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# Design of a Panel Flutter Experiment in a Short Duration Hypersonic Facility

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## Abstract

This work discusses the design of a panel flutter experiment in a Mach 5.8 free-piston compression-heated Ludwieg tube. Small test duration, low freestream pressure and limited space available within the coreflow have driven the choice of boundary conditions, material and panel geometry. The test piece is a 100 mm long and 40 mm wide aluminium panel. The panel boundary condition is clamped-free-clamped-free, with the free edges parallel to the flow direction. The aerodynamic load can be varied by changing the inclination of the panel with respect to the freestream. The pressure in the cavity underneath the panel is reproduced passively by channelling the external flow and creating a recirculation region. Several strategies are employed to reduce the pressure differential between windward and cavity side of the panel. On the basis of steady-state simulations, analytical results and empirical laws, it is possible to state that panel can experience flutter during the test. Further investigation should focus on start-up transients and temperature effects.

## Introduction

Hypersonic aeroelasticity has historically been characterised by a substantial lack of experimental data [1]. In the last ten years, fully-coupled numerical simulations have benefit from the rapidly increasing computational power available, while the experimental counterpart is still relatively limited. Nonetheless, the need for validation cases have contributed towards a renewed interest in hypersonic aeroelastic experimentation [2]. Typical experiments consist of fundamental geometries representative of idealised hypersonic vehicle skin panels [5, 6] and control surfaces [7]. Between the 1950s and the early 1990s, hypersonic aeroelastic experiments have been focussed primarily on flutter [1]. Conversely, modern experiments are generally concerned with validating existing low-fidelity and reduced-order models rather than defining the instability boundaries of vehicle components.

In recent years, Australian researchers have played an important role in producing fundamental hypersonic fluid-structure interaction experiments [2, 8, 9, 10]. However, the majority of Australian hypersonic wind tunnels have limited test duration. This has generally discouraged the study of flutter, which is a form of dynamic structural instability that manifests abruptly but develops over time. Additionally, the relatively small space available within the hypersonic core-flow has normally resulted in stiff small scale models, thus insensitive to structural instabilities.

The objective of this work is to design a panel flutter experiments in a hypersonic short duration wind tunnel. The first section describes the hypersonic facility in terms of test duration, freestream conditions and available test envelope. The second section describes panel boundary conditions, geometry and material employed. The design choices are made in order to reduce the impact of the torsional mode on the plate dynamics, and to minimise the pressure non-uniformity on the panel. On the basis of the flutter considerations discussed in the third section, the dynamic instability boundaries are defined for every panel inclination value. Finally the wind tunnel model is introduced with preliminary steady-state numerical results.

## The facility

The designated facility is a free-piston compression-heated Ludwig tube [3] (TUSQ) which can be equipped with a Mach 5.8 nozzle. With a flow time of 200 ms, that is approximately one or two order of magnitude longer than typical shock tunnels, TUSQ has proven to be suitable for hypersonic aeroelastic investigation [8, 9, 2]. The nominal freestream pressure, Mach number and temperature are the following:

$$p_\infty = 750 \pm 50\,\mathrm{Pa}, \quad M_\infty = 5.8 \pm 0.01, \quad T_\infty = 75 \pm 2\,\mathrm{K} \quad (1)$$

with a frestream Reynolds number of $Re_\infty = 7.1 \times 10^6\ \mathrm{m}^{-1}$. The freestream pressure $p_\infty$ is generally insufficient to induce flutter, as it will be discussed later. Thus the inclination of the test plate can be varied to increase the aerodynamic load. For large inclination angles, the plate length is constrained by the limited space available within the coreflow. Additionally, the test-section pressure increases progressively during the test, resulting in over expanded nozzle conditions. The cone in figure 1 represents the smallest hypersonic coreflow exiting the nozzle during the experiment.

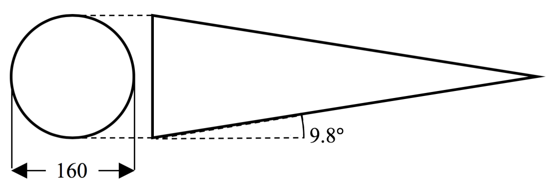


Figure 1: Nominal core-flow (dimensions in millimetres).

To ensure that the model is fully immersed in the hypersonic flow for the whole test duration, the panel dimensions have to be chosen accordingly. Small panels are generally less likely to flutter. Thus, very small panels thickness are considered in the present work, as it is illustrated in the next section.

## The panel

In order to facilitate flutter, the compliant panel is modelled as a shim of Aluminium alloy with the following properties

$$\rho_{Al} = 2770\,kg/m^3, \quad E = 7.1\,GPa, \quad \sigma_y = 280\,MPa \quad (2)$$

For practical reasons dictated by the manufacturing process, plate thicknesses ($h$) smaller than 0.07 mm were not considered.

The clamped-free-clamped-free (CFCF) boundary condition (see Figure 2) was chosen as a compromise between fully clamped and cantilevered configurations. A cantilevered panel presents relatively larger displacements but features lower frequencies, which implies a longer time to onset flutter ($\tau_{FL}$) [5]. Most importantly, a cantilevered panel is not flat at rest. Thus the initial transient loads characterising the beginning of the hypersonic flow can result in fluid-structure interactions that are difficult to model numerically. The main advantage of a panel clamped on all sides is the ability to seal the cavity underneath. However, for the same value of aerodynamic load, a fully clamped panel will experience flutter for plate thicknesses significantly larger than a cantilevered panel. One of the most important reasons behind the choice of a CFCF configuration is the ability to simulate the problem with 2D numerical simulations, which require significantly lower computational resources with respect to 3D simulations.

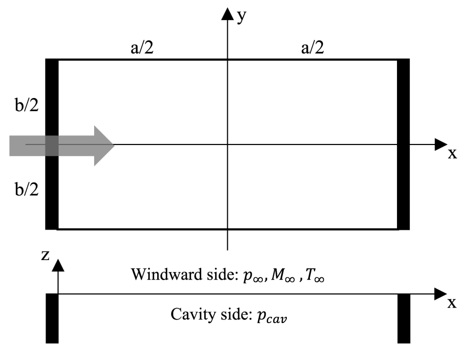


Figure 2: CFCF panel.

The aspect ratio ($AR = b/a$) was chosen to shift the torsional mode towards higher frequencies, *i.e.* to reduce the three-dimensional behaviour of the panel. Using linear theory and assuming a uniform load on the panel, it is possible to define a parameter that is indicative of the three-dimensionality as

$$\eta_{3D} = \frac{w_e - w_c}{w_c} \tag{3}$$

where $w_c = w(0,0)$ and $w_e = w(0, \pm b/2)$ is the displacement at the plate centre and at the free-edges respectively. The dependency of $\eta_{3D}$ on $AR$ is given in figure 3. AR was reduced such that the relative displacement between the free-edges and plate centre were below 10%. In the presence of a pressure differential between cavity and windward side, the plate would be subjected to spillage from the free-edges that can result in a non uniform pressure distribution. In order to avoid the potential of flow spillage, $AR$ was chosen to be 0.4 which corresponds to $\eta_{3D} \sim 6\%$.

Initial design considered a panel length of 200 mm. However, in light of flutter considerations that will be revealed in the next section, a large panel inclination was required to reach the desired pressure above and below the plate. For this reason, a $40 \times 100$ mm panel was chosen in order to allow the inclined model to lay within the coreflow for the whole duration of the test. Additionally, a shorter panel is beneficial in terms of pressure uniformity. The panel modes are shown in figure 4.

It can be demonstrated that the time to onset flutter is approximately [5]:

$$\tau_{FL} \sim 10/f_{FL} \tag{4}$$

where the subscript $FL$ refers to flutter. Assuming a two-dimensional structural behaviour, the flutter frequency can be

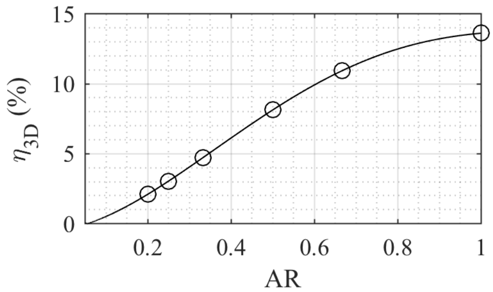


Figure 3: Three-dimensionality parameter as a function of the aspect ratio.

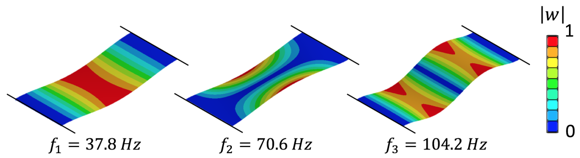


Figure 4: First three (computed) modes for a plate with a length of 100 mm, a thickness of 0.07 mm and an aspect ratio of 0.4.

approximated with the third natural frequency in figure 4 [5]. For $h = 0.07$ mm time to onset flutter is $\tau_{FL} \sim 90$ ms, which is smaller than the test duration. However, employing thicker panels could further reduce this value.

### Flutter considerations

According to the study conducted by Kordes *et al.* [4] on the skin panels of the X-15, it is possible to define a flutter parameter $Q$ that is indicative of the aerodynamic load and the panel stiffness as:

$$Q = \left( \sqrt{(M_2^2 - 1)} \frac{E}{q_2} \right)^{1/3} h/a \tag{5}$$

where the subscript 2 indicates the conditions *past-the-shock*. Thus $q_2 = \gamma M_2^2 p_2/2$ is the aerodynamic load acting on the windward side of the panel. The condition past the shock can be changed by varying the inclination of the panel with respect to the freestream flow. Referring to figure 5, empirical evidence showed that, using an aspect ratio of $AR = 0.4$, flutter takes place for $Q_{FL} < 0.28$. This finding also suggests that only for a plate thickness of $h = 0.07$ mm, flutter occurs for the expected wind tunnel test conditions of the planned experiment.

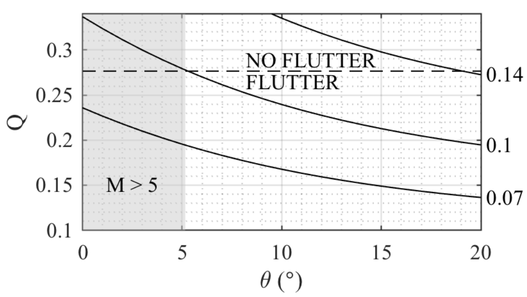


Figure 5: Flutter boundaries for $AR = 0.4$ and $\Delta p \sim 0$. Present values of $Q$ are plotted for three different values of thickness (namely 0.07, 0.1 and 0.14 mm).

In order to reproduce the internal environment of a typical aircraft skin-panel, a cavity is created under the panel that is characterised by pressure $p_{cav}$. The empirical flutter boundary in figure 5 was evaluated assuming a pressure differential $\Delta p = p_2 - p_{cav} = 0$. However, reproducing a zero pressure differential is extremely challenging. Generally speaking, the presence of a pressure differential increases the natural frequencies of the panel. As a result, flutter occurs for larger aerodynamic loads.

Because of the CFCF conditions, it is not possible to pressurise the panel cavity before the test. Even for a fully clamped configuration, the panel would be subjected to high pressure loads prior the runs, possibly resulting in static failure. Additionally, the freestream pressure is not constant but varies by approximately ±50 Pa during the test, thus a pressurising system should continuously adjust $p_{cav}$ to match $p_2$. In this framework, the cavity pressure is reproduced passively by creating a recirculation region under the plate. This strategy, however, significantly reduces the ability to fine tune $p_{cav}$.

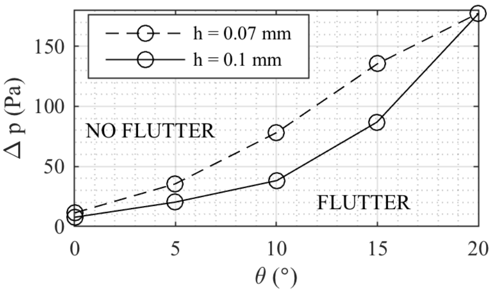


Figure 6: Computed flutter boundaries for $AR = 0.4$ and $a = 100$ mm.

Figure 6 presents some of the analytical results obtained for different values of $\Delta p$ and $\theta$. The solutions are obtained for a panel clamped on its leading and trailing edges using a non linear structural model (essentially a one dimensional version of the Von Karman plate model) that includes the effect of the static pressure differential across the panel. The aerodynamic load on the windward side of the panel is modelled with the piston theory. For the conditions of the wind tunnel experimental model, this is expected to be a good representation of the physical phenomena of flutter and the subsequent limit cycle oscillation. Prior experiments in the supersonic flow region have shown good correlation with such an analytical model [5]. The results in figure 6 demonstrate that a change in $\Delta p$ of approximately 100 - 200 Pa can inhibit the onset of dynamic instability. While a larger value of $\theta$ results in wider operational margin, they also increase the frontal-area of the wind-tunnel model. Blockage can increase the risk of core-flow chocking. Thus, the panel inclination should be chosen to maximise the flutter margin and minimise the blockage. In the next section, the design will employ a panel inclination of $\theta = 12°$ ($M_2 = 4.3$) and a panel thickness of $h = 0.07$ mm.

### The wind tunnel model

The following experimental design is based on static steady-state simulations. The wind tunnel model not only acts as a support for the panel but its main function is reducing the pressure differential across the panel.

The wind tunnel model is comprised of a plate and a ramp, as shown in figure 7. The panel is clamped to the top surface of the plate and exposed directly to the flow. The top profile of the plate has to be planar. Early design employed leading-edge wedge, with an angle of 10 or 15 degrees. This generally resulted in large pressure non-uniformities on the windward side of the panel, due to the interaction between expansion waves and the leading edge shock. With the current design, weak viscous interactions result in a gradual pressure drop of approximately 50 Pa.

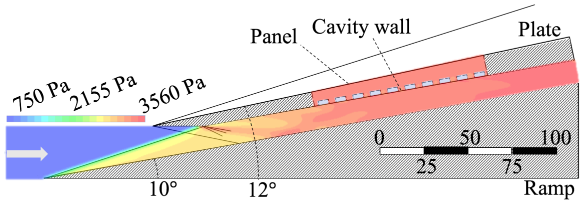


Figure 7: Side view of the wind tunnel model and laminar pressure solution (dimensions in millimetres).

The ramp compresses the flow under the plate to increase the pressure of the recirculation region beneath the panel. For the same value of inclination, the ramp determines a cavity pressure $p_{cav} \sim 1.2 p_2$. For this reason the ramp is inclined by a smaller angle, as shown in figure 7. The perforation of the cavity wall is obtained with 2 mm long and 40 mm wide rectangular vents that run spanwise along the plate width. *Bleed* is necessary to reproduce a uniform pressure under the panel and it reduces the pressure fluctuation by approximately a factor 10. The plate and the ramp constitute a system very similar to a hypersonic intake. The leading-edge shock from the ramp impinges where the plate profile changes geometry resulting in a weaker reflected wave.

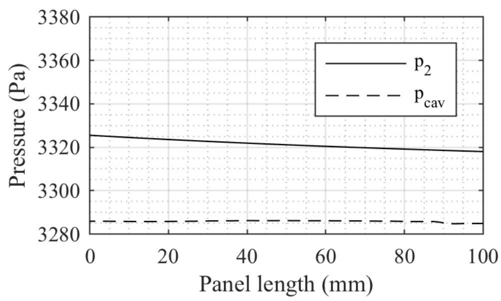


Figure 8: Pressure acting on the windward and cavity side of the plate from laminar CFD.

Figure 8 shows that, for $\theta = 12°$ and a ramp angle of 10.5°, the pressure differential between top and bottom of the plate is smaller than $\Delta p_{cav} = 50$ Pa. During the experiment, the inclination of the ramp shall be adjustable in order to further decrease the pressure differential. Using this configuration, flutter could occur also for a panel thickness of 0.1 mm, as shown in figure 6.

The width of the plate (and of the ramp) is chosen to minimise pressure non-uniformity on the compliant panel and in the cavity. As it is shown in figure 9, with a plate width of 150 mm the panel is predicted to lay outside the Mach cones. Within the shaded area, the pressure drop in the vicinity of the plate edges can be considered of the order of 50 to 100 Pa [2].

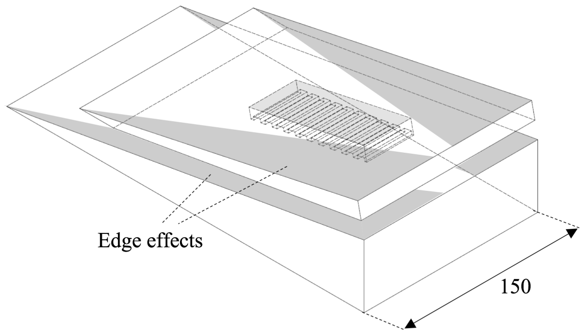


Figure 9: Isometric drawing of the wind-tunnel model with detail of the edge-effects extent on both plate and ramp. (dimensions in millimetres).

#### Conclusion and future work

This work has demonstrated that it is theoretically possible to reproduce flutter in a hypersonic impulsive facility. However, further study is required to improved the accuracy of the predictions. For instance, transient effects have not been treated in this study. While the flow is fully established after 2 ms, the cavity could take some time to reach the designed value of pressure. Transient simulations should be performed to quantify the cavity pressure evolution.

Thermal effects can result in buckling which may induce or inhibit the occurrence of flutter. The panel is heated by the hypersonic flow and cooled by the air trapped in the cavity underneath. Thermal analysis and fluid-thermal-structure interactions simulations should be employed to predict the flutter boundaries with increased accuracy.

During the actual experiment, pressure in the cavity and upstream of the panel should be monitored with the use of pressure transducers. Edge effects are predicted to marginally impact on the panel structural behaviour. However, thermal and/or pressure surface measurement techniques (such as infrared thermography and pressure-sensitive paint) should be employed to measure the extent of the edge effects on both the rigid plate and the compliant panel. Additionally, the ramp inclination should be adjustable in order to effectively control the cavity pressure.

Finally, recent work has been focused on increasing the freestream pressure of the facility by a factor 2 [11]. Such an improvement could increase the chances of reproducing flutter, as the sensitivity to pressure differential generally decreases for larger aerodynamic loads.

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