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THE FLUTTER MODEL CHARACTERISTIC STUDY AND WIND-TUNNEL TEST FOR WING-MOUNTED CIVIL AIRCRAFT

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Abstract

The body-like aerodynamic model are used for the fuselage and nacelle component. The influence of the flutter characteristic due to aerodynamic of the fuselage and nacelle are studied and verified through low-speed flutter model wind-tunnel test of the aircraft. The theoretical results and test results show that the flutter characteristic of the aircraft are changed considering aerodynamic effect of fuselage and nacelle.

1 Introduction

The aerodynamic modeling technology is one of the critical technology of the flutter analysis for the wing-mounted civil aircraft[1,2]. The aerodynamic effect of the nacelle and fuselage are not considered in aerodynamic modeling technology[3]. It is not appropriate for modern civil aircraft.

High bypass ratio engines are used to reduce fuel consumption for modern civil aircraft. The larger and massive engines have a significant impact on dynamic characteristics of structure and unsteady aerodynamic of aircraft, which maybe result in the low damping flutter mode called "hump mode"[4,5]. The aerodynamic effects of fuselage and engine have a great influence on the hump mode flutter, which is coupled between the elastic mode of wing and the pitch mode of engine.

In the present work, the body-like aerodynamic model are used for the fuselage and nacelle component. The influence of the flutter characteristic due to aerodynamic of fuselage and nacelle are studied and verified through low-speed flutter wind-tunnel test of the aircraft.

2 Mathematical model

2.1 Governing Aeroelastic Equations of Motion

The aeroelastic equations of motion in generalized coordinates can be expressed as[6]

$$\boldsymbol{M}_{qq}\ddot{\boldsymbol{q}} + \boldsymbol{C}_{qq}\dot{\boldsymbol{q}} + \boldsymbol{K}_{qq}\boldsymbol{q} = \frac{1}{2}\rho \boldsymbol{V}^2 \boldsymbol{Q}_{qq}\boldsymbol{q} \qquad (1)$$

where $\boldsymbol{q}$ is the generalized coordinate, ρ is air density, $\boldsymbol{V}$ is airspeed, $\boldsymbol{M}_{qq}$, $\boldsymbol{C}_{qq}$ and $\boldsymbol{K}_{qq}$ are generalized mass, damp and stiff matrices, $\boldsymbol{Q}_{qq}$ is generalized unsteady aerodynamic influence coefficient matrix.

2.2 Computation of Unsteady Aerodynamic

The linearized small disturbance equation can be expressed as[7]

$$(1-M_\infty^2)\Phi_{xx} + \Phi_{yy} + \Phi_{zz} - 2\frac{M_\infty}{a_\infty}\Phi_{xt} - \frac{1}{a_\infty^2}\Phi_{tt} = 0 \qquad (2)$$

where M_∞ is the Mach number, Φ is the total velocity potential, it consists of two parts: the steady potential ϕ_0 as well as the unsteady potential ϕ_1.

Substituting the two parts into Eq.(2) and collecting the like-order terms yield the equations for ϕ_0 and ϕ_1

$$(1-M_\infty^2)\phi_{0xx}+\phi_{0yy}+\phi_{0zz}=0 \quad (3)$$

$$(1-M_\infty^2)\phi_{1xx}+\phi_{1yy}+\phi_{1zz}-2\frac{M_\infty}{a_\infty}\phi_{1xt}-\frac{1}{a_\infty^2}\phi_{1tt}=0 \quad (4)$$

Consider an aircraft of interest performs a simple harmonic motion, the unsteady potential ϕ_1 can be expressed in a reduced form:

$$\phi_1=\phi e^{i\omega t} \quad (5)$$

where ω is oscillation frequency, ϕ is the reduced frequency-domain potential.

Let: $x'=L\beta x$, $y'=Ly$, $z'=Lz$

where L is the reference length and $\beta=\sqrt{\left|1-M_\infty^2\right|}$

Introducing the modified potential

$$\phi=\bar{\phi}e^{i\lambda M_\infty x'} \quad (6)$$

where $\lambda=kM_\infty/\beta$ is compressible reduced frequency, k is the reduced frequency.
Substituting Eq.(6) into Eq.(4):

$$\bar{\phi}_{x'x'}+\mu\bar{\phi}_{y'y'}+\mu\bar{\phi}_{z'z'}+\lambda^2\bar{\phi}=0 \quad (7)$$

where $\mu=1$ for $M_\infty<1$ and $\mu=-1$ for $M_\infty>1$.
An integral solution can be obtained in terms of the unsteady source and doublet singularity distributions over the surface of the configuration. Transforming this integral solution back to an expression for ϕ , one obtains:

$$\phi(x_0,y_0,z_0)=-\frac{1}{4\pi}\iint_S\sigma(x,y,z)e^{i\lambda M_\infty\xi}KdS$$
$$+\frac{1}{4\pi}\iint_{S+W}\Delta\phi(x,y,z)e^{i\lambda M_\infty\xi}\frac{\partial}{\partial n}KdS \quad (8)$$

where $\frac{\partial}{\partial n}$ is the out-normal vector, K is Kernel function
All wing-like components are assumed to be flat plate. Source singularity is usually used to simulate the thickness effects whereas doublet singularity to generate lift, Eq.(8) can be expressed as

$$\phi(x_0,y_0,z_0)=\phi_W(x_0,y_0,z_0)+\phi_B(x_0,y_0,z_0) \quad (9)$$

where ϕ_W is potential influence due to the wing-like components

$$\phi_W(x_0,y_0,z_0)=\frac{1}{4\pi}\iint_{Wing+wake}\Delta\phi(x,y,z)e^{i\lambda M_\infty\xi}\frac{\partial}{\partial n}KdS \quad (10)$$

ϕ_B is the potential due to the body-like components

$$\phi_B(x_0,y_0,z_0)=-\frac{1}{4\pi}\iint_S\sigma(x,y,z)e^{i\lambda M_\infty\xi}KdS \quad (11)$$

The potential and velocity influence coefficient of the body box and the wing box are obtained by solving the elementary integrals and the elementary pressure Kernel integrals. Construct influence coefficient matrices and compute the unsteady aerodynamic according to the boundary conditions of the wing boxes and the body boxes.

2.3 Body Wake Effect

The wake generated by flow separation at the tail section or behind the base of a body-like component has considerable influence to wing-body or body-alone aerodynamics.
This non-iterative body wake modeling requires a given base pressure coefficient C_{Pbase} , the pressure of the adjacent boxes to the body base is given by $C_{p0}=C_{pbase}$. Imbedded singularities are placed in the assigned proximity of the body base regime to simulate the exterior wake flow. The constant pressure condition is imposed at the body base. This boundary condition can be expressed as $C_{p0}=C_{pbase}$, $C_p=0$ where C_{p0} and C_p are the steady and unsteady pressure, respectively.
The combination of this constant pressure condition and the steady and unsteady boundary conditions yields a compact expression in terms of the velocities, the mode shape and its derivative:

$$a\phi=b\phi_0 \quad (12)$$

where

$$a=V+ik \quad (13)$$

$$b = \frac{dc}{dx} + ikc \qquad (14)$$

c is a function of the mode shape, ϕ_0 and ϕ are the steady and unsteady potential due to the imbedded singularity, respectively.

The unsteady aerodynamic can be obtained according to the boundary condition.

2.4 Aerodynamic of Engine Inlets

For body boxes on the inlet face, the boundary condition must be modified for the "flow-through" condition. This type of body boxes is called "inlet box". Let A_c be the height of the stream tube containing the maximum mass flow which can enter the inlet, length A_0 be the height of the stream tube actually entering the inlet, the mass flow ratio(MFR) is defined as

$$MFR = \frac{A_0}{A_c} \qquad (15)$$

For a given mass flow ratio, the steady boundary condition and unsteady boundary condition can be modified and compute the aerodynamic.

2.5 Computation of Flutter

Introducing the harmonic assumption, Eq. (1) can be expressed as

$$\begin{bmatrix} \left(\frac{V}{L}\right)^2 p^2 \boldsymbol{M}_{qq} + \left(\frac{V}{L}\right) p \boldsymbol{C}_{qq} \\ + \boldsymbol{K}_{qq} - \frac{1}{2}\rho V^2 \left(\boldsymbol{Q}_{qq}^R + \frac{p}{k}\boldsymbol{Q}_{qq}^I\right) \end{bmatrix} \boldsymbol{q} = 0 \qquad (16)$$

The flutter characteristic of aircraft can be obtained by p-k methods.

3 Example

The influence of the flutter characteristic due to aerodynamic of the fuselage and nacelle are studied and verified through low-speed flutter model wind-tunnel test of the aircraft.

The finite element of certain type of aircraft is shown as Fig.1.

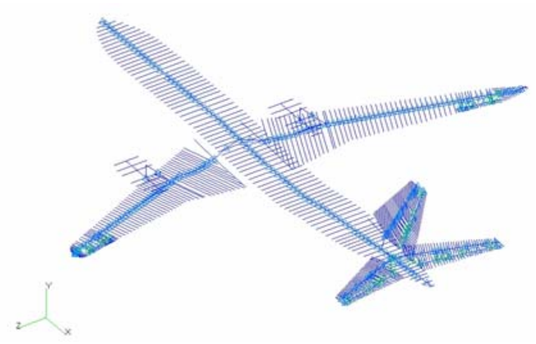

Fig.1 Finite element of certain type of the aircraft

The structural dynamic analysis of aircraft is shown as Tab.1.

Tab.1 Structural dynamic analysis of aircraft

阶数	频率/Hz	模态描述
7	f_0	Symmetry 1st bending of wing
9	$1.35f_0$	Symmetry translation of the engine
11	$1.95f_0$	Symmetry pitch mode of the engine
14	$2.31f_0$	1st bending of the fuselage

3.2 Aerodynamic effect of fuselage

The theoretical results and test results of aircraft flutter characteristic influenced by the aerodynamic effect of fuselage refer to Fig. 1 and Table 1. Both theoretical results and test results show that the flutter speed of the aircraft will reduced as a result of the aerodynamic effect of fuselage.

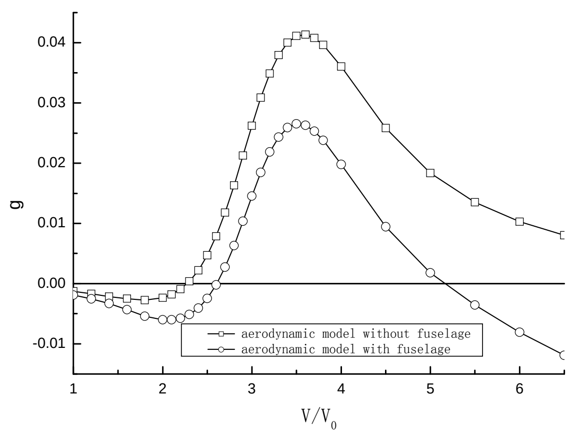

Fig.1 the influence of fuselage aerodynamic model to the flutter characteristic of aircraft

Table 1 wind-tunnel test results considering to aerodynamic effect of fuselage

Status	V/V_0	F/F_0
without aerodynamic effect of fuselage	2.35	3.17
With aerodynamic effect of fuselage	2.75	3.19

3.3 Aerodynamic effect of naccelle

The theoretical results and test results of aircraft flutter characteristic induced by the aerodynamic effect of nacelle refer to Fig. 2 and Table 2. Both theoretical results and test results show that flutter speed of the aircraft will reduced as a result of the aerodynamic effect of nacelle.

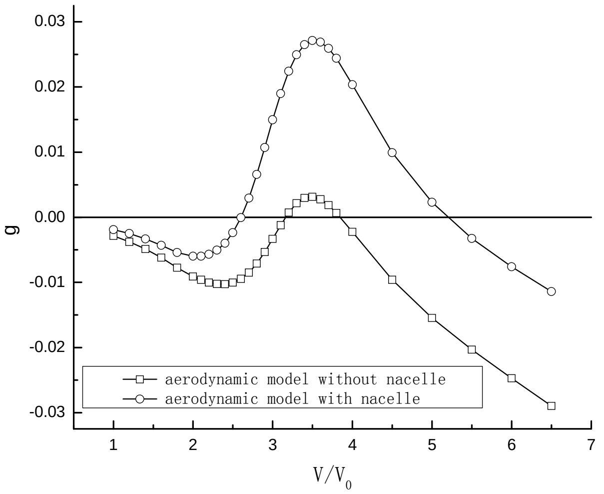

Fig.2 the influence of nacelle aerodynamic model to the flutter characteristic of aircraft

Table 2 wind-tunnel test results considering to aerodynamic effect of nacelle

Status	V/V_0	F/F_0
without aerodynamic effect of nacelle	3.20	3.23
With aerodynamic effect of nacelle	2.65	3.09

3.3 Different Aerodynamic model of naccelle

Aerodynamic effects of nacelle simulated by cross panel aerodynamic model and by the body-like aerodynamic model refer to Fig. 3 and Table 3. According to theoretical results and test results, the above two methods of modeling the aerodynamic of nacelle are equivalent.

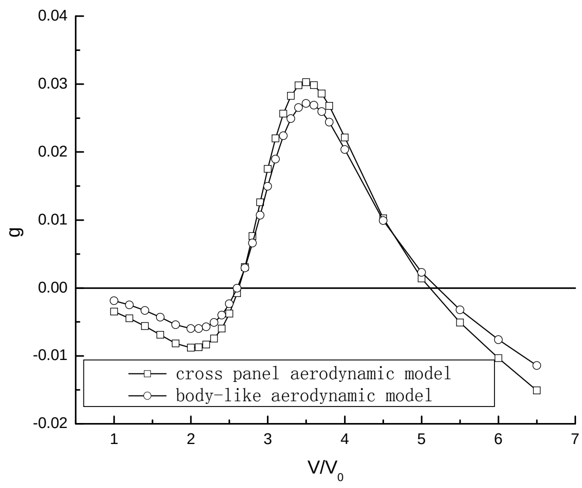

Fig.3 the influence of nacelle aerodynamic model method to the flutter characteristic of aircraft

Table 3 wind-tunnel test results considering to nacelle aerodynamic model method

Status	V/V_0	F/F_0
cross panel aerodynamic model	2.64	3.04
body-like aerodynamic model	2.65	3.05

4 Conclusions

Focusing on the civil aircraft, the aerodynamic effect of the body-like component to the flutter characteristic are studied and verified through low-speed flutter wind-tunnel test. The theoretical results and test results show that

(1) the flutter speed of the aircraft is reduced due to the aerodynamic effect of nacelle;

(2) the flutter speed of the aircraft is increased due to the aerodynamic effect of fuselage;

(3) the cross panel modeling method which is used for modeling the aerodynamic of nacelle is equivalent to the body-like aerodynamic modeling method.

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