestad[47] performed a brief study of a cargo transport airplane to illustrate the effect of composites on the aeroelasticity of a high aspect ratio wing with an aft sweep of 35 deg. Effects of flexibility, jig twisting, and anisotropy on a composite and a conventional aluminum wing were explored. Gimmestad's conclusions included: 1) the need for accounting for aeroelastic effects and jig twist in preliminary design for performance reasons; 2) anisotropic effects can have several consequences, particularly on stability and control; and 3) anisotropic effects in conventional metal structures obtained by structural element orientation are similar to those in composites, although not as pronounced.

In a second aeroelastic tailoring study, Gimmestad[82] examined a composite winglet for a KC-135. Using TSO, he showed that the winglet could be designed for substantially larger aeroelastic losses (washout) in order to reduce wing bending moments.

Triplett[83] has performed studies using TSO on fighter aircraft and has shown that aeroelastic tailoring can play a significant role in their design. His applications included the F-15 composite wing, a preliminary design horizontal tail, a prototype aircraft movable outer wing panel, and a conceptual aircraft wing. With weight as the objective function, Triplett designed the F-15 wing with a 55-lb weight savings. With wing twist as the objective function, drag reduction and an improvement in roll effectiveness were achieved. For the conceptual aircraft wing with weight as the objective function, a 3% savings per side was achieved, but with a 4.6 deg wash-out twist as the objective, the weight increased 2.5%. In a validation study of the TSO procedure using the F-15 wing, Triplett showed that, with skillful use of this preliminary design procedure, good results may be obtained in final design.

Using TSO, Triplett[84] also conducted a study comparing forward and aft-swept wings. His objective was to determine the weight penalty to prevent divergence of the forward-swept wing. He showed no weight penalty because satisfying strength requirements precluded divergence. Induced drag was shown to be higher on the forward-swept wing than the aft-swept wing.

Sensburg et al.[85] studied the application of aeroelastic tailoring for passive load alleviation on an extended wing version of the Airbus A300. It was shown that a rigid extended wing resulted in a 7% increase in root bending moment, while the aeroelastically tailored extension increased bending moments only 1.7%.

A recent study by Schweiger et al.[86] concluded that judicious use of laminate orientation on a high aspect ratio glider could be used to control wing/body flutter arising from

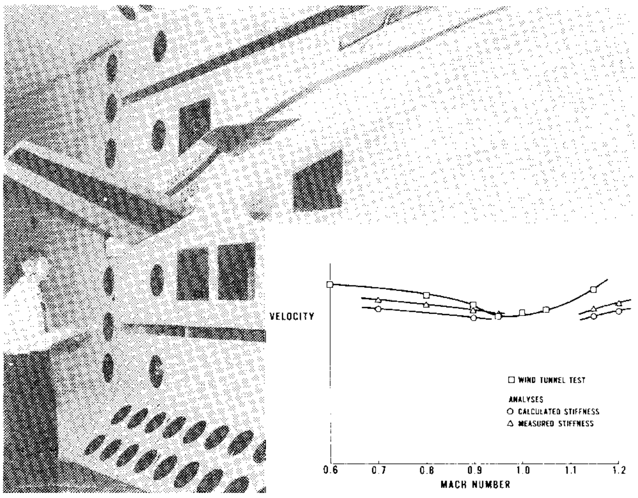


Fig. 16 Grumman forward-swept wing aeroelastic model.[79]

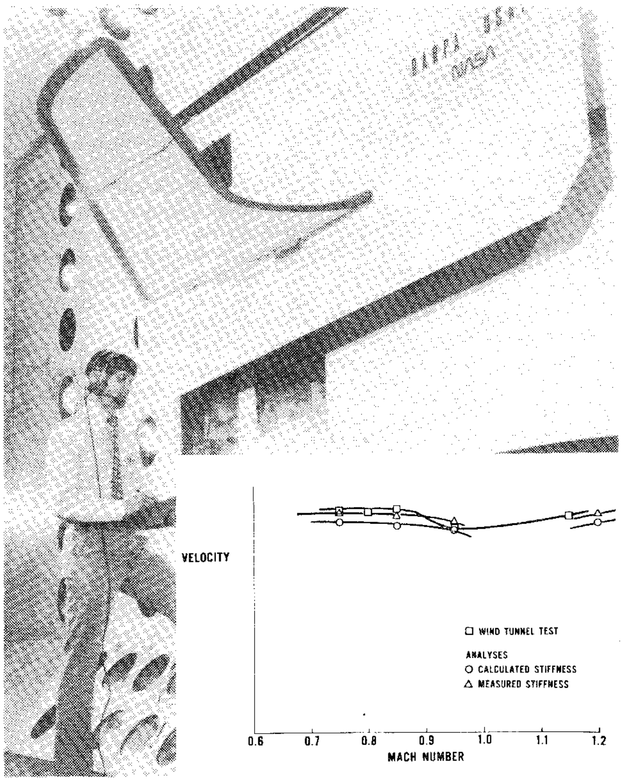


Fig. 17 Rockwell forward-swept wing aeroelastic model.[79]

the interaction between swept wing bending and the short-period mode.

A new candidate for aeroelastic tailoring has appeared recently. The Lavi fighter, part of which was designed by Grumman for Israel Aircraft Industries, is currently being fabricated. In Grumman's design studies on the Lavi,[87] FASTOP was used to determine the optimum stiffening of advanced composite structures to increase the control effectiveness of the wing elevons and the overall effectiveness of the fin.

The Future of Aeroelastic Tailoring

In the preceding sections of this article aeroelastic tailoring technology, as it currently exists, has been summarized. The basis and history, the underlying theory, some trend studies, and specific applications of aeroelastic tailoring have been presented. Figure 18 summarizes the benefits of aeroelastic tailoring as related to the deformation produced.

To a large degree aeroelastic tailoring has been linked to advanced filamentary composites and mathematical programming techniques. However, formal stategies for the efficient utilization of advanced composite materials in aircraft design have not yet been fully developed. Since the structural dynamic behavior and flexibility of an aircraft are important to the performance and durability of a particular design, the development of these strategies assumes particular importance. The effects of pronounced directional stiffness and the aerodynamic coupling that results have been shown to have important effects upon a number of areas of aircraft performance. The authors feel that, because of the possibilities raised herein, structural design will have an increasingly active role in the development of modern aerospace forms.

An analysis and design tool currently being developed under Air Force Wright Aeronautical Laboratories Contract[88] by the Northrop Corporation is expected to significantly increase the ability to carry out the aeroelastic tailoring design function. This Automated Strength-Aeroelastic Design Program will incorporate the best available finite-element-based structural analysis method, linear aerodynamic methods, and optimization methods. It will be able to perform a preliminary design function for strength, stiffness, aeroelasticity, and control response. The pilot program is expected to be operational in early 1986 and released to the American aerospace community in 1987.

The effective integration of active controls and structural stiffness is another area of potential reward. The aeroelastic benefits derived from deformation control due to structural tailoring and the movement of actively controlled surfaces each have limits. The synergistic effect derived by the optimum interaction of each may be significant and needs to be explored. Issues of controllability and observability of aircraft dynamics (including flutter) are strongly influenced by the flexibility of the structure. The robustness of automatic controls and sensitivity to damage (damage tolerance) are areas in which the flexibility of the structure plays an important role. Interactive design or modification of the structure and its stability augmentation system is not a trivial pursuit, but one that offers potentially rich rewards.[89]

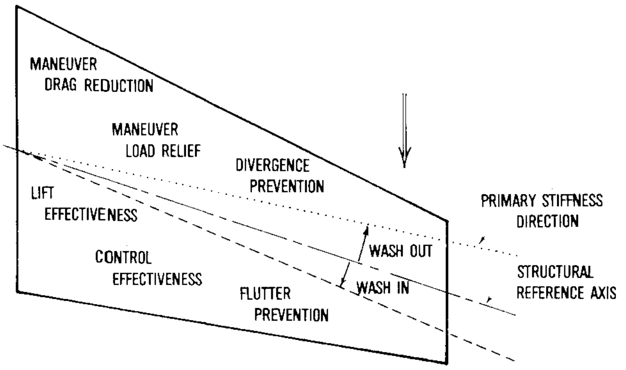


Fig. 18 Benefits of aeroelastic tailoring.

Large space structures is another area deserving closer scrutiny. The periodic lattice arrangement of a number of proposed space structures lends itself to "anisotropic" designs. Tailoring the orientations of the structural members to provide passive modal control can augment the active control system of the space structure. Regrettably, while a great amount of effort has been expended on the active control of large space structures, little visible effort has been directed at control through structural tailoring.

Aeroelastic tailoring is becoming an integral part of formal optimization procedures to design aerospace structures. When such procedures become available, aeroelastic tailoring will no longer be regarded as an isolated phenomenon, but rather an obvious, logical extension and integral part of efficient design practice. It is hoped that this review will hasten the day when aeroelastic tailoring is an accepted component of such a procedure.

Acknowledgments

The authors express their sincere appreciation to all those who contributed to this review. The authors would appreciate receiving additional material that may be of value in making a more complete survey of the aeroelastic tailoring area. The third author wishes to acknowledge support from the National Aeronautics and Space Administration for some of his research included herein.

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