Application of Direct Search Method to Aeroelastic Tailoring of an Arrow Wing Configuration

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Abstract. A computer code for areoelastic tailoring of an arrow wing supersonic cruise configuration is developed. A direct search method is employed to find the optimum fiber orientation angles and thickness distributions of the upper and lower skin panels of the wing box for the minimum weight design under the multiple constraints. The static strength, symmetric and antisymmetric flutter velocities are taken into account at the same time as the constraints. The code is applied to a typical arrow wing configuration to demonstrate its capabilities.

Key words: Aeroelasticity, SST, Arrow wing, Aeroelastic tailoring, Composite, Optimization

1. Introduction

The flutter characteristics, especially in the transonic regime, play the critical role in structural design of an arrow wing supersonic cruise configuration[1]. For example, the design studies performed by Turner and Grande[2] of the early Boeing Supersonic Transport (SST) Model 969-512B disclosed that the strength designed configuration does not meet the flutter requirement and an unrealistically high mass penalty was expected to achieve the flutter clearance ($1.2V_D$=259 m/s EAS at M=0.90 which was initially set. In order to improve the flutter characteristics of an arrow wing configuration without mass penalty, the application of the aeroelastic tailoring technology might be one of the most promising approaches. However, its effectiveness for the arrow wing configuration has not yet been well examined, though it has been shown that it is highly effective for the high aspect-ratio transport type wings[3)~5)].

In order to perform the trend study on the effectiveness of the aeroelastic tailoring for the structural design of an arrow wing supersonic cruise configuration, a preliminary design code is developed. In the present code, a direct search method (the Complex Method [5), 6)]), which does not depend on the derivatives of the objective and constraint functions, is employed to find the optimum fiber orientation angles and the thickness distributions of the upper and lower skin panels and the thickness of the spar and rib materials of the wing box for the minimum weight design under the multiple constraints. One of the characteristics of the code is that it can treat the static strength, the symmetric/antisymmetric flutter velocities and the minimum gauges at the same time as the constraints. In the next sections, the outline of the code and the results obtained by applying the present code to a typical arrow wing configuration will be presented.

2. The Outline of the Optimum Design Code

In order to perform the aeroelastic tailoring, we need several analysis codes as the elements of the optimization code. For the strength and vibration analyses, the in-house Finite Element Method (FEM) code is developed since we should know the fine-details of the FEM code to develop the aeroelastic optimization code by combining it with the aeroelastic analysis code. The in-house FEM code, in which the membrane elements are employed, is specialized to an arbitrary arrow wing configuration. That is, only a few parameters can generate, automatically, the FEM grids for the wing box of an arbitrary double delta type wing planform. For aeroelastic analyses, the modal approach is taken by using the symmetric/antisymmetric natural vibration modes (16 mode shapes including rigid body modes are employed) obtained by the FEM code. The unsteady aerodynamic forces are calculated by Doublet Lattice Method (DLM)[7] code in which the 100 panels (10 chordwise by 10 spanwise) are employed. In order that the aeroelastic analysis code is integrated effectively in the optimization code, the symmetric/antisymmetric flutter velocities should be calculated automatically.

As to the optimization algorithm, the Complex Method which is originally proposed by Box[6] is employed. Applicability of the complex method to the aeroelastic tailoring of the high aspect-ratio transport type wings are extensively examined in Ref. 5. The complex method can handle multiple (inequality type) constraints without recourse to gradients. According to our experiences[5] in the aeroelastic tailoring study of the high aspect-ratio transport type wings, the complex method is very effective and robust in finding the optimum fiber orientation angles and the thickness distributions of the upper/lower skin panels of the wing box, while the deficiency of the method is that the rate of convergence of the objective function degrades rapidly with increasing number of design variables. Therefore, it is indispensable to reduce the number of design variables as small as possible when we apply the complex method to the aeroelastic tailoring. (See Refs. (5), (6), (8) for the detailed procedure of the complex method.)

In Fig. 1, the planform of the arrow wing model, for which the present design study is performed, is shown. (The further details of the model specification will be given in the next section.) The hatched part of the planform shown in Fig. 1 indicates the wing box location. Fig. 2 shows the arrangement of ribs and spars, and it also shows the FEM grids on the upper and lower skin panels. The total 670 triangular elements are used for the present FEM analyses. In order to reduce the number of the design variables in the optimization process, the upper/lower skin panels are divided into 7 blocks for each panels, respectively, as shown in Fig. 3, and the thickness of the skin within each block is assumed to be the same. It is also assumed that the laminate construction of the upper/lower skin panels is symmetric and the thickness of each layer having different fiber orientation angle is the

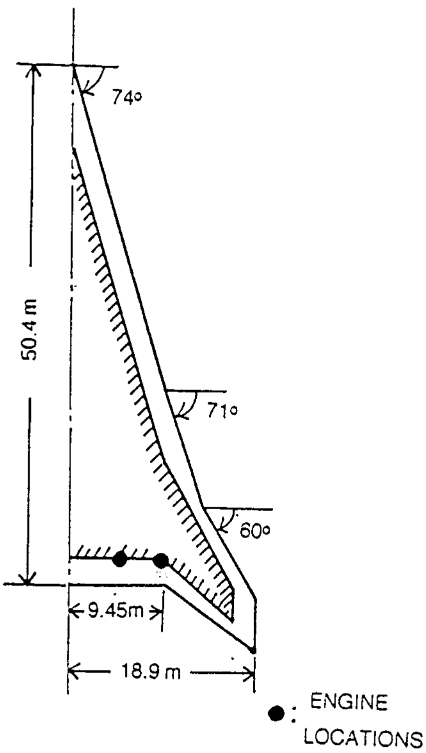


Fig. 1 Planform of Arrow Wing Model

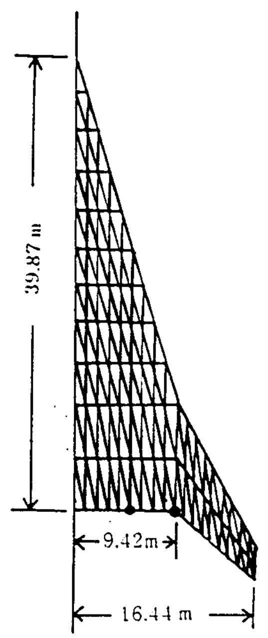


Fig. 2 Finite Element Grid

same for each other. As to the spars and ribs, the several elements which seems to be sensitive to the static strength and stiffness are selected as the design variables as shown later. In addition to this, the laminate constructions of the spars and ribs are assumed to be quasi-isotropic.

Thus, the following 25 design variables are selected:

(a) The thickness of each block of the upper/lower skin panels (the number of design variable: 7x2=14)

(b) The fiber orientation angles of the upper/lower skin panels (2)

(c) The thickness of the fore- and hind-spars of the inboard wing (2)

(d) The thickness of the fore- and hind-spars of the outboard wing (2)

(e) The thickness' of the spars other than (c) and (d) (1)

(f) The thickness of the rib at the span station where the inboard engine is located (1)

(g) The thickness of the rib at the span station where the outboard engine is located (1)

(h) The thickness of the rib at the tip station of the wing box (1)

(i) The thickness of the rib other than (f), (g) and (h) (1)

Although the total 25 design variables mentioned above is employed for the present study, the design variables up to 34 (the maximum number of blocks up to 10 for each upper/lower skin panels and the maximum number of fiber orientation angle up to 5) can be taken in the present optimization code.

The objective function is the structural weight of the wing box, namely, the total sum of the weights of the upper/lower skin panels, spar materials and ribs.

The constraints are the static strength, the symmetric/antisymmetric flutter velocities and the minimum gauges for the upper/lower skin panels,

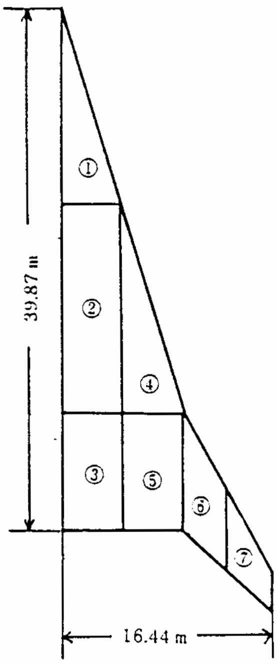


Fig. 3 Zoning of Upper/Lower Skin Panels

the spars and ribs. Tasi-Wu failure criterion[9] is employed to identify the structural failure.

3. Results and Discussions

As an example of the application of the present optimization code, the design study has been performed of an arrow wing configuration shown in Fig. 1. The length of the root chord is 50.4 m and the semispan length is 18.9 m. The leading edge sweep angles of the inner and outer wings are 74° and 60°, respectively. The full-span wing area is about 830 m^2 and the aspect ratio is 1.61. The airfoil section is 3 percent thick circular-arc. The engine mass is assumed to be 6,500 Kg for each of the four engines. The engines are expressed by the concentrated masses at the locations indicated in Fig. 1. For the full fuel condition, which is the most critical for flutter, 200,000 Kg of the fuel mass is assumed. The maximum gross take-off mass is assumed to be 374,500 Kg. Therefore the zero fuel mass becomes 174,500 Kg. The structural materials used in the present study is Graphite/PEEK (APC2), whose material properties are E_L=134 GPa, E_T=8.90 GPa, ν_{LT}=0.28, and G_{LT}=5.10 GPa.

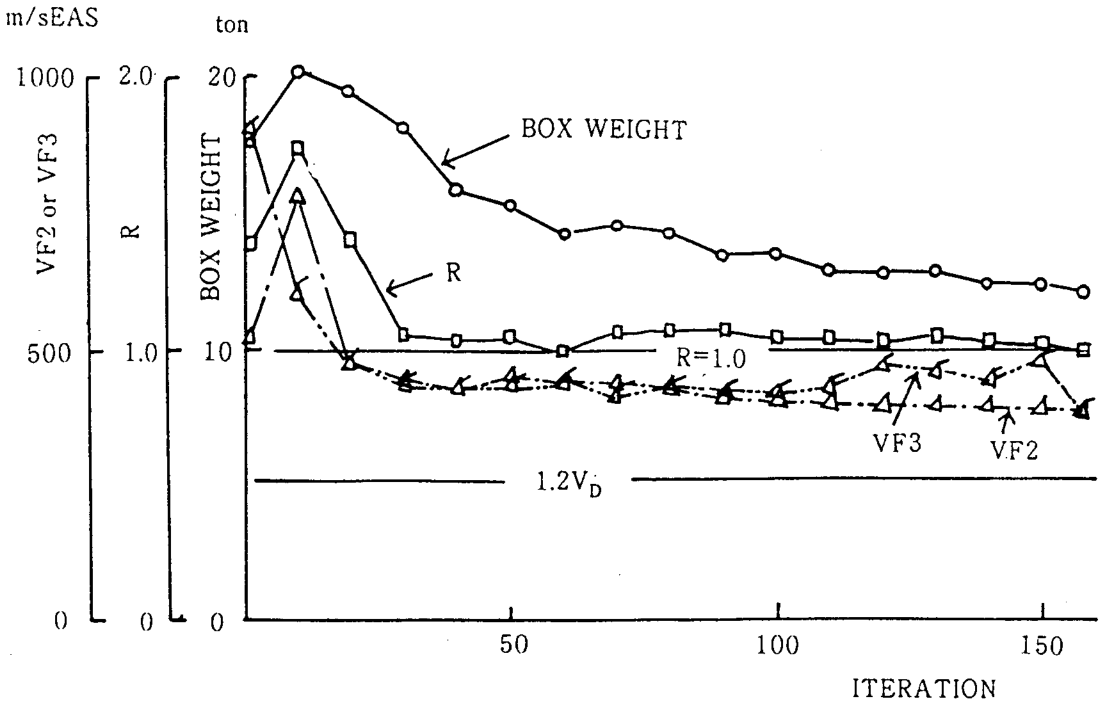


Fig. 4 Convergence Histories of the Box Weight, Strength Ratio and Symmetric/Antisymmetric Flutter Velocities during Optimization Process

The minimum weight design is performed under the following design conditions (inequality constraints):

a) Static Strength

The strength requirement is to sustain 2.5g load of the maximum take off gross weight which corresponds with 9.175×10^6 N. This static load can be realized at M=0.90 and $\alpha=5.1^{\circ}$. The load distributions calculated by using DLM is applied at each node point of the FEM grid.

b) Flutter Velocity Requirement

The symmetric/antisymmetric flutter velocities should clear 1.2 V_D=259 m/s EAS at M=0.90.

c) Minimum Gauges

Since the laminate construction of the upper/lower skin panels of the present model is assumed to be $(\beta_1:50\%;\ \beta_2:50\%)_s$ where β_1 and β_2 are the fiber orientation angles (design variables), the minimum gauge for the upper/lower skin panels is taken to be 0.52 mm. As to the minimum gauge for the spars and ribs, 1.04 mm is assumed since the laminate constructions of them are quasi-isotropic.

In Fig. 4, the convergence histories of the wing box structural weight (the objective function), the strength ratio R, the symmetric (VF2) and antisymmetric (VF3) flutter velocities during optimization process are plotted. The value of the wing box weight has converged to 12.148 ton after 158 iterations. As seen from the figure, the strength ratio R has reached to 1.0 at the optimum point, while the flutter velocities at the optimum point are VF2=387 m/s EAS and VF3=388 m/s EAS, that are considerably higher than 1.2 V_D=259 m/s EAS. This fact suggests that the structure obtained by the present optimum design is strength critical rather than flutter critical.

The total wing box structural weight of 12.148 ton is composed from 3.656 ton of the upper/lower skin panels, 6.604 ton of the spar materials and 1.888 ton of the ribs. The optimum fiber orientation angles and the thickness distributions of the upper/lower skin panels are shown in Fig. 5. The 12.148 ton of the wing box

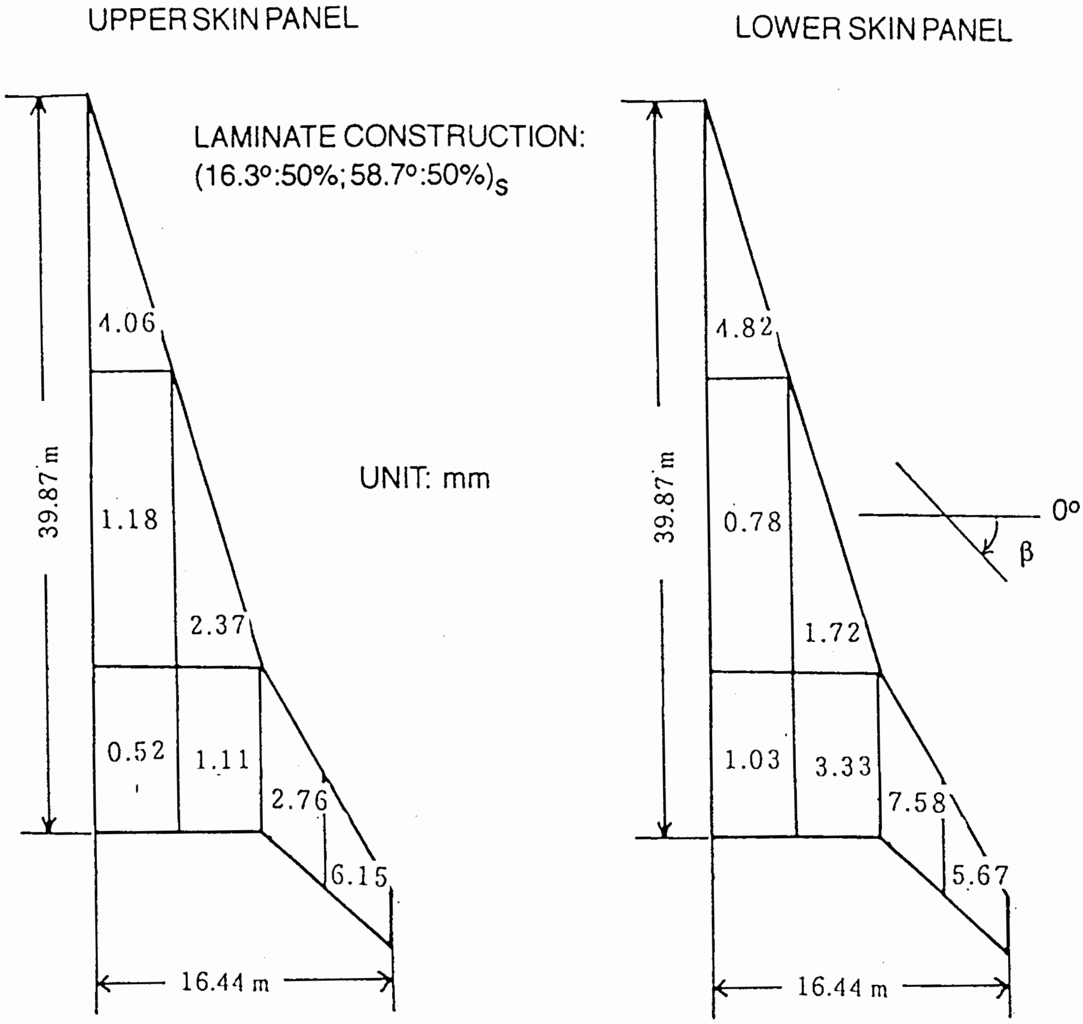


Fig. 5 Fiber Orientation Angles and Thickness Distributions of Upper/Lower Skin Panels

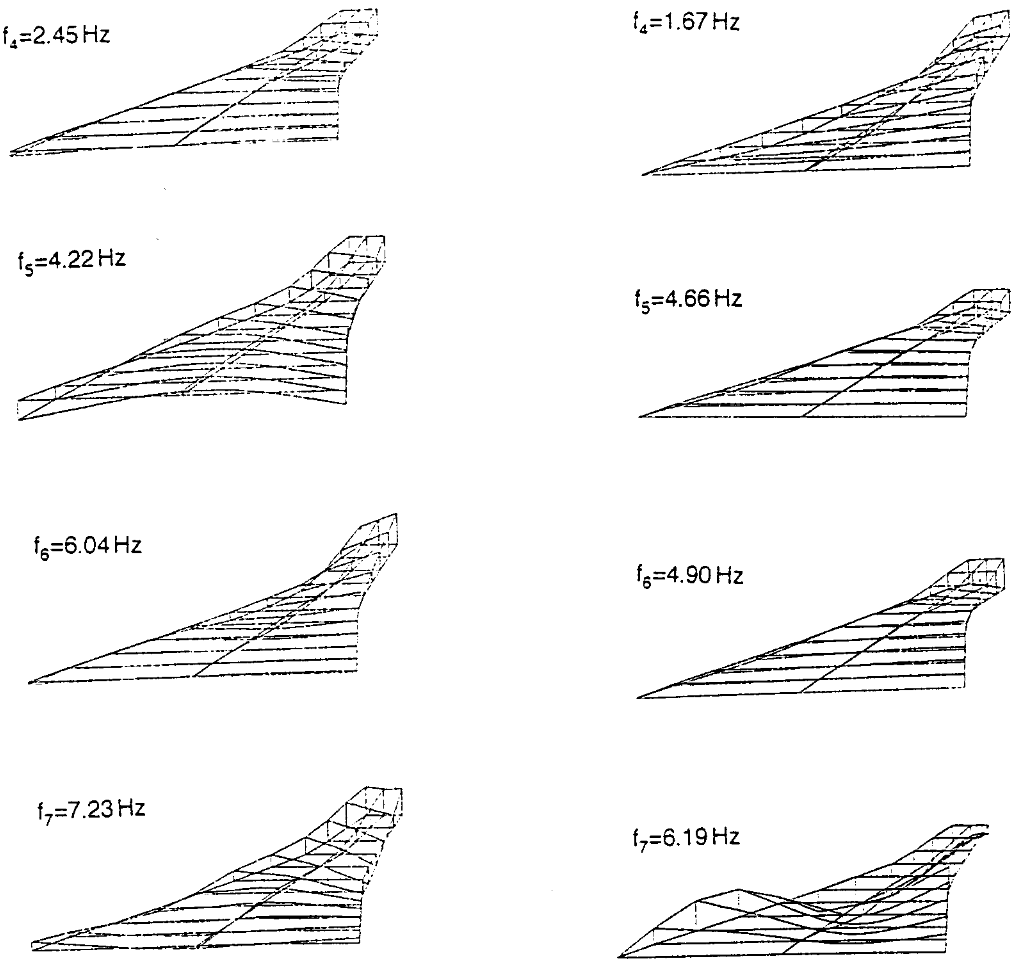
structural weight obtained by the present optimum design is about 19% reduction of the corresponding wing box structural weight of our previous design[10], which was obtained by the trial and error design under the same design conditions.

In Figs. 6a and 6b, the symmetric and antisymmetric natural vibration mode shapes and frequencies of the present optimized structure are shown, respectively. It should be noted that the first three modes are the rigid body modes, namely, $f_1=f_2=f_3=0$ and that only the elastic modes are shown in the figures.

As already mentioned, the structural weight reduction attained by the present optimization is about 19 % compared with our previous trial and error design. When we notice that the present optimized model is strength critical rather than flutter critical, it could be said that the aeroelastic tailoring might be more effective than the present example if we apply the present code to the arrow wing model which is flutter critical rather than strength critical.

4. Concluding Remarks

A preliminary design code for aeroelastic tailoring of an arrow wing supersonic cruise configuration has been developed. A direct search method, which does not depend on the derivatives of the objective and constraint functions, is employed to find the optimum fiber orientation angles and thickness distributions of the upper and lower skin panels, and to find the optimum thickness of the spar and rib materials of the wing box structure for the minimum weight design under the multiple constraints. The static



(a) Symmetric Mode

(b) Anti-Symmetric Mode

Fig. 6 Natural Vibration Mode Shapes and Frequencies of Optimum Designed Structure

strength, symmetric and antisymmetric flutter velocities are taken into account at the same time as the constraints. The code is applied to a typical arrow wing configuration to demonstrate its capabilities. It has been shown that the 19% reduction of the structural weight can be attained by the optimization compared with our previous trial and error design obtained under the same design conditions.

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