The three-dimensional wing calculations are influenced by the increased wing circulation that results from the wing angle-of-attack, 13.2 deg, required to match the desired lift coefficient of 0.4 at the $2y/b = 0.9$ station.

Summary

On the model centerline where three-dimensional effects are small, the two-dimensional analysis presented, predicts reasonably well the droplet impingement on a three-dimensional yawed wing. Near the wing tip $[(2y/b) = 0.9]$ the two-dimensional model fails to accurately predict the droplet-impingement on a yawed wing. Based on these calculations and the more detailed analysis of Ref. 3, it is clear that the two-dimensional analysis works well on yawed wings away from the tips. However, a three-dimensional analysis must be used near the tip of a finite wing. It is anticipated that in other cases where a significant three-dimensional flow field effect is present, a three-dimensional analysis would also be required.

Acknowledgment

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Demonstration of Structural Optimization Applied to Wind-Tunnel Model Design

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Introduction

ONE of the most important tasks in the design of an aeroelastically scaled wind-tunnel model wing is making sure the stiffness characteristics are correct. The engineer must design a model structure whose stiffness characteristics match known values. These known values are derived by scaling the stiffness characteristics of the full-size structure that the model represents.

It is assumed that a target flexibility matrix is known for the scaled model. A column of a flexibility matrix represents the displacements at all the grid points on the wing due to a unit load at one grid point. If the desired flexibility matrix is known for the model, a displacement constraint can be written for the deflection at each grid point in the structure due to a unit load placed at some grid point. If a structure can be designed so that all the constraints are active; that is, they lie on the boundary of the feasible region, it will have the desired response to the unit load placed on it.

Using this approach, there is no need to know any more about the desired structure than the flexibility matrix and the basic geometry of the structure. The model's structure need not bear any resemblance to that of the original structure as long as the overall stiffness characteristics match the scaled stiffness of the full-size structure. The possibility then exists of modeling an anisotropic structure with an isotropic one.

Background

It has been shown that a general purpose structural optimization code can be used to simplify the wind-tunnel model design process considerably.[1,2] A general purpose finite-element-based analysis and optimization program[3] was used to design a structure made up of beam and plate elements. Using only the widths of the beam elements as design variables, a design was obtained that satisfied the stiffness constraints, and a sample structure was manufactured. The displacement of the structure due to loads applied at various grid points was measured using laser holographic techniques. The stiffness of the test article was found to agree well with the finite element predictions. The previous approach was more cumbersome than desirable because the program involved was applied to a problem for which it was not well suited. Also, the procedure resulted in a structure that was unnecessarily difficult to manufacture. To improve the design procedure, a new finite element based optimization program was written and the problem described in Ref. 1 was reworked using a different finite element representation.

Analysis

To allow easy comparison of the results between the current research and that cited in Ref. 1, the same 1/9-scale fighter wing was selected. The wing was constructed largely of composite materials and was built to demonstrate the feasibility of using aeroelastic tailoring on fighter wings (Fig. 1). The structure involved in this effort represents only the structural box of the original wing. Both the planforms of the previously manufactured test article[1] and model structure described here are the same size as the 1/9-scale wing.

Reference 4 presents a flexibility matrix generated from a finite element model of the 1/9-scale wing. Flexibility coefficients are given at 28 points on the surface of the wing. The location of these points is presented in Fig. 2. This flexibility matrix was used as the basis for the design of the test structure. A set of displacement constraints for the optimization problem can be written using a column of the flexibility matrix; a load is placed at some point on the wing and the terms from the column of the flexibility matrix are input as displacement constraints. Each column of the flexibility matrix is considered

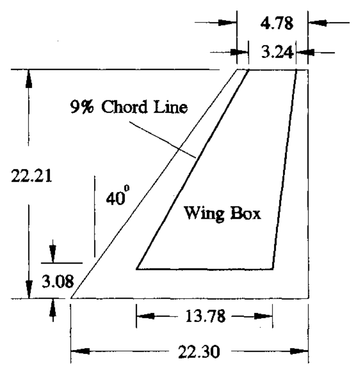

Fig. 1 Planform of 1/9-scale wing.

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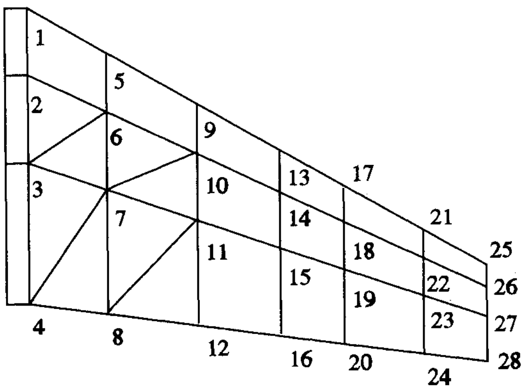

Fig. 2 Finite element representation of aeroelastically scaled model.

as a separate load case. A normalized set of constraints can be written as

$$g_i(x) = \frac{x_{ij} - \delta_{ij}}{\delta_{ij}} \leq 0, \quad j = 1, n \tag{1}$$

where x_{ij} is the calculated displacement at the jth grid point due to a unit load at the ith grid point and δ_{ij} is the desired displacement at the jth grid point due to a unit load at the ith grid point.

Previously, structural mass was used as the objective function because it is assumed in the code used. This choice is reasonable because one would expect a minimum weight structure to be a relatively flexible one and, thus, one for which many of the constraints are active, or nearly so. However, because the goal of the design procedure is to minimize the difference between the desired and actual deformation at the grid points, the problem was reformulated to use a squared error function as the objective function

$$F = \sum_{i=1}^{n} \left(\frac{\delta_i - x_i}{\delta_i} \right)^2 = \sum_{i=1}^{n} g_i(x)^2 \tag{2}$$

The design variables for the problem are the widths and heights of the beam elements. The values do not show up explicitly in the objective function; however, the calculated deformations that are used in forming the objective function are, in turn, functions of the element sizes. In addition to the displacement constraints described above, side constraints were used to define minimum acceptable element sizes. This was done to avoid possible problems in fabricating extremely small gauge elements.

The 1/9-scale wing model chosen was originally intended for transonic testing and is extremely stiff. To make stiffness testing of the new model easier, the terms of the flexibility matrix were multiplied by 10. This was considered reasonable because the purpose of this experiment was to show that an arbitrary stiffness distribution can be modeled with a simple isotropic structure, rather than model a specific wing. The result was a structure flexible enough to give easily measurable displacements under a modest load.

In order to match the scaled stiffness properties of the 1/9-scale model exactly, a complete set of displacement constraints would need to be applied for every column of the flexibility matrix. However, this approach would result in an unreasonably large problem. Another approach is to appeal to intuition and assume that if columns of the flexibility matrix are correct for a small number of unit loads applied at widely separated grid points the remaining columns are correct, or nearly so.

A second assumption can be made to simplify the optimization process further. The deformations at the inboard grid points are often very small but can have undesirably large influence on the design problem; very small absolute differences between the desired and calculated displacements can still result in very large normalized constraint values. Ignoring constraints at the inboard grid points when calculating the objective function helps ensure that the optimization algorithm does not get bogged down trying to cope with highly violated constraints that have little effect on the results. All constraints, including those omitted from the objective function calculation were used to define the boundary of the feasible region.

Previously, a structure composed of beam- and plate-bending elements was used to represent the structure of the aeroelastically scaled model. The results were good, but the existence of the plate elements caused problems in fabricating a test specimen. To address this problem, only beam elements were used in this effort. The structure is a lattice of beam elements connecting the points at which flexibility coefficients were given.

A FORTRAN program was written to model the wing structure using finite elements and to generate function values and gradients for passing to an optimization program. The program uses 6 degree of freedom beam elements to model the bars. Two different optimization methods were used for different versions of the program: ADS (Automated Design Synthesis)[5] and compound scaling, as implemented in FUNOPT[6,7] (FUNctional OPTimization). The Modified Method of Feasible Directions (MFD) was used in ADS. All analysis work was done on a Sun SPARCstation 1.

A number of different constraint sets was specified during the course of the design process. Initial runs were made using a single set of constraints and the number was gradually increased. It was found that four displacement vectors were sufficient to design the wing. The four columns of the flexibility matrix correspond to unit loads placed at the leading edge of the tip, trailing edge of the tip, leading edge of the midspan, and trailing edge of the midspan. These correspond to points 13, 16, 25, and 28 on Fig. 2. The resulting design problem had 106 design variables (width and height for each of 53 beam elements) and 112 constraints (4 load cases and 28 constraints per load case).

Results

Both methods produced acceptable final designs. The ADS design had 28 constraints within 5% of the boundary of the feasible region, but most of these were concentrated in the last load case. For the second load case, there were no constraints within 5% of the boundary. The FUNOPT design was the better of the two because approximately 60 constraints were within 5% of the boundary of the feasible region. This indicates that FUNOPT was able to find an approximate intersection of 60 constraints. The caveat should be made that both methods used here have parameters that can be varied to improve performance. ADS may have produced a better design if the optimization parameters had been set differently.

It is difficult to present results from the analyses described here compactly, but some feel for the quality of the results can be obtained by examining the deflections along the leading and trailing edges of the structure due to a unit load at a tip grid point. Fig. 3 compares the displacements along the leading edges of the ADS and FUNOPT designs due to a unit load at grid point 28 to the desired displacements. Fig. 4 compares the displacements at the trailing edge of the two designs with the desired displacements due to the same load.

The biggest problem encountered in the optimization process was getting the optimization routines to converge on an answer. ADS, in particular, was very sensitive to the initial design chosen. If the initial design was infeasible, ADS often could not find a feasible solution. The strategy that seemed to work the best with ADS was to vary the initial design by hand until none of the constraints was violated. There was very little trouble getting FUNOPT to converge to a good answer; however, there was no good exit criteria. The result is that it will often run longer than desired.

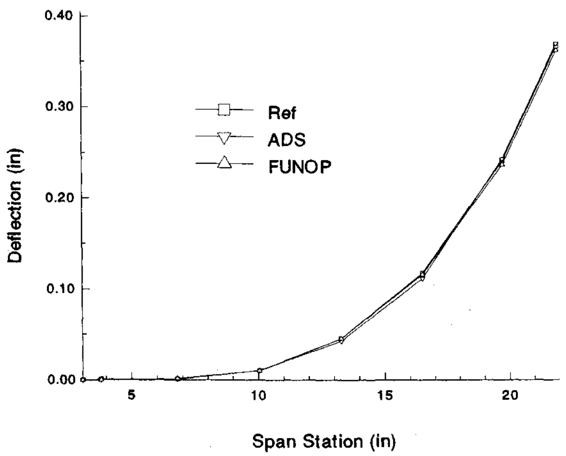

Fig. 3 Deflections along leading edge due to unit load at point 28.

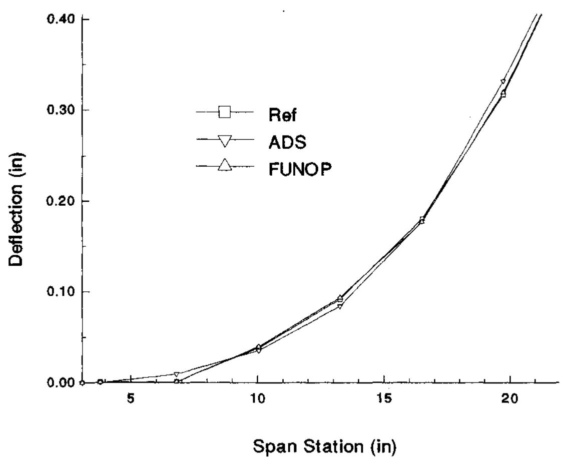

Fig. 4 Deflections along trailing edge due to unit load at point 28.

Conclusions

It is difficult to determine how much deviation between actual and desired stiffness properties is allowable in aeroelasticity models. (Ideally, there is none but this is almost never the case.) The allowable deviation depends on such factors as wing geometry and the flight regime. The results presented above indicate that using structural optimization to design wind-tunnel models can result in a procedure that matches desired stiffnesses well enough to be very useful in sizing the structures of aeroelastic models.

The design procedure presented here demonstrates that optimization can be useful in designing aeroelastically scaled wind-tunnel models. The resulting structure effectively models an aeroelastically tailored composite wing with a simple aluminum beam structure. This structure should be inexpensive to manufacture compared to a composite one.

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Errata

Minimum Induced Drag for Wings with Spanwise Camber

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EQUATION (4) should read as follows:

$$a(\alpha) = \int_0^1 (1 - \xi)^{-(1-\alpha)}[(1 - \alpha)/\alpha + \xi)]^{-\alpha}\xi \, d\xi$$