Aerofoil flutter: fluid-mechanical analysis and wind tunnel testing

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Abstract. This paper describes a three dimensional wing model, which has been developed for the purpose of studying flutter, both computationally and through wind tunnel testing. A three dimensional, laminar flow aerofoil wing, based on the NACA aerofoil has been designed. The natural frequencies for this aerofoil were obtained through modal analysis. A scale model wing, without taper was manufactured in the laboratory and tested in a wind tunnel. The pressure data was obtained from fluid flow analysis and the deformation results obtained through structural analysis. The analysis was performed in the ANSYS Workbench Environment, accessing FLUENT CFX for the computational fluid dynamics analysis and the ANSYS FEA package for the mechanical analysis. The computational results obtained are compared with the experimental data obtained in the wind tunnel. Comparison of the analysis and test results provides further understanding of the flutter characteristics.

1. Introduction
Flutter is an example of unstable self-excited vibration, and can occur under conditions of steady-state airflow. In the design of aircraft and aerospace components, design for aero-elastic performance is of fundamental importance: where flutter vibration amplitude cannot be controlled, catastrophic structural failure can result. The advent of computational flow analysis capability and high performance computing opens up the challenge of aero-elasticity assessment \[1\], and this work explores suitable methodologies. Computational fluid dynamics (CFD) and finite element method (FEM) provide the basic tools for predicting flutter, buffeting and limit cycle oscillation, hence computational aero-elasticity is expected to play a vital role in numerical modelling of combined solid-fluid interaction in the context of aerospace component and structure design. In this project, CFD analysis predicts the flow characteristics of the aerofoil, including turbulence and flow separation prediction. FEM analysis is used to predict the mode shapes and frequencies that may be excited in flutter \[2, 3\].

An additional objective of the project was to build a scale model of an aerofoil with a light-weight internal structure similar to that used in aircraft wing design. This aerofoil would be used in a wind tunnel, as an undergraduate laboratory demonstration of aero-elastic phenomena. With low airflow velocity and such a flexible structure, the intention was to find angle of attack conditions under which the aerofoil could be induced to flutter at controlled low amplitude. Under conditions of controlled amplitude, the energy supplied to the vibration from the air flow is exactly balanced by the vibration...
damping losses. Low amplitude vibration should give rise to low stress levels, and it is anticipate that the demonstrator aerofoil will have several years fatigue life in careful use.

2. Methodology
This paper describes a three dimensional wing model, which has been developed for the purpose of studying flutter, both computationally and through wind tunnel testing [4]. A three dimensional laminar flow aerofoil wing was designed in SolidWorks. The external aerofoil design was based on the scaled NACA aerofoil without taper, but the internal construction was hollow, and comprised of five subsections (Figure 1). The purpose of this light-weight structure was to make the aerofoil more flexible, and therefore more susceptible to aero-elastic phenomena. The natural frequencies for this aerofoil were obtained through modal analysis [4-7]. The scale model wing was manufactured in the laboratory and tested in a wind tunnel. The analysis was performed in the ANSYS Workbench environment, accessing FLUENT CFX for the computational fluid dynamics analysis, and ANSYS FEA for the mechanical analysis. The computational results obtained are compared with the experimental data obtained in the wind tunnel [2, 4]. Comparison of the analysis and test results provides further understanding of the flutter characteristics.

3. Wing design & Manufacturing
The wing has five aerofoil sections, joined by two stringers, and with a centre rod along the longitudinal direction of wing. The centre rod provides the mounting point into the wind tunnel. The aerofoil skeleton structure is then covered with a thin surface skin of aluminium foil. The wing structure is shown in the diagram below: length of the wing – 280 mm, chord – 160 mm, and the maximum thickness – 17 mm.

![Figure 1. Cross-section through the wing in SolidWorks.](image1)

![Figure 2. Assembled Wing structure without skin.](image2)

**Table 1. Materials used in wing component manufacture.**

| No | Materials      | Young’s Modulus (GPa) | Poisson Ratio | Density (Kg/m³) |
|----|----------------|-----------------------|---------------|-----------------|
| 1  | ABS Plastic    | 2.62                  | 0.35          | 1005            |
| 2  | Bright steel   | 210                   | 0.3           | 7850            |
| 3  | Aluminium      | 70                    | 0.35          | 2700            |

With the exception of the centre rod and the skin, all parts of the aerofoil were manufactured in ABS plastic using a rapid prototyping 3D printer. Initially all the aerofoil sections, the sheet and the rod were filed to remove any sharp edges. The two stringers were manufactured as four parts; and
joined, the stringers were then assembled through bossed holes in the wing sections and glued for more support. The central rod was then passed through the aligned holes in the sections, and glued using araldite. The whole setup was then allowed to cure for 8 hours, after which the aluminium sheet was formed to the aerofoil shape and bonded around the structure, to form the final completed wing. It was then clamped for 24 hours to allow the glue to set.

4. Wind tunnel testing
Air enters the wind tunnel through the front cone shaped structure which increases the airspeed linearly before it reaches the test section. The air then leaves the test section and passes through the grill before reaching the fan and diffuser. The speed of the axial fan is controlled by an instrument unit attached separately to the wind tunnel. In this study the airspeed was varied from 5 m/s to 40 m/s and aerofoil incidence angles from 0° to 15°. The test model is fixed within the mount before starting the wind tunnel. The velocity and pressure values were measured using the Pitot-static tube fitted in the test section. All the results obtained are accessed by the computer connected to the electronic system [2, 4 and 8].

![Figure 3. Wing mounted in the wind tunnel for testing.](image)

![Figure 4. Lift coefficient wind tunnel results.](image)

![Figure 5. Drag coefficient wind tunnel results.](image)

5. ANSYS analysis
In order to perform finite element analysis, meshing is important and a fine mesh gives a potentially more precise result. The total number of nodes used here was ~200,000, and elements ~184,000. The fluid domain around the wing was also meshed. The two types of 3D cell types used here are
tetrahedron and hexahedron. The structural analysis was performed to study the linear elasticity behaviour of the wing.

Different meshes were tried in order to confirm that they give the same modal frequencies [9, 10]. The first four mode shapes are shown in the Table 2. The flow analysis was performed with the intention of predicting insipient flutter. The Reynolds number for this scaled model was 963,280 for an airspeed of 40 m/s. When operating the wind tunnel at this speed, and with the aerofoil angle of attack at 15°, the wing will vibrate. We believe this to be the airspeed for incipient flutter. Analysis performed in ANSYS for airspeed at 40 m/s predicts the lift value obtained in the wind tunnel to within 5%.

![Figure 6. Mesh on the mounting rod.](image1)

![Figure 7. Mesh on the trailing edge.](image2)

![Figure 8. Tetrahedron and Hexahedron mesh.](image3)

![Figure 9. Mesh on the leading edge.](image4)

| Mode | Frequency (Hz) |
|------|----------------|
| 100  | 23.6           |
| 150  | 34.6           |
| 200  | 23.8           |
| 250  | 27.9           |

6. Discussion
The measured and predicted lift and drag coefficients compared at the airspeed of 40 m/s are within 5%. In the wind tunnel tests, the lift increases rapidly up to a certain level, after some time it stabilises and then gradually increases. The drag also increases, initially to a maximum, and then decreases to a
constant stable value. In view of this, it would seem that transient analysis is pertinent. It was also noted that while the wing can only be made to start vibrating at the speed of 40 m/s, it will continue as the speed is slowly reduced, and stops vibrating at 30 m/s. The flutter of the wing was only seen when the angle of attack is maximum at 15°.

There is some discrepancy between the wind tunnel result for pressure and the CFD prediction. The difference is thought to result from the roughness and irregularities of the wing surface, which was compromised by the limited bending and shaping tools available for the aerofoil construction. At the speed of 40 m/s the turbulence observed in the CFD result is quite normal and hence no boundary layer separation. The modal frequencies were designed to be high, by designing the wing to be light but stiff, using five aerofoil sections. This was for the purpose of allowing the wing to flutter at low speed.

![Image of wing modes](image)

**Figure 10.** The first four mode shapes of the wing, (FEA results).

7. Conclusion
An aerofoil wing was designed, for which the flutter phenomenon was observed in the wind tunnel. It is well known that when the flutter exists at high velocity, any decrease in velocity of the aircraft will reduce the amplitude of flutter. This was demonstrated in the wind tunnel test, as flutter was observed at 40 m/s, and as the velocity was reduced to 30 m/s, the amplitude of vibration decreased until the wing stopped vibrating. Flutter was only observed at high angle of attack (15°), equating to flight conditions of cross wind or climb.

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