Aeroelastic modeling and analysis of the wing/engine system of a large aircraft

Libo Wang\textsuperscript{a*}, Zhiqiang Wan\textsuperscript{a}, Qiang Wu\textsuperscript{a}, Chao Yang\textsuperscript{a}

\textsuperscript{a}School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

Abstract

An aeroelastic model of the wing/engine system of a large commercial aircraft is established. Taking into account the engine inertia force and thrust, static aeroelastic deformation of the wing structure and load distributions including shear force, bending moment and torque are studied. Models of the clean wing and the wing/engine system are compared and effects of chordwise and spanwise locations of the wing-mounted engines on the wing’s natural vibration and flutter characteristics are analyzed. The research indicates that the bending moment at the root part of the wing is alleviated by the engine, and the combination of the engine inertia force and thrust will change the torque there remarkably, while not affect the bending and torsion deformations of the wing structure much. The results also show that wing-mounted engines will affect the wing’s natural frequency of vibration, consequently having great effects on the flutter characteristics of the wing. Besides the classic wing flutter induced by the coupling of bending and torsion modes, a low-damping flutter type appears from the coupling of engine-pitch mode and the bending and torsion modes of the wing. Variations in chordwise and spanwise position of the wing-mounted engines will change the frequency of the engine-pitch mode, and further affect the low-damping flutter characteristics mentioned above, to which much attention should be paid in engineering application.

© 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of Kunming University of Science and Technology

Keywords: aeroelasticity; static aeroelasticity; flutter; wing; wing-mounted engine;

1. Introduction

Two or four high bypass ratio turbofan engines are usually used to power a large commercial airplane.

\* Corresponding author. Tel.: +86-10-8233-8723.
E-mail address: wanglibo@ase.buaa.edu.cn.
The podded engines have variety of installations, and they are typically attached under the wing or to the tail of the aircraft [1]. The engine nacelles can account for 10~15% of empty weight of the aircraft according to statistics. Change the position of engines will make a difference on the center of gravity of the aircraft, and further affects the trim condition as well as the control and stability characteristics [2,3]. Flow field around the wing will also become more complex because of the nacelles [4]. Otherwise the structural flexibility of large airplanes now is much more significantly, and aeroelasticity of large aspect ratio wings becomes much more important. The static aeroelastic responses of the wing will be affected by the gravity and thrust of wing-mounted engines. Design experience also shows that the mass, inertia, and natural vibration characteristics of the wing will also be changed, and a flutter phenomenon named "wing-engine nacelle flutter" will easily be excited [5].

The engine nacelle whether be attached to the wing or not, and change of spanwise/chordwise positions where the engine is located will have great effects on the structural type, aerodynamic principles, load distribution and flutter characteristics of the wing and the whole aircraft. Some qualitative conclusions have been summarized in previous studies, more detail rules in static aeroelasticity and flutter characteristics of the wing induced by different combination of the wing and engine are needed to be further studied, which will provide references for aircraft design.

2. Theory

Combination of the clean wing and the wing-mounted engine here is treated as a local system, both the aeroelastic characteristics of the clean wing and the wing/engine system are studied. The system is modeled based on the clean wing by considering effects of inertia force, gravity and thrust of the engine.

2.1. Equation for static aeroelastic responses analysis

The general equation for static aeroelastic responses analysis is[6]

\[
(k - q_D Q_a) u_a + m \ddot{u}_a = q_D Q_a u_d + P_e
\]  

(1)

Where \( k \) and \( m \) are the stiffness matrix and mass matrix of the structure; \( q_D \) is the dynamic pressure; \( Q_a \) is the aerodynamic influence coefficients matrix; \( u_a \) is the structural deformation vector; \( Q_d \) is the unit aerodynamic load matrix; \( u_d \) is the vector of additional freedoms; \( P_e \) is the vector of external loads.

If structural deformation caused by gravity and thrust of the engine is considered only, then the terms of aerodynamics could be omitted, and the static equilibrium problem could be solved as

\[ ku_a = P_{Te} + P_{Ge} \]  

(2)

Where \( P_{Te} \) is the thrust vector of the engine; \( P_{Ge} \) is the gravity vector of the engine.

Substitute the thrust vector into equation (1) as external load \( P_e \), and then deformation of the elastic structure, trim variables and load distributions could be solved.

2.2. Equation for flutter analysis

General mode coordinates \( q \) are used in flutter analysis, where the natural vibration modes are the shape functions. The general equation of aeroelastic motion is

\[ M \ddot{q} + Kq = Q \]  

(3)

Where \( M \) and \( K \) are the general mass and stiffness matrix; \( Q \) is the vector of general unsteady aerodynamic loads. The flutter characteristics could be solved by \( V-g \) method or \( p-k \) method [7].
3. Analysis model

Structural finite element models of the clean wing and the wing/engine system are established, one of them is shown in figure 1.(a). The wing structure is simulated by beam frames, whose stiffness and mass distributions have been optimized by the constrains of static aeroelasticity and flutter [8]. The engine is simulated by lumped mass elements and beam elements.

In the wing/engine system, the engine is initially set at 35% semi-span of the wing, the protrusion distance between its center of gravity (c.g.) and leading edge of the wing is 0.45\(b\), and the subsidence distance is 0.42\(b\), where \(b\) here is the mean aerodynamic chord of the wing. Mass of the engine is 0.10\(M\), the max take off thrust is 0.27\(Mg\); and the max cruise thrust at altitude 11000m and Mach 0.80 is 0.06\(Mg\), where \(Mg\) is the gross weight of the model. Flat plate aerodynamic model is established as shown in figure 1.(b), and the unsteady aerodynamics are calculated by doublet lattice method.

4. Static aeroelastic analysis

4.1. Elastic deformations induced by the engine

When the engine attaches to the wing, it will add its thrust and gravity onto the wing and induce elastic deformations. Figure 2 shows the induced bending and torsional deformation of the wing, where \(Y/S\) is the relative spanwise location, label \(T\) and \(G\) mean the effect of engine thrust and gravity. \(w\) is positive when it deforms upwards, and \(\theta\) is positive when the profile leading rises. Figure 2 shows that the maximum engine thrust will cause a positive torsional deformation about +0.1°. And gravity of the engine will cause a negative torsional deformation about -0.1°. So thrust and gravity have the opposite effects.

4.2. Static aeroelastic analysis

Both of Static aeroelasticities of the clean wing and the wing/engine system have been analyzed in condition of altitude 11000m, Mach 0.785. Reference coordinate for aerodynamic loads and total loads is shown in figure 1. Table 1 lists the trim angles of attack at 1g level flight, where System-R is a reference computation case of the wing/engine system model, in which thrust of the engine is not considered, which is different from the case system. Figure 3 ~ 6 show the results of bending and torsional elastic
deformations, aerodynamic loads and total loads (a combination of aerodynamics loads, inertia loads and thrust of the engine).

Table 1. Trim angle of attack at 1.0g cruise

<table>
<thead>
<tr>
<th>Case</th>
<th>Thrust</th>
<th>Angle of attack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean wing</td>
<td>/</td>
<td>2.61°</td>
</tr>
<tr>
<td>System-R</td>
<td>No</td>
<td>2.66°</td>
</tr>
<tr>
<td>System</td>
<td>Yes</td>
<td>2.65°</td>
</tr>
</tbody>
</table>

Fig. 3. Elastic deformation of the wing at 1.0g cruise, (a) Bending; (b) Torsion

Fig. 4. Aerodynamic load of the wing at 1.0g cruise, (a) Shear force ($F_A$); (b) Bending moment ($M_A$); (c) Torque ($T_A$)

Fig. 5. Aeroelastic load increments of the wing at 1.0g cruise, (a) Shear force increment ($\Delta F_A$); (b) Bending moment increment ($\Delta M_A$); (c) Torque increment ($\Delta T_A$)
By comparing the results of two models in figure 3 ~ 5, it shows that thrust and inertia loads of the engine will make few deference on deformation of the wing, and change the trim angle of attack a little, also they affects the shear force, bending moment and torque of aerodynamics slightly. Differences between the wing and the system mainly take place in aeroelastic loads increments, which of the system is always greater than the clean wing. As the wing and the wing/engine system have the same wing structure inertia loads, so the total loads shown in figure 6 just consider the inertia and thrust loads of engine and aerodynamic loads of the wing. It indicates that thrust and inertia loads of the engine will mainly affect the structural loads at wing root part, which releases the shear force and the bending moment significantly, and change the torque there greatly.

5. Flutter analysis

5.1. Flutter characteristics of the clean wing and the wing/engine system

Natural vibration modes of the clean wing and the wing/engine system are listed in table 2. For the wing/engine system, frequencies of the wing’s second bending mode and third bending mode are higher than the clean wing, and it also has three new modes, which are the engine pith mode, engine yaw mode and engine lateral pendular mode. Flutter characteristics are solved by p-k method. The $V-g$ charts and $V-f$ charts are shown in figure 7 and 8. The flutter velocity of the clean wing is 315m/s, and the flutter couples of the wing’s first bending mode, second bending mode and the first torsion mode. The classic wing flutter velocity of the wing/engine system is 319m/s, and the coupled modes of flutter have little difference with the clean wing. But the $V-g$ chart shows that the wing/engine system will have a low-damping flutter mode that excited by the engine pitch mode. It should be take care of during engineering.

Table 2. Natural vibration modes of the clean wing and the wing/engine system

<table>
<thead>
<tr>
<th>No.</th>
<th>The clean wing Mode</th>
<th>No.</th>
<th>The wing/engine system Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.68 Hz 1st bending</td>
<td>1</td>
<td>2.65 Hz 1st bending</td>
</tr>
<tr>
<td>2</td>
<td>7.13 Hz 1st fore-aft bending</td>
<td>2</td>
<td>4.06 Hz Engine lateral pendular</td>
</tr>
<tr>
<td>3</td>
<td>9.37 Hz 2nd bending</td>
<td>3</td>
<td>4.55 Hz Engine pitch</td>
</tr>
<tr>
<td>4</td>
<td>16.51 Hz 1st torsion</td>
<td>4</td>
<td>6.43 Hz Engine yaw</td>
</tr>
<tr>
<td>5</td>
<td>20.78 Hz 3rd bending</td>
<td>5</td>
<td>7.13 Hz 1st fore-aft bending</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>9.18 Hz 2nd bending</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>17.27 Hz 1st torsion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>17.96 Hz 3rd bending</td>
</tr>
</tbody>
</table>

Fig. 6. Total load distribution of the wing at 1.0g cruise, (a) Shear force ($F$); (b) Bending moment ($M$); (c) Torque ($T$)
5.2. Influence of the engine position on the flutter characteristics of wing/engine system

Influence of the position where engine is attached on the flutter characteristics of the wing/engine system is analyzed by moving the engine module along spanwise and chordwise directions.

For comparing, distance between the engine c.g. and the wing elastic axis is hold constantly, then the engine is moved from 30% to 35% semispan of the wing, the maximum mode damping of engine pitch mode and the flutter velocity of classic wing surface flutter are calculated and illustrated in figure 9. It is indicated that frequency of the engine pitch mode will get lower when the engine moves toward outer spanwise, which makes the maximum mode damping of engine pitch mode decreasing at the same time. However the wing flutter velocity is slightly changed.

Keep steady of the engine’s spanwise position, and move the engine form -0.04b to 0.08b chordwise around the reference position. Then the maximum mode damping of engine pitch mode and the wing flutter velocity are also solved and listed in figure 10. When the engine moves backwards along the chordwise, the engine pylons will be shorten, and the stiffness of the pylons will be strengthen relatively, which increases the frequency of engine pitch mode, and then increases the maximum mode damping level of engine pitch mode. The wing flutter velocity is also slightly changed.
6. Conclusions

Aeroelastic analysis models of the clean wing and the wing/engine system are established, by comparing the static aeroelastic and flutter characteristics of those models, conclusions are summarized as below:

- Aeroelastic differences between the clean wing and the wing/engine system are induced by inertia loads and thrust of the engine.
- For the wing/engine system, the bending moment at the root part of the wing is alleviated by the engine, and the combination of the engine inertia force and thrust will change the torque there remarkably, while not affect the bending and torsion deformations of the wing structure much.
- The wing-mounted engines will affect the wing’s natural frequency of vibration, consequently having great effects on the flutter characteristics of the wing. Besides the classic wing flutter induced by the coupling of bending and torsion modes, a low-damping flutter type appears from the coupling of engine-pitch mode and the bending and torsion modes of the wing. Variations in chordwise and spanwise position of the wing-mounted engines will change the frequency of the engine-pitch mode, and further affect the low-damping flutter, to which much attention should be paid in engineering application.

References