Study and Analysis on the Influence of Flutter Frequency on Airplane Stability

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Abstract – In the nationwide requirement of the growth in commercial aviation safety and profit, the field of Aeroelastic science plays a vital role. Flutter is one of the dynamic aeroelastic problems, it mainly occurs at lifting surfaces when the airplane cruises at high speeds. At relatively low speeds, the torsional stiffness of the wing is enough to counteract the twisting. However, the variation in flutter frequency causes the instability motion on aircraft. Therefore, the wing displacement against the flow field plays a vital role in dynamic stability analysis. As per the commercial aviation concern, an aircraft which is able to overcome the significant aeroelastic problems can yield maximum running profit. In order to maintain the airplane stability in high-speed, wings can be designed to minimize the distance between aerodynamic centre and shear centre (on the elastic axis). The main focus of this project is to calculate the frequency of an aircraft wing while it is subjected to aeroelastic (flutter) instability. The analytical process identified for this work is the Eigen value method. By using MATLAB solver, the optimization has been carried out along the span of real-time model. In future, the efficient structural model is then simulated and analysis is carried out to evaluate the longitudinal stability due to flutter phenomena.

Keywords – Dynamic Aeroelasticity, MATLAB, Flutter, Eigen Value Method, Stability, etc.

I. INTRODUCTION

Aeroelasticity phenomena involve the study of the interaction between aerodynamic forces and elastic forces are known as static aeroelasticity, also aerodynamic forces, inertia forces and elastic forces are known as dynamic aeroelasticity, finally aerodynamic forces, inertia forces, elastic forces and control laws are known as aero-servoelasticity. The flexibility of the modern aircraft structures makes aeroelastic study an important aspect of aircraft design and stability verification procedures. The wing torsional divergence and the flutter are the two major aeroelastic phenomena considered in aircraft design. The divergence is a static instability which occurs when the static aerodynamic effects counteract the torsional stiffness of the structure. The flutter is a dynamic aeroelastic instability characterized by sustained oscillation of structure arising from interaction between elastic, inertial and aerodynamic forces acting on the body. The input values for flutter analysis is taken by the experimental results of wing model. This is giving precise solution when the aircraft is subjected to an aeroelastic forces. At some critical speed, known as the flutter speed, the structure sustains oscillations following some initial disturbance. Below this flutter speed the oscillations are damped, whereas above it any one of the modes becomes negatively damped and (often violent) unstable oscillations occur, unless some form of nonlinearity (not considered in detail here) bounds the motion. Flutter can take various forms involving different pairs of interacting modes, e.g. wing bending/torsion, wing torsion/control surface, wing/engine, etc. An established method for determining aerodynamic derivatives from wind-tunnel experiments is to mount a scaled model of the aircraft onto a test rig and observe the model’s free or forced oscillatory response. By connecting the rig to a suitable balance, the derivatives of forces and moments with respect to the motion variables can be obtained. A different approach to the problem is to emulate flight test like experiments in the wind-tunnel environment.

II. DYNAMIC AEROELASTICITY

In dynamic aeroelasticity flutter, buffeting and dynamic response are the three problems identified. A brief coverage will be given here to show how this interaction leads to aeroelasticity phenomena.
a. Flutter:

Flutter phenomena occurs at a critical or flutter speed $V_f$ which in turn is defined as the lowest airspeed at which a given structure will oscillate with sustained simple harmonic motion. Flight at speeds below and above the flutter speed represents conditions of stable and unstable (that is divergent) structural oscillation, respectively. It is found most frequently in aircraft structures subjected to large aerodynamic loads such as wings, tail units and control surfaces.

Generally, an elastic system having just one degree of freedom cannot be unstable unless some peculiar mechanical characteristic exists such as a negative spring force or a negative damping force. However, it is possible for systems with two or more degrees of freedom to be unstable without possessing unusual characteristics. The forces associated with each individual degree of freedom can interact, causing divergent oscillations for certain phase differences. The flutter of a wing in which the flexural and torsional modes are coupled is an important example of this type of instability. Some indication of the physical nature of wing-bending–torsion-flutter may be had from an examination of aerodynamic and inertia forces during a combined bending and torsional oscillation in which the individual motions are 90° out of phase. In a pure bending or pure torsional oscillation the aerodynamic forces produced by the effective wing incidence oppose the motion; the geometric incidence in pure bending remains constant and therefore does not affect the aerodynamic damping force, while in pure torsion the geometric incidence produces aerodynamic forces which oppose the motion during one-half of the cycle but assist it during the other half so that the overall effect is nil. Thus, pure bending or pure torsional oscillations are quickly damped out. This is not the case in the combined oscillation when the maximum twist occurs at zero bending and vice versa; i.e. a 90° phase difference.

b. Flutter Speed

In modern aircraft, the flutter speed (the air speed at which flutter, a dynamic aeroelastic instability, occurs) is usually reached before the divergence speed (the air speed at which divergence occurs) so divergence is not normally a problem. Because of this problem, flutter speed is a useful measure of the aircraft structure and must be considered as part of the certification process (CS-25 and FAR-25).

III. THEORETICAL EVALUATION

The lift per unit span for an aerofoil may be expressed, for a particular reduced frequency, as

$$L = \rho V^2 \left( L_c z + L_c \frac{b^2 z}{V} + L_\theta b \theta + \frac{L_\theta b^2 \theta}{V} \right)$$

The moment per unit span for an aerofoil may be expressed, for a particular reduced frequency, as

$$M = \rho V^2 \left( M_c z + M_c \frac{b^2 z}{V} + M_\theta b \theta + \frac{M_\theta b^2 \theta}{V} \right)$$

Taking the quasi-steady assumption ($k \to 0$, $F \to 1$, $G \to 0$) for all of the aerodynamic derivatives, then the lift per unit span about the flexural axis become,

$$L = \frac{1}{2} \rho V^2 c a_1 \left( \theta + \frac{z}{V} \right)$$

Pitching Moment per unit span about the flexural axis become,

$$M = \frac{1}{2} \rho V^2 c e a_1 \left( \theta + \frac{z}{V} \right)$$

The major drawback in using quasi-steady aerodynamics is that no account is made for the time that it takes for changes in the wake associated with the aerofoil motion to develop (as defined by Wagner’s function) and this can lead to serious aeroelastic modeling errors. Then adds a pitch damping term to the pitching moment Equation (4) and the model then becomes,

$$M = \frac{1}{2} \rho V^2 c^2 e a_1 \left[ \theta + \frac{z}{V} \right] + M_\theta \frac{\theta}{4V}$$

Where $M_\theta$ is negative and will initially be assumed to be constant. This ‘simplified unsteady aerodynamic’ model will now be used to develop a binary aeroelastic model. The simple unswept/untapered (i.e. rectangular) wing model shown in Figure (1) is used throughout this chapter to illustrate classical binary flutter. The rectangular wing of span $s$ and chord $c$ is rigid but has two rotational springs at the root to provide flap ($k$) and pitch ($\theta$) degrees of freedom. Note that there is no stiffness coupling between the two motions. The springs are attached at a distance $e c$ behind the aerodynamic centre (on the quarter chord), defining the position of the flexural axis. The wing is assumed to have a uniform mass distribution and thus the mass axis lies on the mid-chord.

**Fig.1:** Binary flutter model
Then it leading to equations of motion for the wing without considering aerodynamic forces, as

\[
\begin{bmatrix}
\frac{m_1}{3} \frac{\dot{c}_1}{v} + \frac{m_2}{3} \frac{\dot{c}_2}{v} \\
\frac{m_1}{3} \frac{\dot{c}_1}{v} - \frac{m_1}{3} \frac{\dot{c}_2}{v} + c_3 \frac{\dot{c}_3}{v}
\end{bmatrix}
\begin{bmatrix}
k \\
\dot{\nu}
\end{bmatrix}
+ \begin{bmatrix}
K_1 & 0 \\
0 & K_2
\end{bmatrix}
\begin{bmatrix}
k \\
\nu
\end{bmatrix}
= \begin{bmatrix}
0 \\
0
\end{bmatrix}
\]  (6)

Applying strip theory, together with the simplified unsteady aerodynamics representation, leads to expressions for lift and pitching moment (about the flexural axis) for each elemental strip dy of

\[
dL = \frac{1}{2} \rho V^2 c \alpha w \left( \frac{y_0}{V} + \theta \right)
\]
\[
dM = \frac{1}{2} \rho V^2 c^2 dy \left[ e \alpha w \left( \frac{y_0}{V} + \theta \right) + M_\theta \frac{\dot{\theta} C}{4 V} \right]
\]  (7)

Where \( y_0 \) is the effective heave velocity (ve downwards) and \( M_\theta < 0 \).

Thus, the full aeroelastic equations of motion become

\[
\begin{bmatrix}
I_\epsilon & L_\epsilon \\
L_\epsilon & I_\epsilon
\end{bmatrix}
\begin{bmatrix}
k \\
\dot{\nu}
\end{bmatrix}
+ \rho V \begin{bmatrix}
\frac{c_3 \alpha w}{6} \\
\frac{c_3 \alpha w}{4}
\end{bmatrix}
\begin{bmatrix}
k \\
\dot{\nu}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 - c_3 k
\end{bmatrix}
\begin{bmatrix}
k \\
\nu
\end{bmatrix}
= \begin{bmatrix}
0 \\
0
\end{bmatrix}
\]  (8)

and it may be seen that the mass and stiffness matrices are symmetric while the aerodynamic matrices are nonsymmetric. Thus the two DOF are coupled and it is this coupling that can give rise to flutter.

General form of the equation (8) is representing,

\[
A \ddot{q} + (\rho V B + D) \dot{q} + (\rho V^2 C + E)q = 0.
\]  (9)

When the flutter frequency is plotted against the velocity in Figure, it can be seen that the frequency decreases gradually with increase in velocity but at certain velocity the frequency starts to increase with velocity increment. This is due to the assumed linear twist shape and would differ if a more complicated shape were chosen or if the wing tapered or if modified strip theory were used.

IV. DESIGN AND ANALYSIS

a. Wing Model Geometry

The geometry of the wing model is created with designing software (CATIA). The aerofoil used in this model is NACA64210. The wing model is given below with dimensions.

![Wing model geometry](image)

Fig. 3 : Wing model geometry

b. Experimental Analysis:

The experimental results are carried out by using wind-tunnel set-up. A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects.

Air speed and pressure forces are measured in several ways in wind tunnels. Aerodynamic forces on the test model are usually measured with the beam balances, connected to test model with beams, strings, or cables. The pressure distributions across the test model have historically been measured by drilling many small holes along airflow path, and using the multi-tube manometers to measure the pressure at each hole. The pressure distributions can more conveniently be measured by the use of the pressure-sensitive paint, in which higher local pressure is indicated by the lowered fluorescence of the paint at that point. The pressure distributions can also be conveniently measured by use of the pressure-sensitive pressure belts, and a recent development in which multiple ultra-miniaturized pressure sensor modules are integrated into a flexible strip. That strip is attached to the model (i.e. aerodynamic surface) with tape, and it is send signals depicting the pressure distributions along its surface.

With the model mounted on a force balance, can measure lift, drag, lateral forces, yaw, roll, and pitching moments at various angle of attack. This variation allows one to produce common curves such as lift coefficient versus angle of attack. Note that the force balance itself creates drag and potential turbulence that will affect the model and introduce errors into the measurements.

![Frequency Vs Velocity](image)

Fig. 2 : Frequency Vs Velocity [2]
c. Theoretical Analysis

Improvements in computer speed and memory, as well as advances in computer architectures, have allowed numerical simulations to be used more frequently to aid in the design process. These simulations are very useful; it must predict quantitatively the features of the actual model under consideration in both an economical and reliable manner. An aircraft is in flight, for example, is subjected to complex interactions between aerodynamics, structures, controls, and propulsion. Traditionally, these disciplines were uncoupled and were solved separately in the absence of powerful computational resources.

Aeroelastic analyses play a major role in aircraft structural design. Manoeuvre trim loads, transient manoeuvre loads, flutter, gust response, and LCO are all aeroelastic phenomena considered in aircraft structural design and certification processes. From a historical perspective, the improvements in aeroelasticity over the past 50 years were reasonably good.

Aeroelastic analysis is based on the coupling of a structural dynamics model and an aerodynamic model, where typically, in an industrial environment, the structure is modelled by a finite-element model, and the aerodynamics is modelled by a linear panel aerodynamic model. Advantages of linear panel methods include quick run times, relatively easy geometrical modelling, and small user interface. The major hindrance of linear aerodynamic methods lays in their inability to predict transonic flow fields that involve nonlinear phenomena such as shock waves and boundary layer separation. Linear aerodynamic tools are also somewhat limited in modelling complex geometries. The use of linear panel methods in aircraft structural design might result in a structure that is inadequate when subjected to the actual flight loads, often requiring significant structural redesign at a late stage of the design process.

MATLAB is a high-level technical computing language and interactive environment for algorithm development, numeric computation, data visualization and data analysis. In a wide range of MATLAB applications, here consider only control system and aerospace toolbox. The MATLAB language is a high-level matrix/array language with control flow statements, functions and object-oriented programming features. It is having a strategy of programming in the small to rapidly create quick programs, which do not intend to reuse. Also MATLAB has extensive facilities for displaying vectors and matrices as graphs, as well as annotating and printing these graphs. It includes high-level functions for 2-D and 3-D data visualization, presentation graphics, animation and image processing. It includes low-level functions that allow to fully customize the appearance of graphics as well as to build complete graphical user interfaces on MATLAB applications.

Currently there exists a large body of computational aeroelastic research studies that aim at these goals. This paper reviews some of the approaches taken in tackling steady aeroelastic problems, such as the evaluation of loads on a manoeuvring elastic aircraft, unsteady aeroelastic problems, such as flutter analysis, and attempts at their integration into the process of aeroservoelastic analyses.

V. RESULTS

Flutter frequency can be calculated by theoretical evaluation and lift, drag forces are calculated by experimental analysis over the real-time wing model.

a. Experimental Results

The aerodynamic forces variation over the wing model is calibrated at various angles of attack by the standard low speed wind tunnel. The results are shown in following figure.

![Experimental Results](image)

b. Theoretical Results

The variation in flutter frequency with respect to velocity along the span of real-time model is shown in following figures:

(i) @ Span=0m

![Theoretical Results](image)
Fig. 6: Damping Ratio Vs Velocity

(ii) @ Span=6m

Fig. 7: Frequency Vs Velocity

Fig. 8: Damping Ratio Vs Velocity

(iii) @ Span=12m

Fig. 9: Frequency Vs Velocity

Fig. 10: Damping Ratio Vs Velocity

(iv) @ Span=18m

Fig. 11: Frequency Vs Velocity

Fig. 12: Damping Ratio Vs Velocity

(v) @ Span=24m

Fig. 13: Frequency Vs Velocity
VI. CONCLUSION AND FUTURE WORK

The experimental results are shown the variation on lift and drag forces in the range of angle of attack of the model. Then the following of that, those plots are representing frequency variations with respect to air speed at different span locations. In comparison with theoretical result, the obtained results are coincides for tapered wing. Hence, flutter speed is increasing from wing root to tip. So the displacement at wing tip is high comparing with root. This displacement variation induces the severe instability of an aircraft.

In future, the corresponding displacements have to be found for the available frequency values. Then it is extended to find the conditions to ensure the stability of an aircraft, which is subjected to the aeroelastic (flutter) forces. Finally this stability results will be validate by the experimental results obtained from 6-component balancing system.

VII. REFERENCES


[4] O O Bendiksen, “Modern developments in computational aeroelasticity”, Mechanical and Aerospace Engineering Department, University of California, 48-121 Engineering IV, Box 951597, Los Angeles, California 90095-1597, USA.


NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>L</td>
<td>Lift (N)</td>
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<tr>
<td>M</td>
<td>Pitching moment (N-m)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (Kg/m³)</td>
</tr>
<tr>
<td>V</td>
<td>Airspeed (m/s)</td>
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<td>Lx, Mx</td>
<td>Non-dimensional numbers</td>
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<td>b</td>
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<tr>
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