Wind Tunnel Experiments with Flexible Plates in Transonic Flows: Draft Paper

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The evolution of adaptive shock control bump (SCB) design has seen the system flexibility increase to a point where the aerodynamic loading can affect the deformation of the plate. By studying the effects of a flexible plate subject to transonic flow the fluid structure interaction can be investigated. In this study an array of thin plates (0.4 and 0.6 mm) with different aspect ratios (1 and 1.33) are exposed to a Mach 1.4 normal shockwave. PIV is used in combination with Schlieren imaging to provide a detailed view of the flow curvature surrounding the plate as well as the global shock structure. A technique that extracts the plate deformation from the PIV images is also presented which provides fluid and structural information for each test. The relationship between plate and flow angle is discussed as well as the effect of plate stiffness and free stream influence of each plate configuration.

I. Introduction

The interaction between fluids and structures is an important field that has featured in all modern aircraft design. These range from full-scale aeroelastic analyses to individual components of the aircraft structure. For example, the wings of the Boeing 787 were designed with a coupled aero-structural approach in order to produce an efficient design that can accommodate a wide range of flight regimes.

Natural laminar flow airfoils are a promising concept that have received a great deal of attention in recent literature.¹ They necessitate a significant increase in the shock strength on the upper surface, pre-shock Mach numbers of 1.4 have been shown to maximise the potential of the laminar flow region. These strong normal shocks have a larger pressure difference across the shock which increases the likelihood of separation. In order to reduce this, numerous flow control techniques were tested with shock control bumps (SCB) proving effective at maintaining high levels of total pressure across the shock.^{2,3} The original concept was envisaged as a thin sheet to be deformed by actuators positioned along the length. Recent optimisation studies⁴ have been designed to evaluate the performance of adaptive SCB. It was found that the flexibility of the structure necessary to produce suitable bump heights also allows the aerodynamic pressure load to affect plate deformation. The influence of the pressure gradient surrounding the shockwave can be utilised to produce a bump-like geometry from pressure loading alone. The bifurcated shock structure that SCB are aiming to introduce can be achieved by a system that is designed for passive control, that is able to produce the desired shock structure by using the properties of the pressure gradients surrounding the shock. Figure 1 illustrates the shock structure that is achievable through the use of a correctly designed flexible plate. Whilst it does not eradicate the need for active adaptive SCB it does highlight that choosing specific structural qualities can have a direct effect on the aerodynamic response.

The flexible plate system has many parallels with the panel flutter studies completed in the late 1960's and 1970's by Dowell^{5,6,7} where piston theory was primarily used to describe the aerodynamic loading. The theoretical models were based upon various models including Rayleigh-Ritz, Galerkin and many finite element and finite difference methods. They primarily focussed upon the limit cycles of the interaction and were primarily theoretical in their approach. The models have been extended to combine three-dimensional Navier-Stokes solvers coupled with finite difference structural models.^{8,9} Both inviscid and viscous solutions have been investigated with viscous solutions showing a higher dynamic pressure for panel flutter onset.

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Experimental studies of plates have been conducted across a wide range of Mach numbers¹⁰ and have predominantly focussed on the structural response of the plate. This ties in with the limit cycle studies of Dowell⁵ and Visbal⁹ however the analysis of the flow structure was not investigated in such great detail. In this study we focus primarily on the aerodynamic nature of the flow field in the vicinity of a flexible plate.

Figure 1. Bifurcated shock induced by flexible plate.

II. Experimental Setup

Experiments have been undertaken in the Imperial College Supersonic tunnel which is capable of producing Mach 1.4 flow for 60 seconds. The total pressure ratio in the tunnel is maintained via a PID controlled valve. A total pressure ratio of approximately $P_{01}/P_{0\infty} \sim 1.32$ was found to be necessary to maintain a normal shock in the test section above the flexible plate. The static pressure in the Mach 1.4 free stream flow ahead of the shock wave is approximately ~ 0.4 bar. The pressure beneath the flexible plate, the cavity pressure, is ~ 0.65 bar. The panel surface was glued to a fixture to avoid any surface discontinuities in the flow which would trigger pressure waves in the flow. It also allowed for the clamped end conditions required for the experiment.

Figure 2. Experimental setup of Imperial College Mach 1.4 wind tunnel with flexible plate installed.

The PIV setup is comprised of a 30 MJ, 527 nm double pulsed Nd-YAG laser, DEHS liquid particles and a Phantom v641 high speed camera. The acquisition frequency for Schlieren imaging and PIV were matched at 700 Hz. The PIV images were double frame images of 2560×1560 pixels and represented a large field of view, $175 \times 112 \text{ mm}^2$. The time period between frames was $1.4 \mu\text{s}$. At this frame rate, the 32 Gb memory allowed capture of 3.9 seconds of real-time flow with 2732 image pairs. The image-processing was kept to a minimum to ensure that any whole-field statistical modifications did not affect the results. The first image processing step was to correct the image to account for any misalignment of the camera. The

mapping function was computed from a known pattern display with a calibration plate, the images were supplied with a scale and coordinate system. A standard cross-correlation was used with multiple passes of decreasing window size with a minimum window of 32×32 pixel windows were used with 75% overlap. This allowed for a suitable vector resolution of 301×210 across the image as well as faster computation times.

III. Plate Design

The concepts for the flexible plates in this study have developed from the design trends of adaptive SCB. The initial sizings are based upon the target of generating a bifurcated shock structure. One of the requirements of the structural system was to balance flexibility with stiffness. The flexibility of the structure is bounded by the yield stress of the material and the requirement to trigger the bifurcated shock structure. The primary goal of this study is to investigate the fluid-structure interaction on a clamped-clamped-free-free plate illustrated in figure 3

Figure 3. Boundary conditions of flexible plate.

l_b	t	a/b
150	0.4	1
150	0.6	1
200	0.4	1.33
200	0.6	1.33

Table 1. Dimensions of plate test cases. Constant span of 150 mm

As Dowell has indicated previously,⁶ the fluctuations in a turbulent boundary layer above a thin plate can begin to introduce small oscillations of the plate. The amplitude of these vibrations is of the order of the thickness of the plate.⁶ The recommendation at the time⁷ was to simply design around panel flutter by using thicker plates or reducing the panel length. These approaches involve increased weight either of the panel itself or the supporting structure required to shorten the plate. If panel flutter did develop during further flight tests, it had to be shown that the flutter was not destructive and remained below the flutter boundary.

The flutter boundary was defined as the variation with Mach number of the dynamic pressure at which the onset of panel flutter begins. Below this boundary the oscillations were typically less than the plate thickness. As the dynamic pressure was increased beyond the flutter boundary the oscillation was observed to become nearly sinusoidal and with an amplitude that increases as the dynamic pressure increases.

In order to investigate panel response due to aerodynamic loading the flutter boundary must first be calculated. Dowell⁶ defined equation 1 as the critical dynamic pressure, λ^* , above which large amplitude,

high frequency response may occur.

$$\lambda^* = \frac{2qa^2}{D} \quad (1)$$

$$D = \frac{2h^3 E}{3(1 - \nu^2)} \quad (2)$$

Where q is the dynamic pressure, a is panel length and D is flexural stiffness.

The relationship was developed for simple isotropic panels and incorporated plate thickness, modulus of elasticity, and length to provide a single parameter. The magnitude of the flutter boundary for a fixed Mach number and aspect ratio determines the severity of the oscillations.

By evaluating with the dimensions of the plates presented in table 1 the flutter onset dynamic pressure is calculated for each setup. The dynamic pressure component, q , was evaluated from initial wind tunnel results from the setup described previously, that placed a shock in the region of the flexible plate. Placing the shock in this region required $P_{01}/P_{atm} \sim 1.3$ which is consistently achievable. Static pressure measurements were taken on the wall of the working section and total pressure losses along through the nozzle were assumed negligible. A value of $\lambda^* > 10^4$ was obtained which place these plates well beyond the flutter onset boundary condition. This value is primarily driven by the thickness of the plate which dominates the flexural stiffness term and has a large effect on the flutter onset dynamic pressure.

The stiffness of the plate is affected by the cavity pressure beneath the plate surface. A high pressure in the cavity beneath the plate causes it to stiffen. Physically, the plate is stiffened by the tension induced by the membrane stresses which are in turn induced by the plate stretching as it bends under the pressure load. The initial studies⁶ acknowledged the effect of the cavity pressure in the theoretical models. They introduced acoustic cavity models which were found to be very reliable in predicting the effect of natural frequencies for panel flutter. By adding this extra level to the panel flutter analysis, the system becomes sensitive to pressure difference across the plate rather than absolute values in the flow. Maintaining the pressure difference requires the management of a complex experimental setup whilst accounting for the imperfect seals that form around the plate. Figure 4 shows the relative magnitudes of pressure acting on each region of the setup based upon experimentally measured values.

The plate deformations caused by the pressure differential across the plate directly interact with the flow and create large scale shock structures. These in turn vary the pressure distribution over the upper surface of the plate and hence cause further deformation. The amplitudes of the plate are limited by the membrane stresses in the material which inhibit crest growth beyond the yield stress. The cavity pressure is maintained at a roughly constant value of $0.5P_{01} \pm 0.02$ in order to limit the pressure differential across the plate and subsequent plate deformations that would cause the plate to yield and undergo irreversible plastic deformation. This value sits between the lower pressure supersonic flow on the front surface of the plate and the higher pressure on the rear surface. The shock structure produced is similar to the that in figure 1 however the effects of plate curvature are seen to affect the overall structure. The results from this report aim to identify the relationship between the curvature of the plate and the flow curvature as well as key differences between the four plate cases presented in table 1.

Figure 4. Approximate pressure ratios between key segments of flow, based on experimentally measured values.

IV. Results

Previous work has shown that surface deformation caused by aerodynamic loading is capable of bifurcating a normal shock wave.⁴ Figure 5 shows the shock structure of a Mach 1.4 flow over a plate $l_b = 150$ mm,

t 0.4 mm. Schlieren images have shown the shock structure over a flexible plate to differ at key regions from the that seen in figure 1. Figure 5 shows how the continuously changing curvature of the plate effects the shock structure. This is most visible at the rear leg of the main λ -shock which is curved towards the downstream direction. The cause of this is the interaction of the main rear leg and the expansion waves that emanate from the convex curvature around the crest region. This has the effect of weakening the rear leg which means that the shock strength is reduced leading to higher velocities downstream. These higher velocities make the flow more susceptible to reacceleration and further shocks as seen by the secondary shock structure in figure 5.

In order to extract more quantitative information from the flow, more advanced experimental techniques are required. Through the use of the PIV procedure outlined previously, the velocity field is extracted on the tunnel centreline to provide two component velocity data in the streamwise plane. Figures 6 and 7 show the mean streamwise and vertical velocity components. The results are consistent with the Schlieren images in figure 5.

l_b	t	Shock		Plate Crest	
		Avg. Posn.	st. dev (Var)	Avg. Posn.	st. dev. (Var)
150	0.4	0.4258 l_b	0.0214 (4.5603e-04)	0.6584 l_b	0.0121 (1.4543e-04)
150	0.6				
200	0.4				
200	0.6				

Table 2. Shock position data for all test cases.

The shock structures remain globally stable throughout the 2732 image pairs with a standard deviation of $0.02l_b$ equivalent to a 15 mm oscillation. For comparison a shock in the clean working section oscillates 50 mm.⁴ The shock position is defined as the main normal shock location, labelled in figure 5 is $x \approx 60$ mm.

information on plate deformation has also been extracted from PIV images and provides the geometry of the plate for each PIV vector field. An example of the image is provided in figure 8 which shows the mean plate displacement throughout during the 3.9 second run. The transient plate location throughout the run is shown in figure 9. The displacements extracted through this technique are very similar to those extracted from the Schlieren images however they remove any errors due to the span wise curvature of the plate. Figure 8b) shows a raw image which highlights the effects of scattering which be identified close to the wall and the regions of high convex curvature near the crest. Reconstruction of the plate surface was compromised here and has been reconstructed using high-order polynomials to estimate the plate crest location. The relatively simple plate-in-bending shape was achievable with very good representation, figure 8a).

To evaluate the relationship between plate and flow curvature the latter must be extracted. In order to obtain this information streamlines have been calculated. The streamlines represent the trajectory of a mass-less particle from a prescribed starting point across the domain. Figure 6 includes the streamlines starting at regular intervals away from the plate surface. The curvature is extracted at discrete points across the field and are shown in figure 10. Analysis for each of the configurations in table 1 is ongoing.

The plate geometries and plate response are similar to the typical numerical panel-flutter studies^{11,12} which focus on limit cycle behaviour. The large scale plate deformations, $\delta > 1.5t$, shown previously⁹ are also apparent in this experiment with a similar pressure distribution. There is significant stiffening of the system due to the clamped constraints and increased stiffness due to the cavity pressure which limits the amplitude and frequency of the plate oscillation. Further work is to be carried out to determine the relationship between plate stiffness and plate oscillations from a dynamically loaded structures viewpoint. This will lead to a flow-plate curvature study comprised of data similar to that presented in figure 10 for each plate case in table 1.

V. Conclusions/Final Paper Content

Experiments with this configuration (l_b 150 mm, $t = 0.4$ mm), have shown that the influence of surface curvature have extended well in to the freestream by the formation of the bifurcated shock structure. The reacceleration region downstream of the rear leg is of particular importance as the flow curvature in this

Figure 5. Schlieren image for flexible plate $l_b = 150 \text{ mm}$ $t = 0.4 \text{ mm}$

Figure 6. Streamwise velocity for flexible plate $l_b = 150 \text{ mm}$ $t = 0.4 \text{ mm}$

Figure 7. Vertical velocity for flexible plate $l_b = 150 \text{ mm}$ $t = 0.4 \text{ mm}$

Figure 8. a) Instantaneous plate deformation and curvature $l_b = 150 \text{ mm}$ $t = 0.4 \text{ mm}$. b) Raw image of laser sheet on plate surface with particle subtraction to enhance position capture. y axis enlarged 5 times for clarity.

Figure 9. Plate deformation variation throughout time. Vertical axis enlarged 6 times for clarity.

Figure 10. Comparison of flow curvature and plate curvature $l_b = 150 \text{ mm}$ $t = 0.4 \text{ mm}$

region determines if the flow remains attached to the surface by following the plate curvature.

The purpose of the study is to investigate the configurations in table 1 and determine the relationship between surface and flow curvature in each. The varying flexural stiffness between each of the plates will highlight the differences in panel characteristics when subjected to a transonic flow field.

The experimental data required has been obtained for each of the test cases with further analysis and comparisons to be included in the final paper.

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