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**AEROELASTIC TAILORING AND
INTEGRATED WING DESIGN**

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PREVIEW

Aeroelastic Tailoring is a design process which is multidisciplinary in nature. Aeroelasticity fundamentally involves interactions between aerodynamics and structures, in addition to the relationship between flexibility and controls (aeroservoelasticity). The use of composite materials and their directional stiffness properties allows a designer to tailor the structure to meet his design goals. Shirk, Hertz and Weisshaar have defined aeroelastic tailoring in an excellent survey paper on the subject [Ref. 1]:

Aeroelastic tailoring is the embodiment of directional stiffness into an aircraft 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.

The key, as with any design process, is to affect the aircraft to gain performance benefits, such as reduced weight, greater roll power, reduced loads, etc. This presentation will demonstrate the use of aeroelastic tailoring in the integrated design environment by discussing fundamental concepts, giving design examples, and portraying its implementation in design.

"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." (Shirk, Hertz, and Weisshaar, 1984)

CONCEPTS

EXAMPLES

IMPLEMENTATION

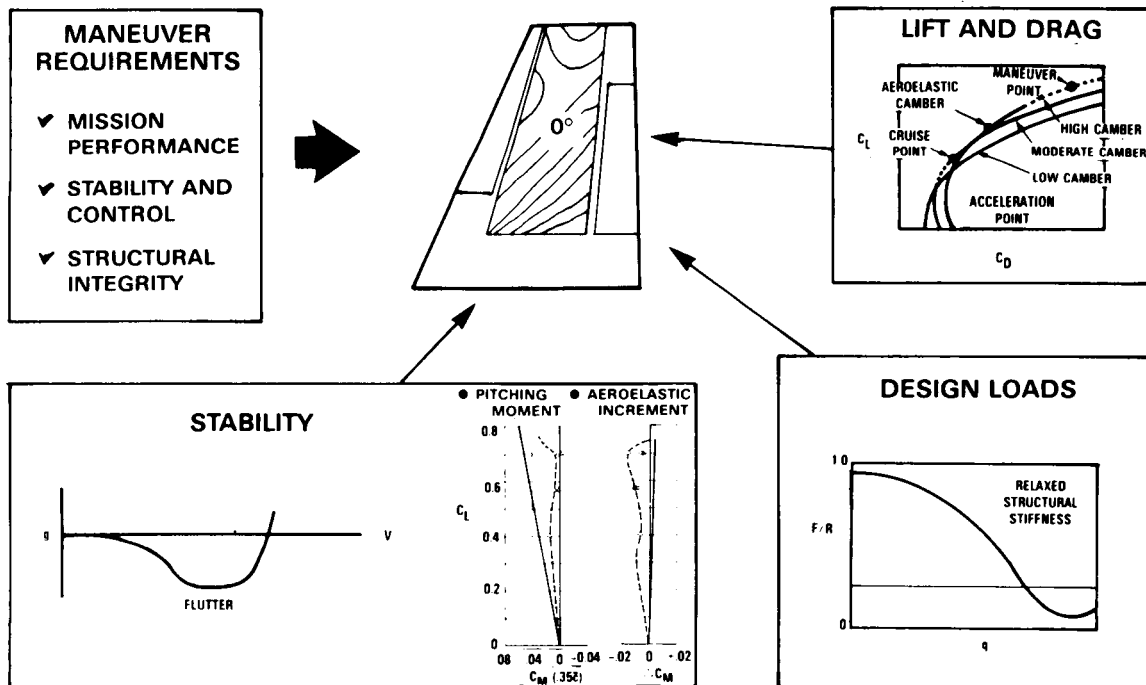
AEROELASTIC TAILORING: AN EMBEDDED PROCESS OF PRELIMINARY DESIGN

Current design trends are recognizing "aeroelasticity as a primary design parameter affecting structural optimization, vehicle aerodynamic stability, control effectiveness, and overall performance" [Ref. 2]. Because of its multidisciplinary nature, aeroelastic tailoring is clearly a process embedded in preliminary design. The objective of maximizing performance is reached subject to certain requirements that the overall configuration must meet. These include mission performance, stability and control, and structural integrity. Aeroelastic tailoring, by its nature of using lightweight, directional composite materials, can oftentimes allow the designer to meet or exceed these maneuver requirements. For example, a composite wing skin may be designed such that the structural stiffness is oriented to give a greater flutter speed. The wing may also be tailored to aeroelastically induce negative twist to reduce maneuver drag. The design objective of aeroelastic tailoring varies according to the specified requirements and goals.

Another important consideration is that flexibility significantly affects the design. Since aeroelastic tailoring impacts aerodynamics, structures, controls, and design loads, its use demands communication and an integration of the design goals. Indeed, aeroelastic tailoring is unworkable outside of an integrated, multidisciplinary design process.

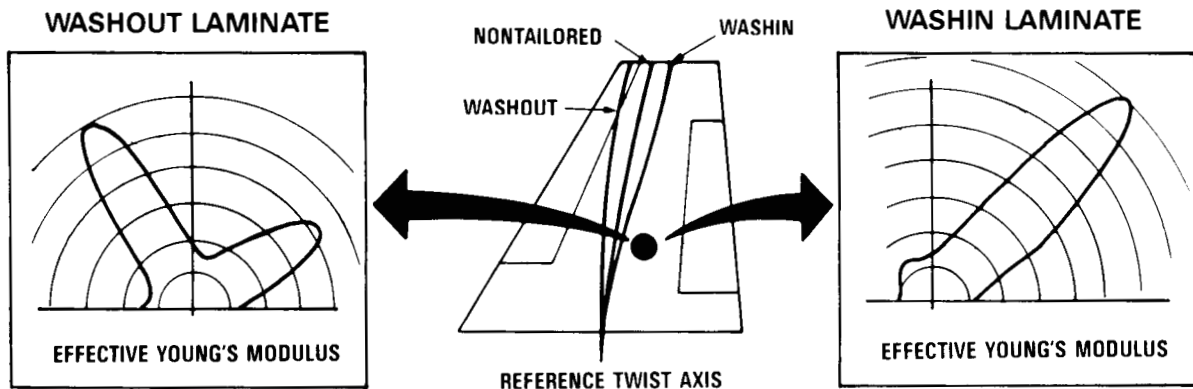
• PRELIMINARY DESIGN OBJECTIVE

OPTIMIZE CONFIGURATION PERFORMANCE SUBJECT TO SET MANEUVER REQUIREMENTS

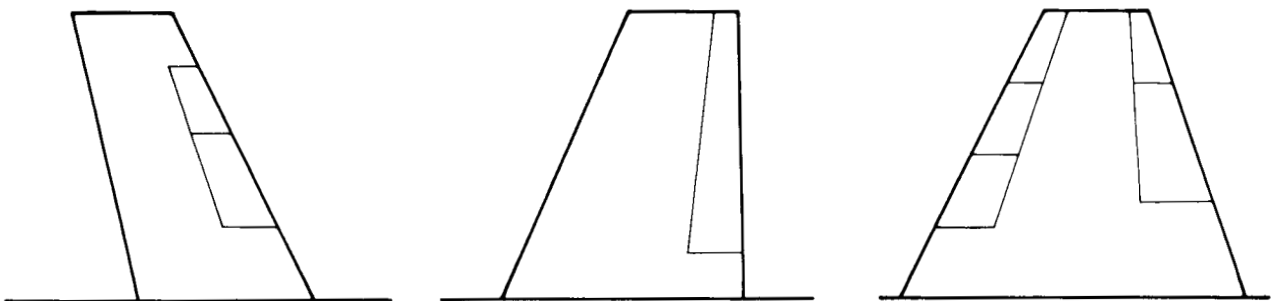


TAILORING CONCEPTS - MANIPULATE TWIST AXIS

There are two fundamental concepts in visualizing how aeroelastic tailoring utilizes composite's directional stiffness to meet design goals. One concept is to design a "washout" composite laminate, which is one where the stiffness is essentially directed most toward the front spar of a wing. This makes the trailing part of the wing less stiff such that under positive vertical load the trailing edge deflects more than the leading edge, giving a negative aeroelastic twist. This negative twist obviously reduces aerodynamic loads. The opposite of washout is "washin," a washin laminate directing stiffness toward the rear spar, giving a positive twist under positive vertical load. A washin design thus increases aerodynamic loads. A washout or washin laminate may also be thought of in terms of the location of the wing's reference twist axis relative to a "nontailored" (metallic) wing, as shown in the figure below. Whether a designer would be most interested in a predominantly washout design or washin design depends to a large extent on the configuration. A swept-forward wing may incorporate a washout design to prohibit wing divergence, while an aft-swept wing may employ some washin concepts to improve lifting surface effectiveness (e.g., a vertical tail).



CONCEPT EFFECTIVENESS IS CONFIGURATION DEPENDENT



OPTIMIZATION METHODS ARE KEY TO DESIGN STUDIES

It is obviously not sufficient for the designer to merely determine how to use aeroelastic tailoring in a fundamental sense. The makeup of the composite wing skin must be determined more exactly, along with assessing its interactions with such issues as, for example, wing planform shape. As stated by McCullers [Ref. 3], the design of a composite laminate "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." Computational methods using optimization algorithms allow one to design a tailored structure to determine structural feasibility and predict the weight required for a given geometric and controls configuration. These two issues are primary tasks of structural design in the preliminary design process. The variance in flexibility achievable in composites necessitates a converged structural design in order to establish valid parametric trades of planform, wing design, controls, and tailoring concepts.

• CONVERGED PRELIMINARY STRUCTURAL DESIGNS

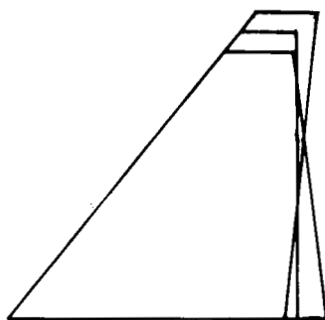
✓ STRUCTURAL FEASIBILITY

- STRENGTH
- FLUTTER
- CONTROL

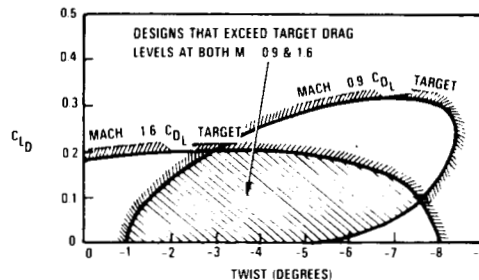
✓ WEIGHT PREDICTION

- ANALYSIS DETAILS
- LAMINATE REQUIREMENTS
- DESIGN DETAILS

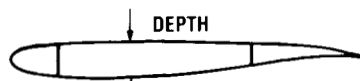
• PARAMETRIC GEOMETRIC TRADE STUDIES



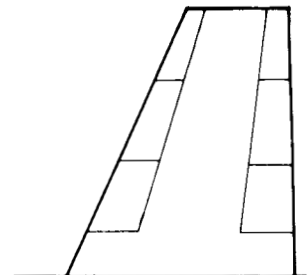
PLANFORM



WING DESIGN



THICKNESS-TO-CHORD



CONTROL SURFACE

TSO - A DESIGN INTEGRATION TOOL TO ADDRESS FEASIBILITY ISSUES

One particular structural optimization tool suited for aeroelastic tailoring studies is TSO, the Wing Aeroelastic Synthesis Procedure [Ref.4]. This code was developed at General Dynamics under Air Force contract in the early 1970's. TSO has been used extensively over the years to explore the use of composites in designing structural box skins of lifting surfaces. TSO applications have given much understanding in realizing practicalities of aeroelastic tailoring.

TSO incorporates a Rayleigh-Ritz equivalent plate technique for the structural model. Linear steady and unsteady aerodynamic codes are used to predict design loads. TSO's nonlinear programming algorithm allows the user to design a structural skin subject to a number of constraints. The design variables include thickness distributions of the composite layers and their fiber orientation angles. Design constraints typically consist of strength, flutter, and the effectiveness of a flaperon to produce rolling moment. TSO's computational efficiency allows the consideration of many design options, and provides an integrated, multidisciplinary tool to address design feasibilities. It is still a preliminary design tool, however, such that it serves as a precursor to finite element model analyses.

- MULTIDISCIPLINARY TOOL

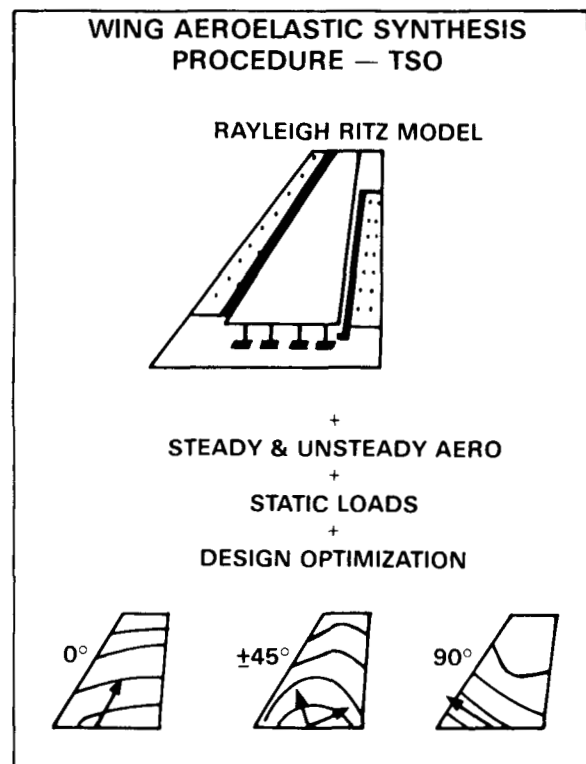
- STRENGTH
- FLUTTER
- STEADY AERO
- NLP OPTIMIZATION

- PRECURSOR TO FINITE ELEMENT METHODS

- SIMPLE MODEL
- MULTI-MANEUVER SIMULATION

- YEARS OF CALIBRATED USE

- "REAL WORLD" UNDERSTANDING
- PRACTICAL DESIGNS

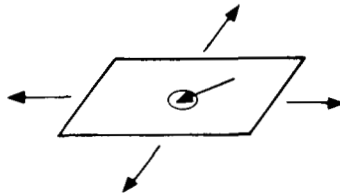


WEIGHT PREDICTION ADDRESSED THROUGH EXPERIENCE

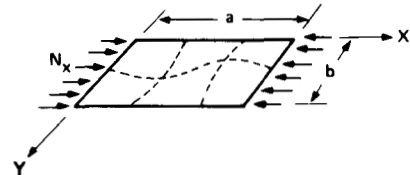
Despite TSO's ability to aeroelastically tailor the skin of a wing or other lifting surfaces for a set of design requirements, it lacks the structural detail of finite element methods. This means that TSO cannot adequately address such design details as buckling or bolted joints. Damage tolerance and manufacturing provide other considerations that affect the makeup of a composite laminate. Such details can have a direct impact on the aeroelastic tailored design produced by TSO. Hence, previous design experience is incorporated into TSO through the use of strain limits, laminate ply percentages, shape functions and min and max gage thicknesses. Bolted joint details and low velocity impact considerations, for example, may be addressed by limiting fiber strains relative to fracture criteria. An envelope of acceptable laminate ply percentages is generally developed to account for ply stacking sequence effects in the sense of potential fracture mechanisms. Constraints have been formulated in TSO's penalty function scheme to address this issue. Weight for design details such as fasteners, sealants, and understructure are estimated through historical data. Buckling must be dealt with on the finite element level of analysis, and its impact to structural design is not to be taken lightly.

• ANALYSIS DETAILS

BOLTED JOINTS (STRAIN LIMITS)



BUCKLING (?)



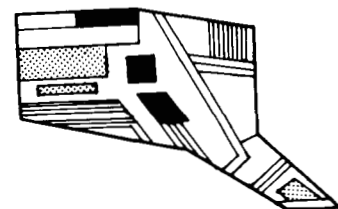
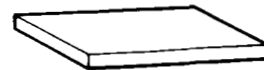
• LAMINATE REQUIREMENTS

✓ DAMAGE TOLERANCE

- STRAIN LIMITS
- PERCENTAGE CONSTRAINTS

✓ MANUFACTURING

- SHAPE FUNCTIONS
- THICKNESS CONSTRAINTS

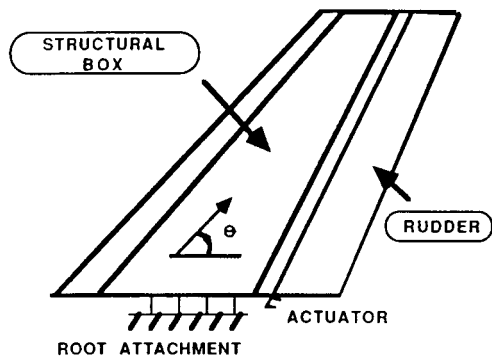


• DESIGN DETAILS (FASTENERS, SEALANT, ETC.)

WASHIN DESIGN INFLUENCED BY MATERIAL PROPERTIES

Let us turn now to three examples that demonstrate design sensitivities derived from implementing aeroelastic tailoring. The results in these examples were taken from TSO design studies of typical fighter aircraft configurations.

This first example is that of a vertical tail with a rudder control surface. The purpose of the study is to determine the effectiveness of various materials on the structural weight for a design criteria of strength, flutter, and primarily for rudder yaw effectiveness. The driving variable in the study was the lamina longitudinal stiffness which is governed by fiber stiffness. A washin laminate design is required to provide the necessary rudder effectiveness at a minimum weight. The graph illustrates a savings in structural weight for an increase in fiber stiffness. Also, the laminate becomes less directional (less washin) with the increase in stiffness. Since increased washin tendencies generally give better rudder effectiveness, the benefits of the greater stiffness are a trade between structural weight and rudder effectiveness. The designer could opt to waive the weight savings associated with a higher stiffness material and reinvest the weight to increase rudder effectiveness. Perhaps another trade might result in the necessity for the lower modulus material versus the requirements for aircraft control.

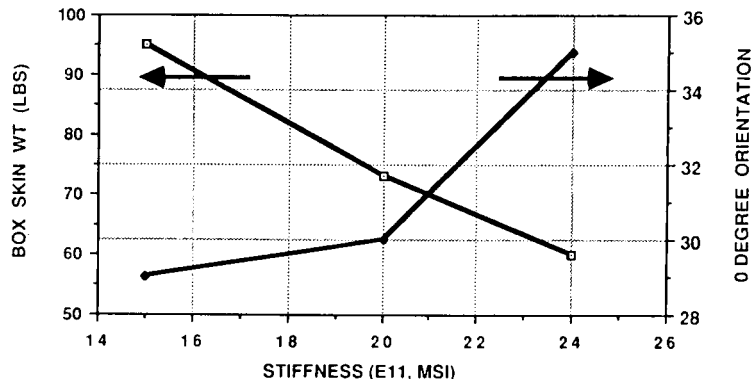


● VERTICAL TAIL (MIN. WEIGHT)

- Rudder Effectiveness
- Flutter
- Strength

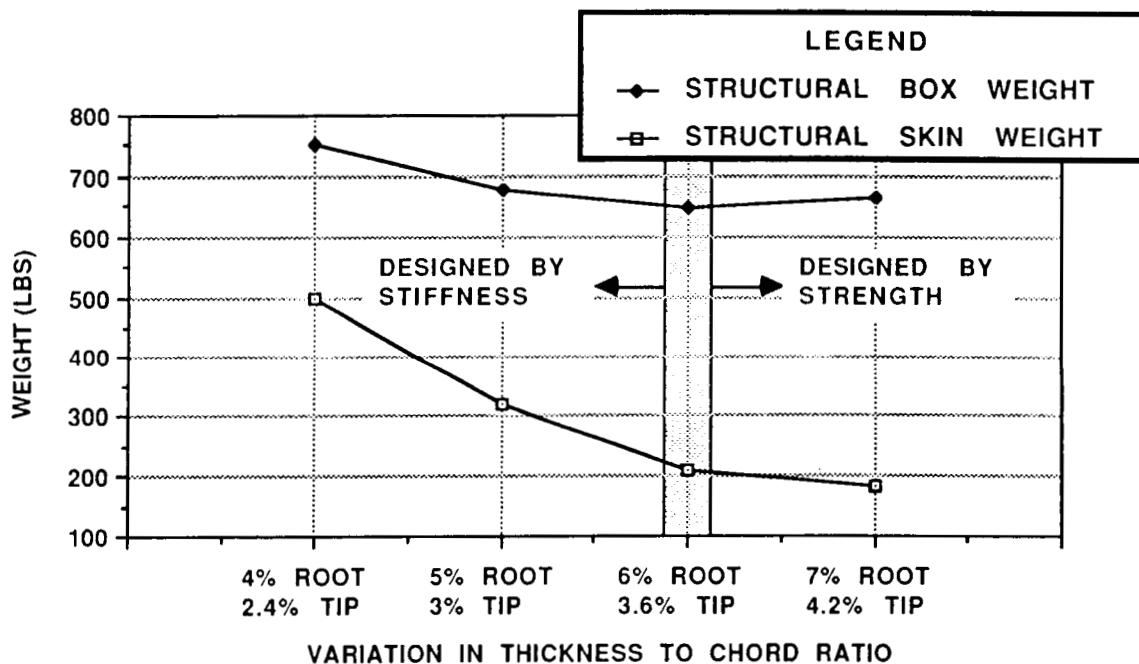
● FIBER STIFFNESS

- Stiffness Increase Gives a Less Washin Laminate
- Implied Effectiveness and Weight Benefits



THICKNESS-TO-CHORD RATIO: STIFFNESS DESIGN VS STRENGTH DESIGN

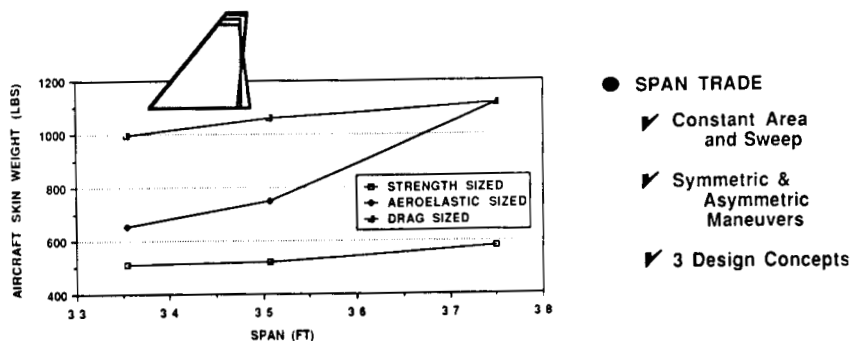
This second example demonstrates the effect of lifting surface depth, and was derived to provide data for a trade between structural weight and supersonic wave drag. The lifting surface depth was varied through the selection of various t/c's. The box details of understructure and fasteners were estimated from historical data and are added to the box skin weight. The surface had been designed for minimum weight, control surface effectiveness, flutter, and strength. The data provides the designer with knowledge of the strength versus stiffness design. Certainly increasing box depth adds stiffness to the structure, such that the wing skin need not add as much stiffness to meet the flutter and control surface effectiveness requirements. Hence, the skin weight decreases with increasing t/c. Eventually a t/c will be reached where the box depth alone provides enough stiffness, leaving the wing skin to be designed only by strength considerations. At this point the skin is said to be strength designed, as opposed to a skin designed primarily for stiffness. It can be observed that as the box gets sufficiently deep, the added understructure weight begins to override the weight savings seen by the box skin.



MULTIDISCIPLINARY DESIGN CONSIDERATION - FIGHTER PERFORMANCE

The final example illustrates an age old design trade of span for turning performance and weight required to achieve structural integrity. This TSO study examined the structural skin weight derived to satisfy three levels of criteria for three planforms. The first criteria consisted of the weight required to satisfy only strength requirements ("strength sized"). The second criteria added flutter and flaperon roll moment effectiveness (flex-to-rigid ratio) to the strength criteria ("aeroelastic sized"). The final criteria added a twist objective to provide aeroelastic washout for reduced lift-induced drag ("drag sized"). The planforms differed only in span. Design loads included 9g symmetric and 5.86g asymmetric maneuvers. The data indicates that a severe weight penalty exists for meeting the flutter and roll requirements, while the increase in span also facilitates the aeroelastic twist.

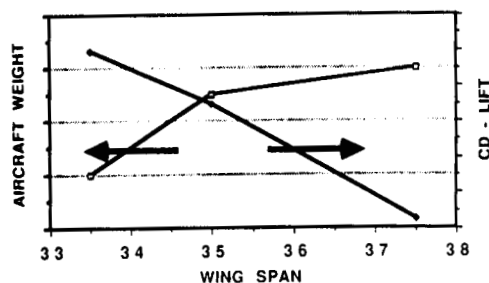
Associated with the structural related data is the trade with aerodynamic performance. Shown in the second graph are the associated weight of the structure designed to twist and the lift-induced drag coefficient at a Mach 0.9, 10,000 ft, 9g maneuver. The chart clearly shows a trade-off between weight and drag. This demonstrates the necessity of integrating the design process to determine how such trade-offs affect vehicle performance. The weight/drag trade-off could be evaluated through how it affects turn rate, since turn rate is directly related to the specific excess power P_s , which considers both weight and drag.



● SUSTAINED PERFORMANCE

- ✓ Δ Weight
- ✓ Δ Drag-Due-to-Lift
- ✓ Δ Turn Rate

$$P_s = \frac{V(T-D)}{W}$$



OPTIMAL DESIGN - A RESULT OF SIMULATION

The previous examples demonstrated the need to integrate the design process while being able to simulate the impacts of various design options on the aeroelastic performance of the vehicle. Many factors enter the picture to adequately address multidisciplinary and integrated issues during optimization. As a result, it is important to be able to computationally simulate many multidisciplinary influences as accurately as possible so that sensitivity data may be generated. The figure below cites several examples of important design considerations. The underlying reason for considering these implications during design is that optimization techniques will exploit weaknesses in the computational simulation. For example, if the structure is preliminarily designed to only symmetric loads, significant redesign will be required later since asymmetric loads stress the wing in critical areas as well.

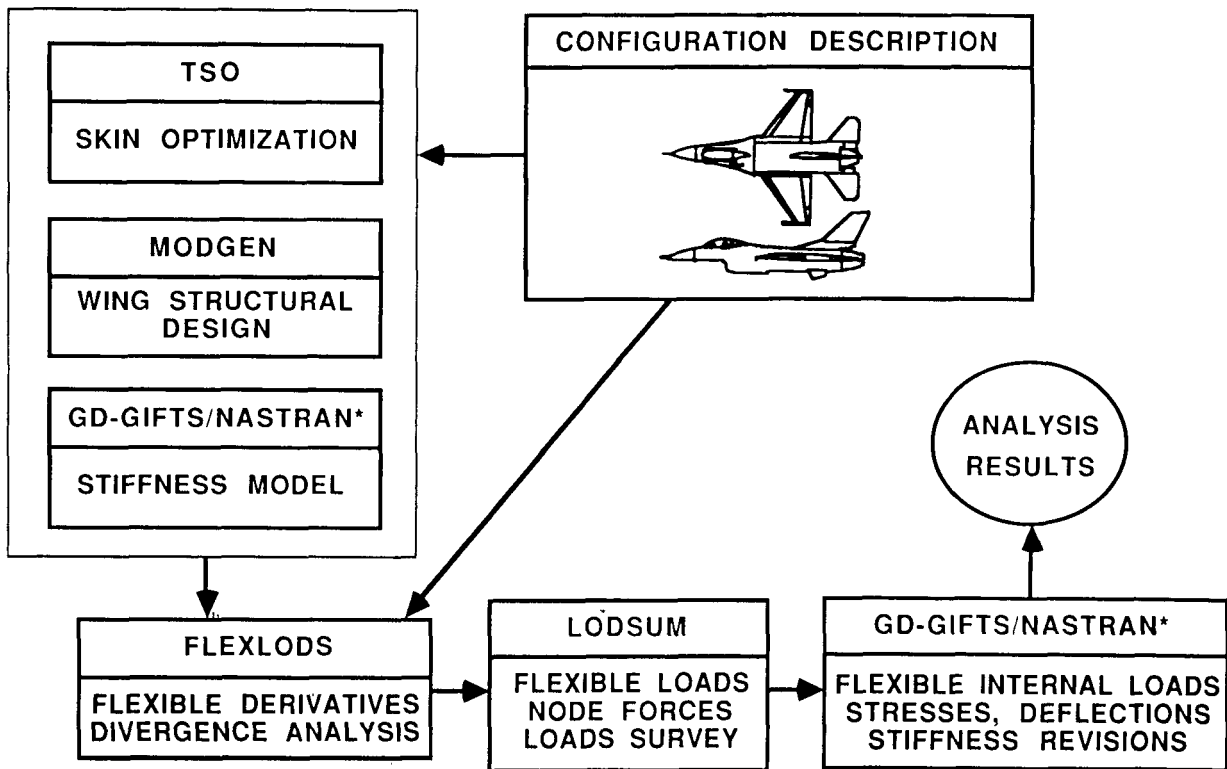
- WING DESIGN
 - ✓ Camber Enhances Steady Aeroelastic Deflections
 - ✓ Twist Reduces Steady Aeroelastic Deflections
- CONTROLS CONFIGURATION
 - ✓ Upwash and Downwash Within Entire Vehicle
 - ✓ Control Surface Blending for Optimal Maneuver
- LOADS
 - ✓ Symmetric and Asymmetric Applied Loads
 - ✓ Internal Loads (Equilibrium, Fuel Pressure, etc.)
- MODELS
 - ✓ Aerodynamics - Mesh Size
 - ✓ Structures - Accurate Idealization
 - ✓ Design - Manufacturing and Performance

BOTTOM LINE - Optimization Techniques Exploit Simulation Weaknesses

OPTIMIZATION AND ANALYSIS INTEGRATION

The question remains as to implementing aeroelastic tailoring into detailed levels of multidisciplinary considerations. The figure below presents a sketch of the integrated aeroelastic design procedure currently employed at General Dynamics.

Aeroelastic tailoring through the TSO procedure is the first step past preliminary configuration definition. As TSO skin designs are passed into finite element models for more detailed analyses, TSO parametric studies continue to determine a wide range of aeroelastic influences, such as with the three examples discussed above. Such studies are valuable since, for example, the initial wing configuration is generally conceived assuming a rigid structure. Information constantly flows through the various computational procedures as "what-if" questions are raised. The analysis results give accurate indications of the integrated aeroelastic performance of the model. The results may be fed back to aerodynamic and stability & control to refine drag estimates and stability margins based upon the flexibilized data, which in turn may be used to re-estimate combat performance.



* NASTRAN is a registered trademark of NASA.

LESSONS LEARNED IMPLEMENTING TSO

In summary, much has been learned from TSO over the years in determining aeroelastic tailoring's place in the integrated design process. Indeed, it has become apparent that aeroelastic tailoring is and should be deeply embedded in design. Aeroelastic tailoring can have tremendous effects on the design loads, and design loads affect every aspect of the design process. While optimization enables the evaluation of design sensitivities, valid computational simulations are required to make these sensitivities valid. Aircraft maneuvers simulated must adequately cover the plane's intended flight envelope, realistic design criteria must be included, and models among the various disciplines must be calibrated among themselves and with any hard-core (e.g., wind tunnel) data available. The information gained and benefits derived from aeroelastic tailoring provide a focal point for the various disciplines to become involved and communicate with one another to reach the best design possible.

- AEROELASTIC TAILORING IS AN EMBEDDED PROCESS OF DESIGN
- OPTIMIZATION ENABLES EVALUATION OF DESIGN SENSITIVITIES
- VALID SENSITIVITIES ARE DERIVED FROM VALID SIMULATIONS
 - ✓ Aircraft Maneuvers Must Be Broad Spectrum
 - ✓ Design Criteria Must Be Accounted For
 - ✓ Discipline Models Must Be Calibrated
- AEROELASTIC TAILORING APPLICATIONS INTEGRATE WING DESIGN
 - ✓ Multiple Disciplines are Involved
 - ✓ Communication is Required

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