APPLICATION OF AEROELASTIC TAILORING TO ARROW WING CONFIGURATION

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Abstract

A computer code for aeroelastic tailoring of an arrow wing configuration of Supersonic Transport (SST) is developed. This computer code includes the strength analysis using an original finite element code and the aeroelastic analysis. In the optimization process of this code, Genetic Algorithm (GA) is employed to find the optimum laminate construction of the wing box for the minimum structural weight under the static strength and the aeroelastic constraints. This code is applied to a preliminary design of an arrow wing configuration. The optimum design satisfying only the static strength constraint is not satisfied with the aeroelastic constraint. In consideration of the aeroelastic constraint, the flutter characteristic is optimized and the optimum laminate construction which satisfies both the static strength and the aeroelastic constraints is obtained.

1 Introduction

From the end of 1980's, the research and development of the next generation Supersonic Transport (SST) has been activated in the world to satisfy passenger demand for high-speed transportation. Arrow wing configuration might be a strong candidate for a main wing of SST. The aeroelastic characteristics have played the significant role in structural design of an arrow wing configuration in the transonic regime [1]. For example, the design studies performed by Turner and Grande [2] of the early Boeing Supersonic Transport Model 969-512B disclosed that the strength designed configuration did 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 $M = 0.9$) in the initial design.

For the improvement of the flutter characteristics of an arrow wing configuration without mass penalty, the application of the aeroelastic tailoring technology might one of the most promising approaches. Aeroelastic tailoring is the concept of using the directional stiffness properties of composites for the design of an aircraft structural component to deform under load in such a way as to benefit the performance of the aircraft. 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. This paper presents application of aeroelastic tailoring to arrow wing configuration and verification of its effectiveness.

2 Description of Computer Code

In order to perform the aeroelastic tailoring, the computer codes such as static strength, buckling and aeroelastic analyses, are required. Also, the optimization code is required to satisfy each design condition and compute the minimum structural weight.

For the static strength and the buckling analyses, the original finite element codes have been developed instead of commercial FEM softwares, being integrated into the aeroelastic and the optimization programs. In addition, the FEM program of the vibration analysis, which computes the natural frequencies and the natural vibration modes for the aeroelastic analysis, has been developed.

For laminated composite structures, each lamina has its greatest stiffness and strength properties along the direction in which the fibres are oriented. Therefore, the mechanical properties of laminated composite structures largely depend on laminate construction. Also composite laminate design variables such as ply thickness and orientation, and involves discontinuous objective functions. Genetic algorithms are ideal optimization algorithms for these type of problems and do not need the derivatives of the objective and constraint functions.

The unsteady aerodynamic forces are computed by using Doublet Lattice Method (DLM) [3].

3 Analytical Model

The arrow wing model employed in the present study is shown in Fig. 1. This model refers to the Boeing Supersonic Transport Model 969-512B. The root chord length is 50.4 m and the semispan length is 18.9 m. The airfoil section is 3 percent thick circular arc. The engine mass is assumed to be 6500 kg for each engine, and set as the concentrated mass at the locations indicated in Fig. 1. For full fuel condition, which is the most critical condition for flutter, 200000 kg of the fuel mass is assumed. The properties of composite materials are shown in Table 1.

Fig. 2 shows the FEM model. This model consists of 680 nodes and 2008 triangular plate bending elements. In order to reduce the number of the design variables in the optimization process, the upper and lower skin panels divided into 6 zones, respectively, as shown in Fig. 3. The thickness of the skin panels of each zone is assumed to be the constant.

It is also assumed that the laminate construction of the upper and lower skin panels is $[\ \alpha_1\ /\ \beta_1\ ]_s$. α and β are the different fiber orientation angles and they are the design variables. The subscript s denotes the symmetric

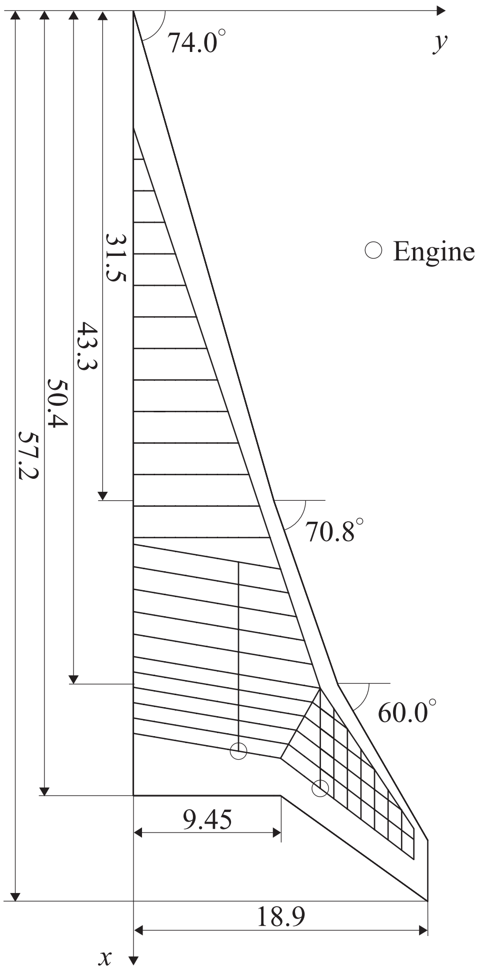


Fig. 1 Arrow wing configuration

Table 1 Composite material properties

E_L	159 GPa
E_T	9.8 GPa
ν_{LT}	0.3
G_{LT}	4.9 GPa
ρ	1600 kg/m^3

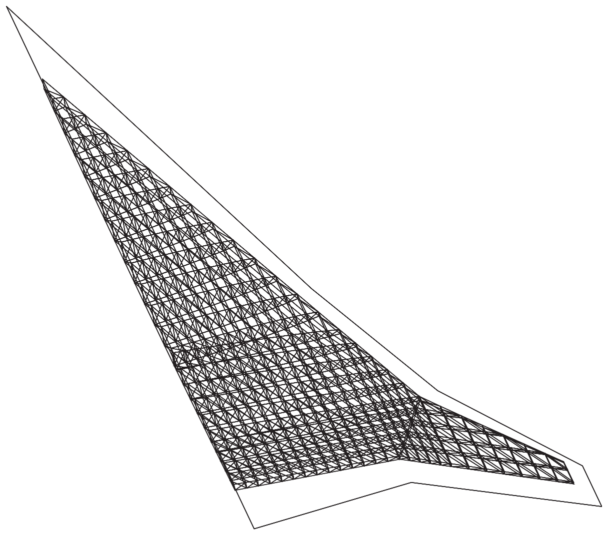


Fig. 2 Finite element Model

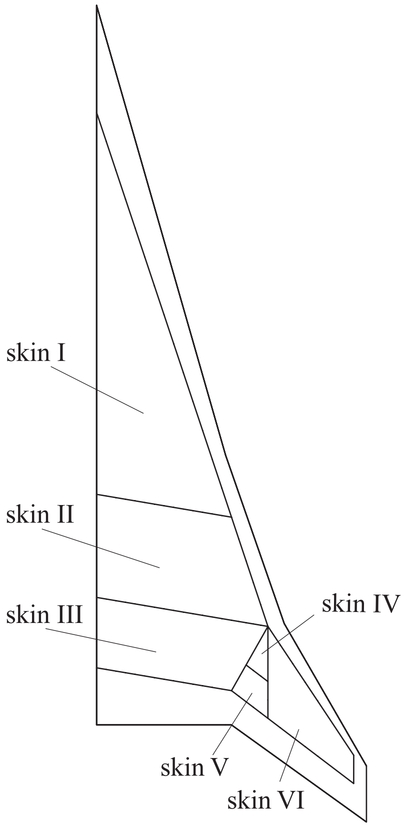


Fig. 3 Zoning of upper and lower skin panels

laminates. In terms of the spars and ribs, the laminate construction is assumed to be quasi-isotropic of $[\ 0^\circ_1\ /\ +45^\circ_1\ /\ 90^\circ_1\ /\ -45^\circ_1\ ]_s$.

4 Numerical Results

To perform the aeroelastic tailoring for the arrow wing configuration shown in Fig. 1, the present optimization problem is as follows :

Objective function
Minimization of structural weights.

Constraint

- Static structural constraint
  The static strength requirement is to sustain 2.5 g load of the maximum take off gross weight which is 9.186×10^6 N. When the Mach number is 0.9 and the angle of attack is 5.2°, this static loads can be achieved. Fig. 4 shows the load distributions predicted by using DLM in which the 100 panels (10 chordwise by 10 spanwise) are employed. The maximum strain criterion is employed to identify the structural failure.

- Aeroelastic constraint
  At $M = 0.9$, the flutter velocity must be higher than $1.2V_D = 259$ m/s EAS (V_D : the design diving speed).

Design variables
The design variables are as follows:

- the fiber orientation angle of the upper and lower skin panels (2)
- the thickness of the upper skin panels of each zone (6)
- the thickness of the lower skin panels of each zone (6)
- the thickness of fore- and hind-spars (2)
- the thickness of each rib (6)

The total design variables are 22. The range of the fiber orientation angle is −90° to +90°. The minimum gage for the upper and lower skin panels, spars and ribs is taken to be 1.92 mm.

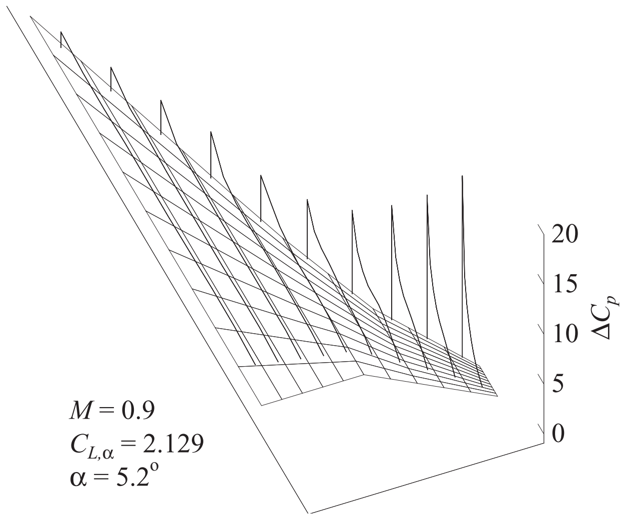


Fig. 4 Load distribution

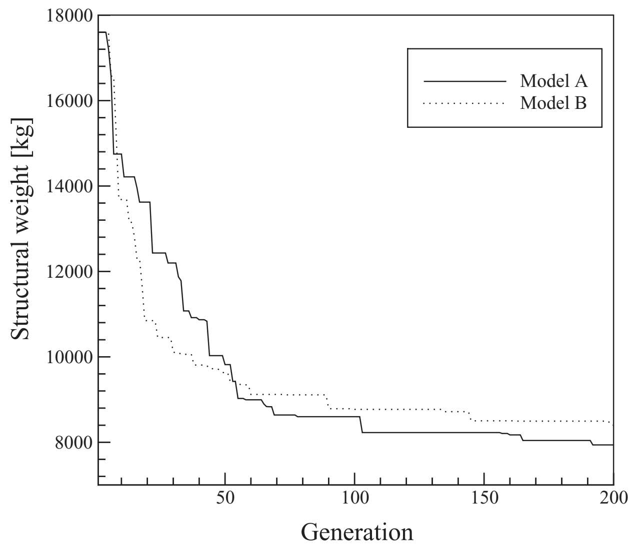


Fig. 5 Convergence histories of structural weights of Model A and Model B

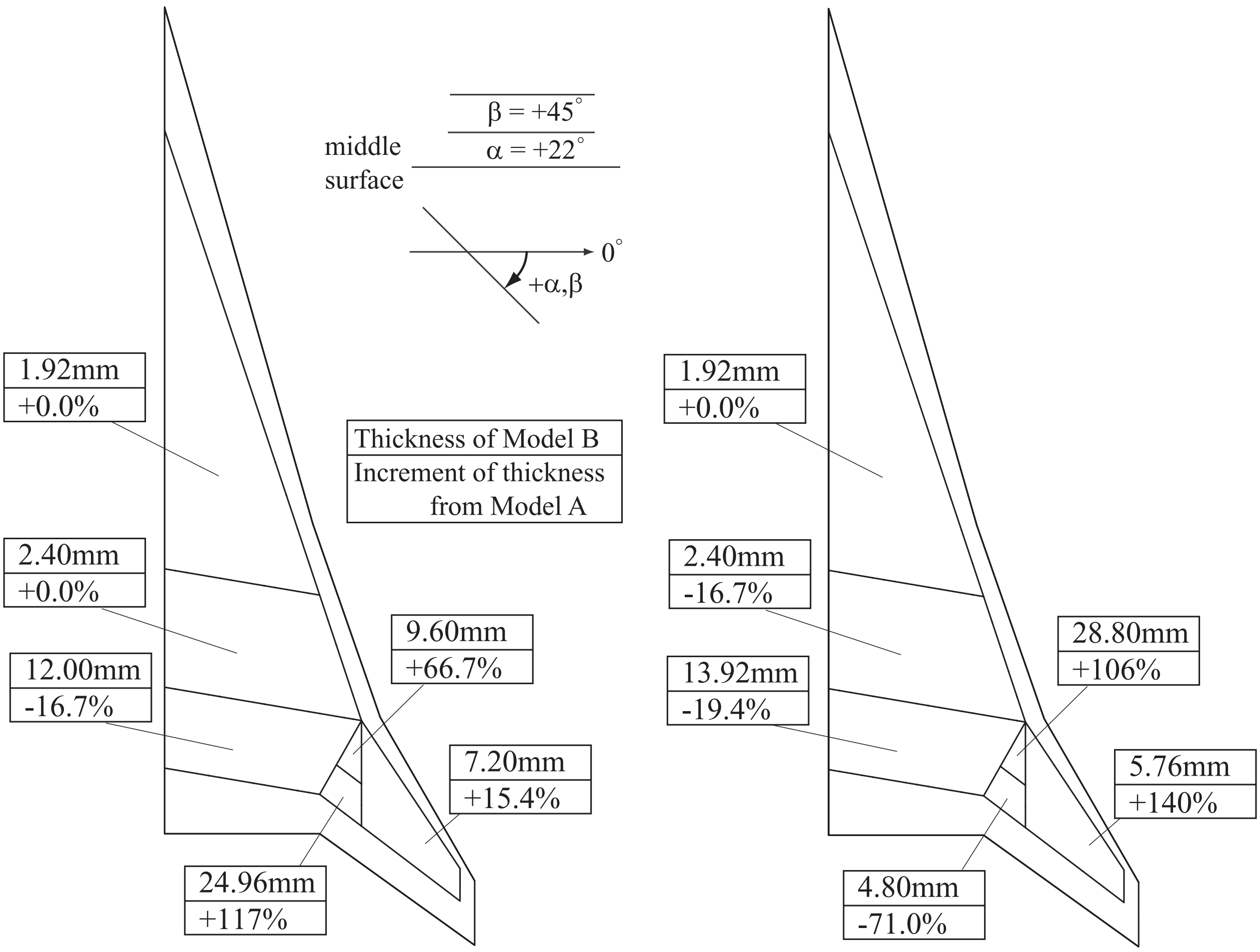
For the implementation of the genetic algorithm in the optimization process, an initial population of the binary coding of design variables with randomly chosen genes is created first. The size of the population used in the present code is constant throughout the genetic optimization. The fitness function is the inverse of the structural weight. The method of selection is tournament selection with a shuffling technique for choosing random pairs for mating. Also, the elite preservation strategy is employed to leave the best individual to the next generation. The benefit of this strategy is that the best individual is not affected by crossover or mutation. The method of crossover is one-point crossover in which children are created by combining a portion of each parent's genetic string in an operation. The individuals of each generation are 20. The crossover probability is 0.6 and the mutation probability is 0.02.

In the present study, the computations have been conducted for two cases. The first one is for satisfying only the static strength constraint (Model A). And the second one is for satisfying both the static strength and the aeroelastic constraints (Model B).

In Fig. 5, the convergence histories of the structural weights for Model A and Model B are shown. The total structural weight of the wing box in the optimum laminate construction is 7937 kg for Model A and 8400 kg for Model B, respectively. In Table. 2, the structural weights of skin panels, spars and ribs, and the increment of structural weights from Model A to Model B are shown. This optimum design of the fiber orientation angles and thickness distributions are obtained from the individual which has the best fitness in the 200th generation.

In Fig. 6, the thickness distributions and the fiber orientation angles of upper and lower skin panels for Model B and the increment of the thickness in each zone are shown. In the skin panels, the increase of the thickness of the outboard is remarkable and the decrease of the thickness of the hind-inboard is seen. The thickness of the fore-inboard is minimum gage and almost no change can be seen. These tendencies show that the torsional stiffness increases in the outboard, and the bending stiffness decreases in the inboard to satisfy the aeroelastic constraint.

The flutter speeds and the flutter frequencies are shown in Table.3. It is obvious that Model A is not satisfied with the aeroelastic constraint. In consideration of the aeroelastic constraint, the flutter characteristic is optimized, and the optimum design which satisfies both the



(a) Upper skin panel (b) Lower skin panel

Fig. 6 Fiber orientation angles and thickness distribution of upper and lower skin panels

Table 2 Structural weights in each zone for Model A and Model B [kg]

	Model A	Model B	Increment of structural weight
Skin panels	4880	4584	−296 (−6.1 %)
Spars	2164	2810	+646 (+29.9 %)
Ribs	893	1006	+113 (+12.7 %)
Total	7937	8400	+463 (+5.8 %)

Table 3 Flutter speeds and flutter frequencies of Model A and Model B

	Model A	Model B
U_F [m/s]	190.5	367.1
ω_F [rad/s]	8.786	11.073

U_F : Flutter speed
ω_F : Flutter frequency

static strength and the aeroelastic constraints is achieved.

5 Concluding Remarks

A computer code for aeroelastic tailoring of an arrow wing configuration of a supersonic transport is developed. This code includes the static strength analysis using the original finite element code and the aeroelastic analysis. In the optimization process of this code, a genetic algorithm is employed to find the optimum laminate construction of the wing box for the minimum structural weight under the static strength and the aeroelastic constraints. This code is applied to a preliminary design of an arrow wing configuration.

The optimum design for Model A is not satisfied with the aeroelastic constraint. In consideration of the aeroelastic constraint, the flutter characteristic is optimized and the optimum laminate construction which satisfies both the static strength constraint and the aeroelastic constraints is obtained.

In the convergence histories of the structural weights (Fig. 5), the optimization process is not enough to converge to the optimum design. For further study, the code should take into consideration of improvement in the speed including parallel computing.

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