Mass Distribution Effect on Flutter Characteristics

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ABSTRACT

Completely rigid structures do not practically exist, so every structure under the action of aerodynamic forces will normally deflect at least by a small amount. This deflection will become increasingly significant at higher air speeds. Elastic stiffness of the material will try to restore the structure to its original shape and in the process, will overshoot the static equilibrium point and the structure will be pushed into expansion. This process will cause the structure to vibrate. If the energy during the period of aerodynamic excitation is more than the natural damping of the structure, the amplitude of vibration will increase. With increase in air speed, the structural damping of the system will diminish to a point where it becomes zero and eventually, its value changes from negative to positive value. At the point, when damping becomes zero, it is said that aeroelastic phenomena commonly known as ‘flutter’ has occurred. This paper presents the computational work carried out using Fluid Structure Interaction module of a commercial software to describe the effect of mass distribution on flutter characteristics of structures subjected to aerodynamic forces.

Keywords: Structural dynamics, Aero-elasticity, Flutter, Vibration Modes and Resonance.

1. INTRODUCTION

Aeroelasticity is the field of science in which the emphasis is on the study of the interaction between the deformation of an elastic structure exposed to an airstream and the resultant aerodynamic force. The mutual interaction of the three disciplines namely; aerodynamics, dynamics, and elasticity can be seen in figure 1. Classical aerodynamic theories provide a mean to assist in determining the forces acting on a body of a given shape while the resultant shape of an elastic body under any load can be determined using theory of elasticity. Lastly, the effects of inertial forces in the overall system are catered by Dynamics. It is only possible with the interdisciplinary knowledge of these three disciplines that the designer is in a position to study and comprehend the implications of the mutual interaction of two or more of these phenomena [1]. The consequences of interaction of these phenomena can be tragic and at times result into heavy losses. One of such interactions called “Flutter” is being briefly touched upon in this paper. It has perhaps the most far reaching effects of all aeroelastic phenomena on the design of high speed aircraft.

Modal analysis is the field of study in which the dynamic response of the structures and/or fluids upon excitation by an input is measured and analysed. Using modal analysis, the dynamic response of the structure can be explicated in terms of damping, natural frequencies, mode shapes and resonance. All computational work included in this research is based upon Modal analysis.

2. HISTORICAL BACKGROUND

Throughout the history of powered flight, it can be witnessed that particular attention has been focused on the aeroelastic phenomenon. [2]. In 1903, significant anhedral of the wings caused lateral instability initially in the Wright flyer aircraft. However, lateral control was achieved on the Wright flyer later, through effective utilization of the controlled warping of the wings which contributed appreciably to the triumph of powered flight. Earlier in 1903, Samuel Langley twice attempted unsuccessfully to achieve powered flight from the roof top of a houseboat in the Potomac River. Aeroelastic divergence resulting from insufficient torsional stiffness ended up in catastrophic failure of the wings. The same
torsional divergence phenomenon kept the biplane design predominant until the early 1930s when adequate torsional stiffness for monoplanes was ultimately realized through “stressed skin” metallic structural configurations.

Flutter on aircraft was first recorded and documented in 1916. The Handley Page O/400 (H.P.12) bomber was World War I (WWI) British bomber which was one of the largest aircraft in the world at that time. Absence of torsion rod connection between the port and star elevators contributed excessively to violent tail oscillations. This led to dynamic fuselage twisting of almost 45 degrees which was complemented by anti symmetric elevator flapping. Airplane flutter due to its associated catastrophic failures emerged as a major design parameter during WWI. Its importance in aircraft design remains so even today.

Implications of the aeroelastic phenomenon can be as mild as onboard human discomfort to as catastrophic as failures resulting in human life loss without warning. In between the above two extreme situations, steady state and transient vibrations can be a likely cause of fatigue damage of the aviation structure on the microscopic level. It is therefore, always recommended to take this aspect of wind tunnel and flight testing thoroughly and seriously. Short cuts in this aspect can result in unwanted/unpleasant circumstances during regular flying of the designed vehicle.

3. STRUCTURES & OSCILLATIONS

Structural nonlinearities are a common concern in the design of aircraft structures, which can occur in both distributed and concentrated form. More often, distributed nonlinearities are significant for large amplitude oscillations, whereas localized nonlinearities could be important at relatively much smaller amplitude levels. Control surface nonlinearities could be attributed to manufacturing defects or wear and tear which leads to loose or worn out control surface hinges. Thus aeroelastic problems with these nonlinear effects have been an important area to study. Nonlinear systems can display sustained limit cycle oscillations at different air speeds, unlike a linear system which shows a limit cycle oscillation only at the critical speed.

In order to explain the modal analysis, a constant force is applied to one corner of a freely hung plate but the frequency of excitation is changed in a sinusoidal fashion as shown in figure 2. As the frequency of constant force changes, response at the excitation point is measured using accelerometer. It can be noticed that level of amplitude of response changes with change in frequency oscillation. It seems odd as the level of excitation is constant. A typical time response is shown in figure 3. The data is converted to frequency domain through Fast Fourier Transform and a frequency response function (FRF) plot is obtained which is shown in figure 4. The peaks in this plot correspond to the frequency of oscillation where the amplitude of response is greatest. The same can be seen by overlaying the time and frequency trace, as the amplitude of response in time trace increases, the amplitude of the FRF also increases (see figure 5). Research revealed that the points of increased amplitude occur at the natural frequency of the system, which depends on the mass and stiffness distributions [3-4].

4. DIFFERENT VIBRATION MODES

The excitation coincides with each of the four resonant frequencies at each of the peaks in the Frequency Response Function (FRF). This can be demonstrated by using a number of scattered accelerometers on the plate. The deformation patterns thus generated by these four modes are different from each other and can be seen in figure 6.

(a) **Mode I**: The coinciding of excitation with first resonant frequency results in the 1st bending mode, where the shape of deformation is a bending motion.
(b) **Mode II**: The coinciding of excitation with second resonant frequency results in the 1st twisting mode, where the shape of deformation is a twisting motion.
(c) **Mode III**: The coinciding of excitation with third resonant frequency results in the 2nd bending mode, where the shape of deformation is a second bending motion.
(d) **Mode IV**: The coinciding of excitation with fourth resonant frequency results in the 2nd twisting mode, where the shape of deformation is a second twisting motion.
4. OSCILLATIONS ON A LIFTING SURFACE

There are two general classes of vibrations viz a viz excitation force - free and forced. When a mechanical system is initially excited by an input force and then the system is allowed to vibrate on its own after the removal of the exciting force, the system is said to be executing 'Free vibration'. Such a system vibrates at one or more of its natural frequency. The vibration gradually decays to zero because of the inherent structural stiffness of the elastic structure.

On the other hand, vibrations that are executed by the system during the active and continual excitation of the system is called 'Forced Vibration'. If the nature of the exciting force is oscillatory, it will compel the system to vibrate at the excitation frequency of the force. If accidently, this excitation frequency matches one of the natural frequencies of the vibrating system then amplitude of oscillation will be exponentially enhanced. This condition is known as ‘resonance’. Resonance is known to have a major contribution to the destruction/damage of airplane wings during flight.

An aerodynamic shape as shown in figure 7 that produces a typical aerodynamic force “lift”, is selected for computations during research. As the structure has high stiffness and fourth natural frequency is very high therefore only first three expected vibration mode shapes for selected lifting surface are being discussed in this paper. The coinciding of excitation for the selected aerodynamic structure with its first, second and third resonant frequency results in the 1st bending mode, 1st twisting mode and 2nd bending mode respectively. The deformation patterns for the selected surface are shown in figure 8.

5. FLUTTER PHENOMENON

The Flutter or critical speed $V_f$ and frequency $\omega_f$ are defined as the lowest airspeed and corresponding circular frequency at which a flying structure at a given atmospheric density and temperature will exhibit sustained simple harmonic oscillations [5]. Flutter is a self excited oscillation of an aerodynamic surface and its associated structure caused by the interaction of the aerodynamic, inertial and elastic characteristics of the components involved. At speeds below the flutter speed, oscillations are damped, but at the flutter speed, undamped oscillations persist with constant amplitude, however, at speeds above the flutter speed undamped oscillations diverge and result in damage or destruction of the structure [6-7]. The divergent behaviour can occur within a few cycles or with very little velocity increment and be catastrophic.

Flutter is said to have occurred when under the action of aerodynamic loads, the lifting surface deflects in such a way as to cause reduction of the applied load.[8] it can be described as a type of vibration which is self feeding and has the potential of destroying the structure eventually. During flutter, the frequency of the aerodynamic load couples itself to the structure’s natural mode of vibration which results in rapid periodic motion. In other words, a positive feedback exists between the aerodynamic loading and structure’s natural vibration characteristics. A ‘divergent response’ in which the amplitude tend to increase throughout the process can occur if the energy input by the air stream flow is greater than the structural damping of the structure. Practically it has been observed that flutter can be induced on an apparently unrelated aerodynamic component of the aircraft by causing a simple change of the mass distribution of an aircraft or the stiffness of a single component. Theodore Von Karman is said to have remarked that “Some men fear flutter because they do not understand it, while others fear it because they do”.

6. EFFECT ON A FLYING VEHICLE

In real life, flutter on a flying vehicle can be caused by the coupling of two or more structural modes. These coupled modes may be wing bending and torsion, wing bending-control surface hinge torsion, wing torsion-fuselage bending, or horizontal/vertical tail-fuselage modes. The phenomenon is explained in Figure 9, which shows velocity vs. frequency plot for four different structural modes. With the increase in speed, frequency of modes 3 and 4 remains stable and these modes do not interact with any other structural mode. However, frequency of modes 1 and 2 change with the increase in speed and they tend to interact with each other. This interaction is explained in Figure 10, where at velocity $V_f$ the modal damping of mode 1 has gone to zero. This is an onset condition for flutter. This is caused by the interaction of free stream energy with the elasticity of the structure and has created the effect of zero total damping (structural and aerodynamic). Increase in speed beyond this value will cause large increase in vibration amplitude, which are divergent and can cause catastrophic damage to the structure [9-10].
7. BALANCE WEIGHT

Balance weights are dead weights added to different location for different purposes. In the aerodynamic structures these are generally used to achieve an optimum mass distribution. In this way, the structure although pays penalty in the shape of additional weight but achieves a required force distribution. This positive change can also result in the delay of aeroelastic phenomenon like flutter. The locations of balance weight for the selected aerodynamic shape structure can be seen in figure 11. The selected structure was modelled and the computations were done in the three configurations as given below:-

(a) Without a balance weight
(b) A balance weight of 6Kg at Leading Edge tip
(c) Different balance weights at Leading Edge root

8. RESULTS & ANALYSIS

Results of analysis conducted without any balance weight, 6kg balance weight at the LE tip, relocating the balance weight from LE tip to LE root and then weight increments are being discussed in subsequent paragraphs. During this analysis, no other changes to the structure model were made.

The research was aimed to reveal the affect of mass distribution while achieving the flutter speed of 400 m/s for the selected structure. The results revealed that with no balance weight and with 6 kg balance weight at the LE tip the flutter speed is much lower than the required value of 400 m/s. The results for computations using these two configurations can be seen in Table 1 whereas the results for computations using different balance weights at the Leading Edge Root are shown in Table 2. \( V_{f0}\% \) and \( V_{f2}\% \) are the flutter speeds for zero and 2 per cent damping respectively. Also, note that the computations for the second mode (which is the first twisting mode) have only been done for the third configuration.

### Table 1: Computed Flutter for 0 & 6 kg balance wt at LE Tip

<table>
<thead>
<tr>
<th>Weigh t (Kg)</th>
<th>( V_{f0}% ) (m/s)</th>
<th>( V_{f2}% ) (m/s)</th>
<th>( \omega_f ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>208</td>
<td>242</td>
<td>33.8</td>
</tr>
<tr>
<td>6</td>
<td>368</td>
<td>378</td>
<td>27.2</td>
</tr>
</tbody>
</table>

### Table 2: Flutter Computations with Balance Weight at LE Root

<table>
<thead>
<tr>
<th>Wt (Kg)</th>
<th>Bending &amp; Twist</th>
<th>2nd Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{f0}% ) (m/s)</td>
<td>( V_{f2}% ) (m/s)</td>
</tr>
<tr>
<td>1</td>
<td>220</td>
<td>261</td>
</tr>
<tr>
<td>2</td>
<td>233</td>
<td>253</td>
</tr>
<tr>
<td>4</td>
<td>247</td>
<td>253</td>
</tr>
<tr>
<td>8</td>
<td>275</td>
<td>328</td>
</tr>
<tr>
<td>10</td>
<td>369</td>
<td>410</td>
</tr>
<tr>
<td>12</td>
<td>493</td>
<td>547</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>-</td>
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<tr>
<td>18</td>
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</tbody>
</table>

Analysis reveals that flutter speed in case of no balance weight and 6 kg weight addition at LE tip is much lower than the required value. However, the flutter speed for bending and twist modes start to improve with increase of balance weight at the LE root. It can be seen that required value of flutter speed that is more than 400 m/s is achievable with balance of 10 Kg or more. Although the improvements with higher balance weights are tremendous but weight plenty is to be paid in return for higher flutter speeds \( V_f \). Computations for 2nd mode show that 400 m/s is not only achievable but the structure is also safe with any amount of balance weight LE root.
Figure 12 shows the trend of flutter speed for relocated different balance weights at the LE root in different modes.

Determination of the flutter boundary of aircraft or the major structural parts is an essential step to be performed during design qualification of any flying vehicle [11]. The flutter boundary can be defined either by analytical calculations or by carrying out flutter wind tunnel tests by using scaled down special flutter models of the concerned structure. The event of flutter dip is another important phenomenon to be computed for flying vehicles that are likely to go into the supersonic region or cross the transonic region. The transonic dip is found either by applying corrections from previous design experiences of similar flying structure or by carrying out the transonic speed flutter wind tunnel testing.

![Figure 12: Computed Flutter speed Vs balance weight](image)

Figure 12: Computed Flutter speed Vs balance weight

Figure 13 shows the Equivalent Air Speed ($V_e$) and Mach Number ($M$) plots for different altitudes and flutter margins. Also shown is the flutter boundary and the transonic dip. The $V_e$-$M$ lines are drawn for different altitudes with sea level line having the highest slope and are shown by solid lines. The dotted lines show the expansion of basic $V_e$-$M$ envelope expanded by using design margin of safety, i.e. 15%. This makes up the design limit speed envelope and it should still remain little below the flutter boundary curve and little right of the transonic dip. This makes up the first flutter qualification requirement for a flying vehicle.

![Figure 13: $V_e$ vs $M$ plots for different altitudes and flutter margins](image)

Figure 13: $V_e$ vs $M$ plots for different altitudes and flutter margins

### 9. CONCLUSION

The study and the computational work done during this research concluded that the flutter speed is a key parameter that predicts the maximum flutter free speed of flying structure. The use of balance weights can enhance the modal characteristics of the flying structures but the structures have to pay heavy plenty in terms of weight increase.

The computations revealed that addition of 10 kg at the root LE can enhance the flutter speed to a required value of 410 m/s. However increase in the supersonic region flutter speed involves more complex computations which are not included in this paper.

Also, in this research, the effect of damping in the control of flutter speed is highlighted. For the same amount of balance weight and its location, additional damping moves the flutter speed to higher values. Additionally, it can be seen that higher margins in flutter speed for the first twisting mode is available with additional damping. Critical analysis of the results further reveal that with increasing value of balance weight, lower circular flutter frequencies are achievable. However, this effect is negligible for the circular flutter frequencies associated with the first twisting mode.

It is to be kept in mind that the increase in damping ratios may increase the structural performance but cannot be kept very high as they tend to make the structures rigid. Vibrating systems are all subject to damping to some degree because energy is dissipated by friction and other resistances. If the damping is small, it has very little influence on the natural frequencies of the system, and hence the calculations for the natural frequencies are generally made on the basis of no damping. On the other hand, damping is of great importance in limiting the amplitude of oscillation at resonance.

### 10. FUTURE DIRECTIONS

Analysis for determining the transonic dip is also required in order to keep the flying structure safer in the transonic and supersonic region. Theoretical work in this regards will be done at a later stage and the results will be published. The experimentation to verify these computations may later be performed to verify the achieved results.

### 10. REFERENCES


