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AEROELASTIC ANALYSIS OF COMPOSITE WING WITH CONTROL SURFACE

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Abstract: A set of computer program package is made of analysis and design of composite structure, including the the finite element analysis, vibration analysis, static and dynamic aeroelastic analysis, and optimal design. A special method is presented to deal with the joint of wing and control surface. The computational program has the ability to get the influence of temperature and humidity to the composite structure. Two practical aircraft structures are given by successful application of the program package.

Introduction

The composite materials are increasingly used for advanced aircraft structures because that they not only have high strength–to–weight ratio, but also they give the design ability to improve the aerodynamic and structural performance of aircraft. In general, the wing structure and the constrol–surface structure are as a single structure for structural and aeroelastic analyses. However, the rationality of the joint analogue of control surface with wing and system will affect the result of aeroelastic analysis. Some analogy methods including dynamic effect on the control surface joint are described in this paper. The temperature influence to composite property is not negligible. The stiffness change due to temperature on the composite structure will produce a different effect from the matel structure.

This problem has not been to deal with in the papers of the composite structure aeroelastic analysis before.

The effect of temperature and humidity to composite wing's static and dynamic aeroelastic performances is described in the paper.

A computer program package of the composite structure analysis and optimum design (CSAOP) is presented. Two practical examples of the aeroelastic analyses of the composite aeronautical structures are provided by using the CSAOP.

Analysis Method and Program Package

The program package CSAOP is designed adaptably to perform various functions which includes the sturctural analysis, static and dynamic aeroelastic analyses, and optimum design. A functional flom diagram of the CSAOP package is presented in Fig.1.

Composite structural analysis

The structural stiffness matrix and flexibility matrix for aeroelastic analysis are obtained by the finite element method which not only have general bar, plate elements of the composite multi–directional laminate, but also have the isoporametric element, non–conforming element and honeycomb element. A half composite web and a half beam element are presented for symmetric structure under anti–symmetric loads, as to that the freedom degree number of the whole structure stiffness matrix is reduced to one half, and it especially is fitted in with the aeroelastic analysis of the lift surface. [1]

Vibration modal analysis

Three methods are used to solve eigen problem of vibration equation in the program package which includes the anti–iteration method, the subspace iteration method and the Lanczos method.

The spectral transformation Lanczos method's idea is to transform a standard eigen matrix A to the following eigenvalue problem

$$(A-\mu I)^{-1}x = Vx \qquad (1)$$

Where the ralation of the original eigenvalue λ with the transformed eigenvalue V is

$$\lambda = \mu + V^{-1} \qquad (2)$$

The computer speed of the Lanczos method is about 4~ 9 times faster than first and second iteration methods.

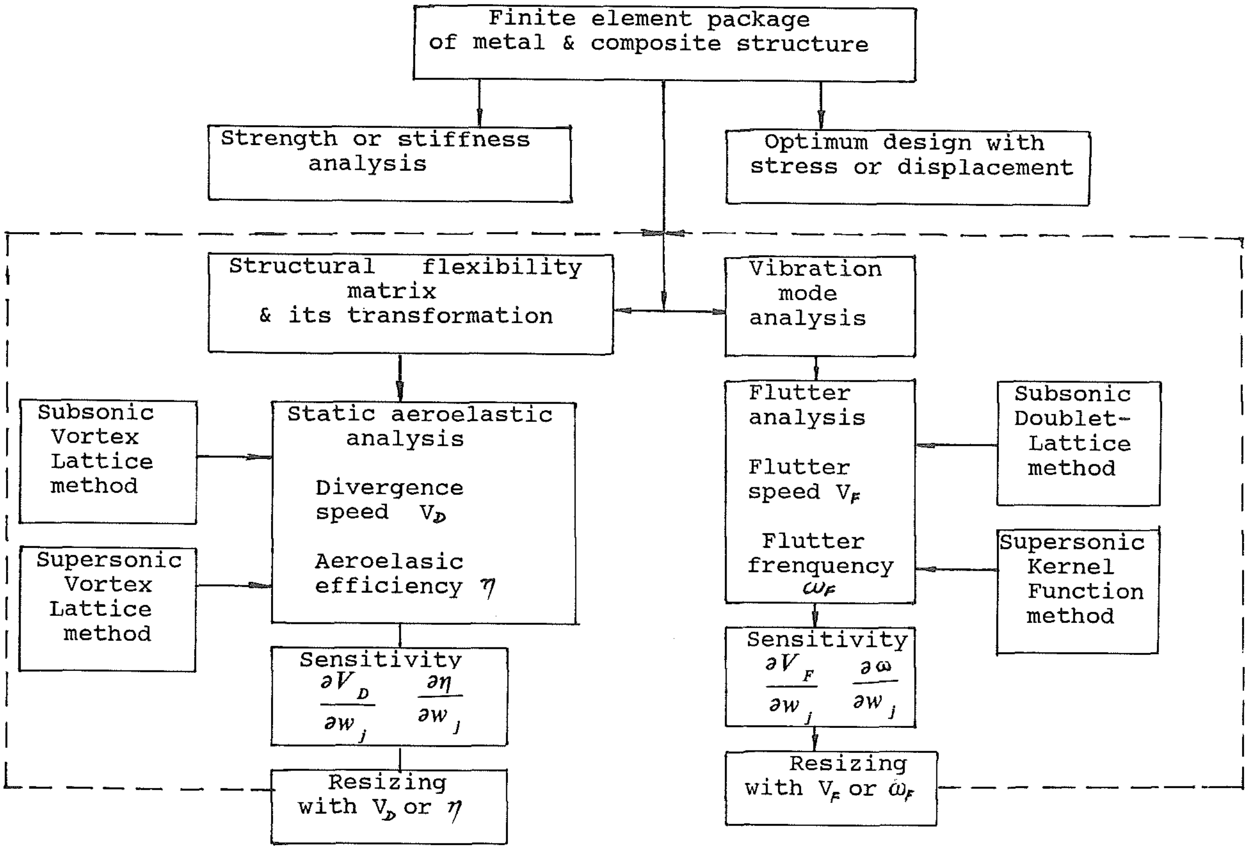


Fig.1 The Functional Flow Chart of The CSAOP

Static aeroelastic analysis

The flexibility influence coefficient matrix on the structural grid must be transformed on the aerodynamic grid for static aeroelastic analysis. The surface spline matries and the priciple of virtual work are employed to get the transformation [3]

$$[S]_{NN} = [T1][K]^{-1}_{MM}[T2] \qquad (3)$$

Where $[K]^{-1}$ and [S] are respectively the flexibility matriex on structure grid points M and on aerodynamic grid points N.

The Steady aerodynamic force is computed by a generalized vortex lattice method including subsonic and supersonic flows. A improved method to predict the nonlinear vortex lift is used for small aspect wing.[7] The results of static aeroelastic analysis contain the divergence speed and the aeroelastic efficiencies of the aerodynamic parameters of wing or control surface.

Flutter analysis

The motion equation for modal flutter analysis is

$$\{[\overline{M}] - (1+ig)\omega^{-2}[\overline{K}] + [\overline{Q}]\}\{u\} = 0 \qquad (4)$$

where the generalized aerodynamic force $\overline{Q}$ is calculated by solving the following the pressure–normal wash integral equation of nonplanar Lifting surface

$$\frac{W^*}{U} = \frac{1}{4\pi\rho U^2}\iint_S \triangle P^*(\xi,\eta,\zeta)K(x-\xi, y-\eta, z-\zeta,\omega,M)ds \qquad (5)$$

For subsonic flow, a subsonic Horseshore vortex–Oscillating Doublet Lattice method is used[3]. For supersonic flow, a improved supersonic Kernel Function method is presented [4]. An automatic interpolation–iteration procedure is designed to get the critical flutter speed and frequency instead of drawing V–g graph by hand.

Optimum design

The optimization procedure of structure design is: first to make the optimum design with the constraint of strength or stiffness which displacement constraint is to imply aeroelastic requirement; second to make the aeroelastic tailoring with static aeroelastic or flutter constraints.

For the structural resizing with static aeroelastic requirements, the following sensitivity analysis derivatives are

$$\frac{\partial V_D}{\partial w_j} = \frac{q_D^2}{\rho V_D} \{\beta_D\}^T [T1][K]^{-1} \frac{\partial [K]}{\partial w_j} [K]^{-1}[T2][a][A]\{\triangle\alpha\} \tag{6}$$

$$\frac{\partial \eta}{\partial w_j} = \frac{-q^2}{L_R} \{a\}^T [A_F][T1][K]^{-1} \frac{\partial [K]}{\partial w_j} [K]^{-1}[T2][a][A_F]\{\alpha + \frac{\partial f}{\partial x}\} \tag{7}$$

where V_D is the divergence speed.

η is the efficiency of aerodynamic parameter of wing or control surface.

For the aeroelastic tailoring with flutter constraint, the sensitivity analysis derivatives are

$$\frac{\partial V_F}{\partial w_j} = \frac{1}{2k\omega}[(R_1 - R_2\frac{\partial k}{\partial w_j})R_3 + (I_1 - I_2\frac{\partial k}{\partial w_j})I_3]/(R_3^2 + I_3^2) - \frac{\omega\,1}{k^2}\frac{\partial k}{\partial w_j} \tag{8}$$

$$\frac{\partial k}{\partial w_j} = (R_1 I_3 - R_3 I_1)/(R_2 I_3 - R_3 I_2) \tag{9}$$

where V_F is the flutter speed

k is the reduced frequency

$$R_1 + iI_1 = V^T(\frac{\partial \overline{K}}{\partial w_j} - \lambda\frac{\partial \overline{M}}{\partial w_j})u \tag{10}$$

$$R_2 + iI_2 = \lambda V^T \frac{\partial \overline{Q}}{\partial k} u \tag{11}$$

$$R_3 + iI_3 = V^T(\overline{M} + \overline{Q})u \tag{12}$$

Two optimization methods of minimum weight structure are used in the program package: the feasible direction method and the sequence quadratic programming method [1,5].

Joints of Control Surface

The rationality of the joint analogy of control surface will affect the analysis accuracy of the control–surface aeroelastic efficiency and the flutter of wing with control surface.

For the hinge joint of control–surface, a method is presented that a hinge joint is constructed by two point analogy in the finite element structure, which one is the point of wing and another point is of control surface. The displacements of the two points must be equal and it only transfer the shear not to transfer the torque between the two points.

For the joint of the control surface with control system, two kinds of analogy technique of the boundary support of the control surface linking the system are presented in the program package: (1) A torque constraint and a stiffness support of link point are given by the analysis of the control system. A structure resisting the torgue is constructed instead of the connected joint of the control system. (2) Another method consider dynamic effect of the control system. First, the dynamic stiffness of joint point B which is transferred from the control system is obtained by the following displacement impedance

$$Z_{B_1} = F(\omega) / \triangle x \tag{13}$$

Second, according to the structural analysis of the control–surface the dynamic stiffness of the joint point B which is transferred from the control surface is obtained by the displacement impedance of joint B

$$Z_{B_2} = f(\omega) \tag{14}$$

Both of the equation (13) and (14) are the functions of the vibration frequency ω. Due to $Z_{B_1} = Z_{B_2}$, therefore a couple natural frequency is obtained from the cross point of the curve (13) and the curve (14).

Effect of Temperature and Humidity

It is indicated from experiments that the temperature have a large effect to the composite structure. And this effect is different from to the metal structure in that the change of the composite structure property due to temperature is directional. The following table is the experimental property comparison of different temperature for the composite plate with single direction fiber [6] (the material is used for the practical structures in this paper).

Table 1 Comparison of the properties of
Composite plate with single direction fiber

temp.	E_L^-	E_L^-	E_T^+	E_T^-	G (GPa)
25℃	145.6	150.4	9.16	8.95	4.74
110℃	140.2	123.1	5.96	5.80	4.087

It is shown from above table that the effect of temperature to the lateral property of composite plate with a single direction fiber is obviously larger than the effect to longitudinal property. The temperature change of the aeronautical structure is not only from its enviroments (outside or inside), but also is produced by aerodynamic–heating of high speed flight. Therefore the change of composite structure stiffness due to temperature is not negligible. In this computer program, the various properties of composite orientation at different temperatures are added to the structural stiffness computation, as to get the temperature effets to aeroelastic performance of aircraf.

According to the experimental results [6] , the humidity effect on the T300 / 648 Epoxy composite's stiffness is very small. The saturation amount of moisture absorption of the composite (at 60℃, for 20 days) is 0.69% ~ 0.98% (wt.). Only the weight effect of composite moisture absorption is considered for aeroelastic analysis.

Application of Two Practical Structures

1. A composite empennage of supersonic aircraft

A empennage configuration is shown in Fig.2. The skin panel and most of the beams, stringers and ribs of the vertical tail and cowling fairing are made of the composite T300 / 648 Epoxy. For aeroelastic analysis a structural finite element model of the vertical tail with rear fuselage is indicated in Fig.3.

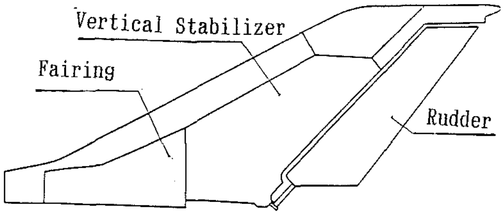


Fig.2 The Configuration of The Vertical Tail of the Supersonic Aircraft

The empennage of the original type aircraft is the full metal structure. The outline configuration of the improved composite empennage is same as the original metal empennage.

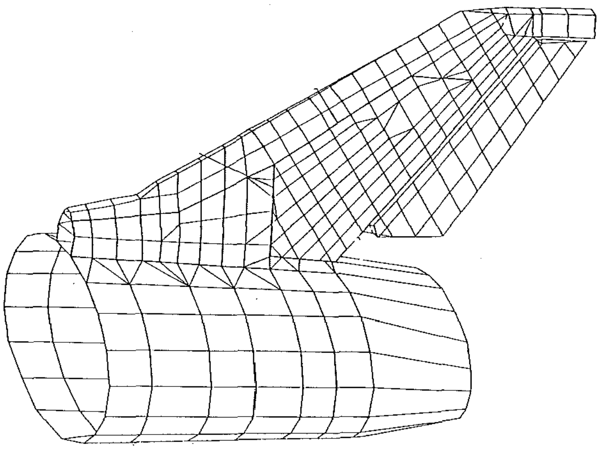


Fig.3 The Finite Element Structure of The Vertical Tail Model I

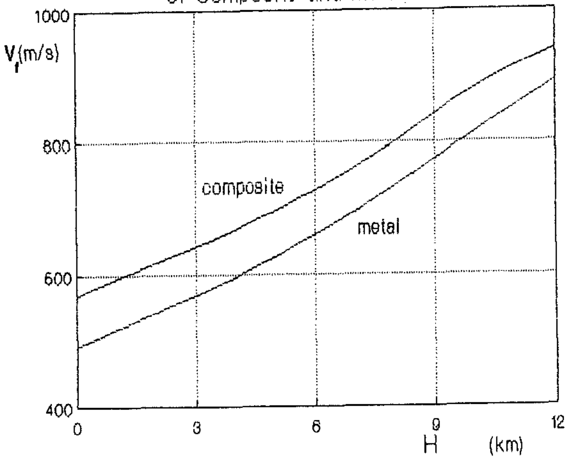
The static and dynamic aeroelastic performances of the compositte tail through optimum design are analyzed.

Table 2 Vibration mode frequencies (Hz)

order	1	2	3	4	5	6
metal	12.9	42.6	45.2	61.7	71.0	79.4
composite	14.5	46.8	53.3	70.5	78.4	87.8

It is seen from Table 2 that the natural frequencies of the composite model are slightly higher than the metal model. It is especially worth notice that the weight of the composite empennage reduces 24.5%,

Fig.4 Composite of Flutter Speeds of Composite and Metal of The Tail



however the flutter speed of the composite tail are larger than the original metal tail. This benefit is because of the composite structure design having a advanced directional stiffness.

Investigating the temperature effect to aeroelastic performances of the composite tail, it is shown (Fig. 5,6) that the flutter speeds at high temperature decrease by 1.5%~ 9.5%; the divergence speeds at high temperrature decrease by 0.8%~ 0.9%; and the rudder aeroelastic efficiencies at high temperature decreased by 0.3%~0.5%.

Fig.5 Comparison of The Flutter Speeds of The Composite Tail at Different Temperature

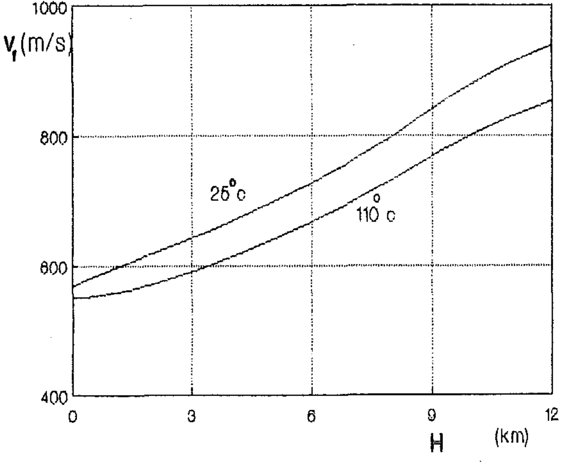


Fig.6a Comparison of The Divergence Speeds at Different Temperatures

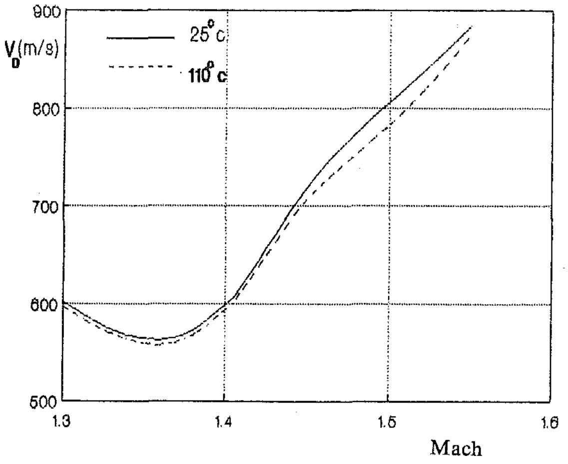
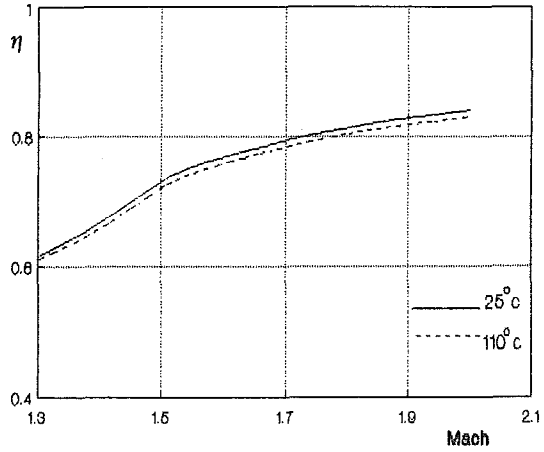


Fig.6b Comparison of Aeroelastic Efficiencies at Different Temperatures



It is considered in the paper that the increase order of the weight is about 1% for the composite tail exposing for long time in humid atmospheres. The calculation result shows that the humidity effect to aeroelastic performances is very small.

2. A composite vertical tail of subsonic aircraft

A composite vertical tail stabilizer and rudder model of a subsonic aircraft is shown in Fig.7. The skin and part of inside structure are made of the composite Graphite / Epoxy. The rudder is made of composite sandwich panel with honeycomb core.

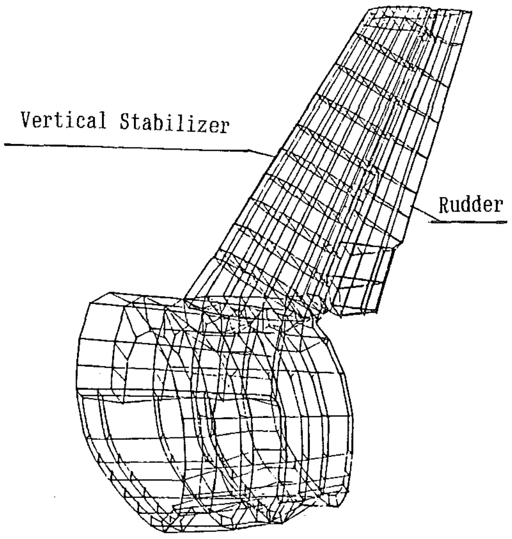


Fig.7 The Structure Model of The Vertical Tail of The Subsonic Aircraft

The vibration mode analysis of the tail is obtained by the Lanczos method which is consistent with the experiment of the model.

Table 3 Vibration mode frequences (HZ)

order	1	2	3	4	5
Calculation	10.2	17.3	67.3	89.9	106.6
experiment	6.3	16.0	66.5	82.1	97.7

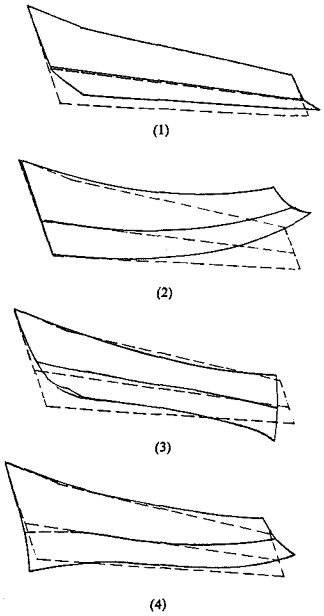


Fig.8 The Vibration Mode of The Composite Tail With Rudder

The first order mode is the rudder ratory which conforms the practical performace because of the rational link analogy of the rudder with control system. The second and the third order modes are respectively bending and torsion vibrations.

The composite tail flutter speed by computation of aeroelastic analysis is slightly higher than the original metal structure.

Conclusion

It is indicated from above practical examples that the application of the CSAOP program package for composite wing with control surface is successful. The advanced composite structure is employed on aircraft structure that not only it reduces weight, but also improves aeroelastic performances in beneficial way. The temperatture effect on the composite wing structure of the high speed aircraft should be considered.

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