Optical Diagnostics in Engineering, Vol 3(1), (1999), 91-101

LOCAL SHEAR STRESS MEASUREMENTS WITHIN A RECTANGULAR YAWED CAVITY USING LIQUID CRYSTALS

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Keywords: *liquid crystals, cavity flows, shear stress, supersonic flow*

Abstract

The present work is an experimental investigation of the surface flow and shear stress distribution within a rectangular cavity at M = 2 for different approach flow yaw angles. The cavity has a length-to-depth ratio of 2 and a planar aspect ratio of 11.79 and was positioned within a turbulent boundary layer at a Reynolds number based on momentum thickness of $Re_q = 7.3 \times 10^4$. Full field surface flow data were provided by recording and processing the colour change of cholesteric shear stress sensitive liquid crystals for nineteen different yaw angles between 0^0 and 90^0.

The information gained from these image analyses was then compared to measurements of the sound pressure fluctuation levels obtained within the cavity in order to explain the possible cause of the changes in these levels as the cavity is yawed.

Nomenclature

D - depth of cavity
dt - incremental time
L - length of cavity
p - instantaneous pressure
p_{av} - average pressure
p' - fluctuating pressure
q_a - reference pressure level
RSPL - relative sound pressure level
$\overline{SPL}$ - sound pressure level (dB)
T - time period
W - width of cavity
y - yaw angle

1 Introduction

Surface cavities are present in many aerodynamic situations such as equipment housing, panel handles, cargo bays and flap recesses, as well as external instruments. These cavities are often immersed in surface bounding flows and can lead to large pressure fluctuations within the boundary layer, thereby producing variations in the local velocity and density, as well as providing a source of acoustic noise. Even the simplest of cavities, such as a rectangular cavity, is complicated by the flow disturbances it can cause, whereby the cavity flowfield may be described as open, closed, or transitional depending on whether the shear layer

(a) spans the cavity (open), or
(b) impinges on the cavity floor (closed).

Cavities that have a length/depth ratio greater than 13 are described as closed and those with a length/depth ratio of less than 10 as open. It is this latter type of cavity that provides strong three-dimensional flow fields and, as such, is complicated, with both the internal and external regions of the flow capable of producing self-sustained oscillations and interactions between the shed vortices from the cavity with those that are present within the cavity. These flowfield characteristics appear to depend primarily on the Mach number and the cavity shape and, to a limited extent, on the Reynolds number [1]. Although those authors performed an exhaustive experimental programme in order to provide a benchmark for different Mach numbers, aspect ratios and flowfields for the subsonic and transonic regimes, no data were reported about the mechanism driving the

pressure oscillations. Many other researchers have also attempted to describe the complicated flowfield that is produced by cavities [2], [3]. However, most of these have been made without the ability to visualise experimentally the flowfield created by a cavity within a supersonic flow [4]. In order to assist the development of these models, shear stress measurements have been performed on selected cavity configurations and orientations. Using shear stress sensitive liquid crystals, lines of constant Hue, and selected shear stress levels, have been obtained within a rectangular cavity placed within a turbulent boundary layer at Mach 2. The use of these crystals in and around the cavity has provided additional insight into the flow characteristics that occur within such a configuration when it is yawed to the freestream.

2 Experimental details

2.1 Cavity model details

Experiments were conducted within an intermittent supersonic blow-down facility at the University of Cincinnati. This wind tunnel has a rectangular test section 152.4 mm wide and 165.4 mm high and is 457 mm in length. For this series of tests a nominal freestream Mach number of Mach 2 was chosen with a Reynolds number, based on momentum thickness, of 7.3 x 10^4. A Schlieren quality glass window served as the front sidewall of the tunnel and was used for visualisation of the test section, with the back wall being used for mounting the cavity model. Here, a 177.8 mm circular aluminium ‘plug’, 63 mm in depth, was mounted such that its front face was flush with the tunnel wall. This plug was configured to provide for a cavity with geometrical dimensions of 123.8 (L) x 10.5 (W) x 5.2 (D)mm, giving a planar aspect ratio of 11.79, and a length/depth ratio of 2 (see Fig. 1).

By rotation of the complete plug assembly the cavity could be yawed to the freestream flow, with the zero degree yaw position being when the major axis of the cavity was perpendicular to the freestream direction. The boundary layer thickness at the model position was approximately 13.9 mm giving a momentum thickness of about 1.92 mm and a displacement thickness of 2.8 mm.

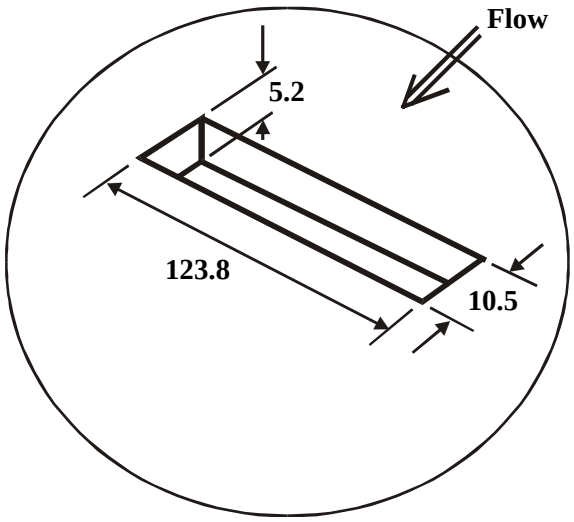


Fig. 1 Dimensions of cavity (in mm)

Pressure measurements were taken with three high speed Entran EPI-080B miniature pressure transducers mounted close to the centre-line of the cavity, with the first transducer positioned 0.25L upstream of the separation lip. A second transducer was position on the cavity floor, 0.67L downstream from the base of the upstream wall, with the third transducer located 0.31L downstream of the cavity aft wall. Measurements of the pressure oscillations for a range of different yaw angles of the cavity, including the sound pressure levels [SPL] in decibels, were recorded prior to the experiment with the liquid crystals. These particular transducers had a resonant frequency of 125 kHz and a flat response to more than 25 kHz. Based on comparison tests the transducer outputs were digitised at 50 kHz using an eight-channel, 16-bit simultaneous sample and hold A/D converter and processed using a PC microcomputer. Prior to the liquid crystal experiment the pressure transducers were removed and ‘dummy’ transducers located in their positions.

2.2 Details of the liquid crystals

Two different shear sensitive liquid crystals were used in this experiment, with both being of the cholesteric type. The first crystal, CN/R7, was applied as a thin layer of approximately 10 μm over the planar surface surrounding the cavity, with the second crystal, CN/R2, applied evenly over the floor of the cavity. These crystals have different viscosities, with the CN/R2 having a viscosity of 4500 cps and the CN/R7 having a much higher viscosity of 13000 cps. For each yaw angle the model was removed from the tunnel and both crystals prepared by ensuring they were returned to their unstressed states. The model was then re-mounted on the wall of the tunnel and the crystals viewed through the opposing glass window. The crystals were illuminated with a white light source mounted outside of the tunnel, at approximately 30^0 normal to the cavity, in the direction of shear (see Fig. 2). The colour change in the crystals was recorded using a 3-CCD Panasonic WV-F250B series NTSC colour video camera, corrected for white balance, and with a F-stop of 5.6, onto a Panasonic AG-7750 SVHS recorder. This camera was mounted at the same level as the lighting source but at approximately 10^0 to the normal to the cavity base in the opposite direction to the shear.

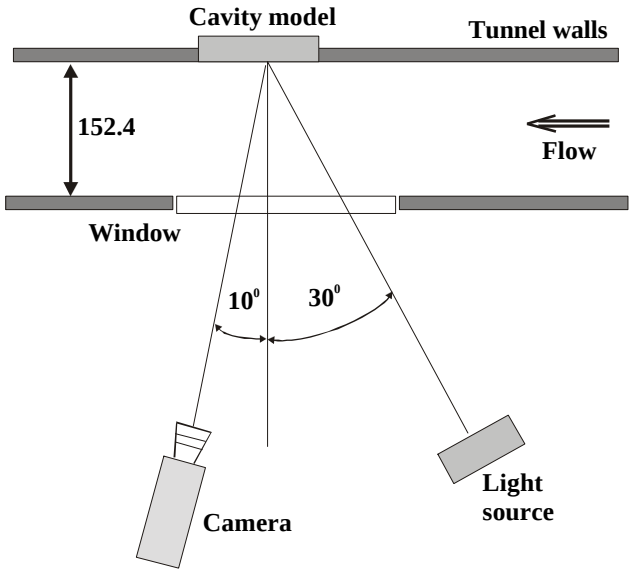


Fig. 2 Diagrammatic sketch of the lighting and viewing angles.

These angles were chosen on the basis of previous experience which showed that they gave the greatest colour play for a given shear stress range [5, 6, 7]. Post-processing of the images was provided by a PC based system, using in-house software to determine the Hue, Saturation and Intensity of each pixel, or group of pixels, which made up the image.

2.3 Experimental Measurements

2.3.1 Pressure Measurements

Prior to any unsteady pressure measurements being taken the boundary layer upstream of the model was fully documented, the results indicating that a fully turbulent boundary layer was established. Velocity profile measurements showed a boundary layer thickness of 13.9 mm. In addition, the local skin friction was determined to be 0.0021, with displacement and momentum thickness determined to be 2.8 mm and 1.92 mm respectively, giving a shape factor of 1.46. Furthermore, by replotting the velocity in terms of wall units good agreement was found to exist for y^+ between 250 and 2500.

In addition to these flow characteristics, the sound pressure level (SPL) in the tunnel was determined in the absence of the cavity model. This was achieved by integrating the fluctuating pressure levels over a time series and transforming the resulting value to a $\overline{SPL}$ using the following equation.

$$\overline{SPL} = 10 \log \left[\frac{\overline{p'^2}}{q_a^2} \right]$$

where

$$\overline{p'^2} = \frac{1}{T} \int_{T_1}^{T_2} (p - p_{av})^2 \, dt$$

and q_a represents a typical reference pressure level used in acoustic studies of 20 x 10^{-6} Pa.

As a result of this process the average $\overline{SPL}$ in the tunnel, without the cavity in place, was measured as 146.42 dB. A subsequent FFT on the fluctuating pressure signal also indicated a low-level, broadband, pressure response without any dominant pressure peaks.

With the cavity present, and orientated at 0^0 to the freestream such that the length/depth ratio (L/D) was 2, the average $\overline{SPL}$ was determined to be 161.78 dB. Further processing of the fluctuating signal with a FFT indicated a pressure peak at 23 kHz, and this robust peak was found to be 10 times greater than the background noise within the cavity [8, 9]. In order to check whether there were any significant pressure oscillations above this 23kHz, further tests were performed with the transducers sampled at 100kHz, but none were found (see [9] for details).

The high-speed pressure transducers located in and around the cavity recorded the combined fluid dynamic and acoustic spectra for a range of yaw angles between 0^0 and 75^0. The change in this sound pressure level as the cavity is yawed is shown normalised with respect to the spectrum level at $\psi = 0^0$ (see Fig. 3), producing a relative sound pressure level (RSPL), given by:

$$RSPL = \frac{\overline{SPL}_y}{\overline{SPL}_{y=0}}$$

Here, it may be observed that there is little change in this RSPL between 0^0 and 20^0, with a reduction occurring to a local minimum at around 35^0, whereupon there is a reverse in the trend, reaching a peak at a yaw angle of approximately 55^0. Beyond this angle, the level, once again, falls quickly in magnitude until an angle of approximately 60^0 is reached, after which it falls gradually with yaw angle increasing to 75^0.

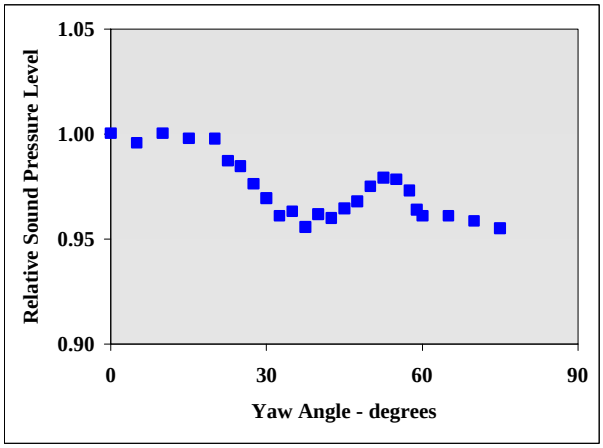


Fig. 3 Variation of pressure spectrum level in a yawed cavity at Mach 2

The variation in the RSPL as the cavity is yawed is, undoubtedly, connected with the changing nature of the flow field within the cavity itself. At a yaw angle of 0^0 the flowfield may be associated with an open cavity, whereas at the larger angle of 75^0 the flowfield is one that is associated with a closed cavity. Between these two extremes the flowfield undergoes changes of a transitional nature.

Indeed, an examination of the data in [9] clearly suggests that the cavity has nominally switched from one dominated by an acoustic mechanism, at $\psi \sim 35^0$, to one dominated by a fluid dynamic mechanism.

In order to provide further insight into how the flowfield within the cavity changes from the open case, through the transitional stage to the closed geometry, shear sensitive liquid crystals have been employed.

2.3.2 Liquid Crystal Measurements

In an earlier experiment with the two types of liquid crystal used in this paper, namely CN/R2 and CN/R7, a calibration of shear stress against hue was obtained (see Fig. 4). This was achieved with a mechanical shear stress rig, whereupon some crystals were placed between two surfaces with one of these surfaces fixed. A force was then exerted on the

second, optically transparent, surface such that the crystals were put under a measurable tangential stress. This optical surface allowed white light to illuminate the crystals in the direction of shear at a similar angle to that described above, with the CCD camera arranged at a similar angle to that previously described. It should be noted that the lighting and viewing angles are important when determining shear stress from the changes in colour of liquid crystals. Variation in lighting angle from the calibrated position may produce incorrectly recorded shear stresses.

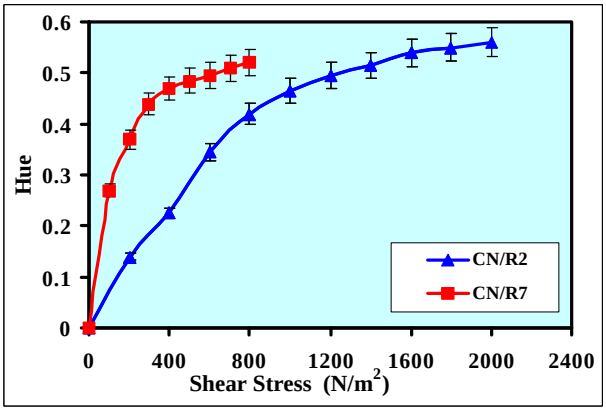


Fig. 4 Calibration of two types of liquid crystals

For this series of experiments with the liquid crystals the run time of the tunnel was approximately 50 seconds. This time period was chosen since it provided optimum operating conditions for the tunnel and was sufficient for the crystals to react to the local shear stress conditions. It also allowed them to move in the direction of shear without causing a dramatic loss in the quantity of crystal at any location. Typical parameters for the operating conditions were:

- Stagnation pressure = 2.93 bar absolute
- Stagnation temperature = 23^0 C
- Static pressure = 0.610 bar
- Manifold pressure = 5.33 bar gauge

and a Barometric reading of 0.988 bar.

These conditions provided a freestream Mach number of 2.0

With the arrangement as described above nineteen yaw angles were investigated, ranging from 0^0 (flow perpendicular to the major axis of the cavity) to 90^0 (with the flow along the major axis) in steps of 5^0.

3 Liquid crystal results and discussion

The relatively short run time of this series of experiments was advantageous to the use of liquid crystals. This allowed the crystals to not only undergo changes in colour due to the local shear stress being applied to them but also allowed the crystals to move in the direction of the applied shear, thus providing both a quantitative and a qualitative aspect to the flow region. This was particularly evident when the cavity was set at high angles of yaw. It should be noted that use of crystals of a lower viscosity was attempted but they were easily removed by the applied shear stresses in the flow. However, it was also observed that a small amount of CN/R7 detached itself from the upstream edge of the cavity and contaminated the CN/R2 crystal on the cavity floor. However, with such a short duration test the contamination was minimal. Nevertheless, it was considered appropriate, although not essential, to change the CN/R2 crystal in the cavity for each experimental run.

In order to describe the surface flow field on the floor of the cavity for different angles of yaw, six still images have been digitised from the SVHS tape. These images are of the cavity at yaw angles of 0^0, 30^0, 45^0, 60^0, 75^0, and 88^0 (see Figs. 5,6 & 8 – 10). This unusual angle of 88^0 was chosen, rather than 90^0, to show that the crystals are sensitive enough to flow conditions even at a yaw angle close to a completely closed cavity geometry. On further examination of the video images it was apparent that the movement of the crystals within the cavity was not always parallel to the freestream direction. This implied that the shear stress vector for the liquid crystals varied within the cavity and, therefore, the local lighting and viewing angles were different for each cavity orientation. Hence, it was necessary to determine, from these figures,

lines of constant Hue using in-house software (see Fig. 12), rather than shear stress values, except for the yaw angles of 0^0 and 90^0, where it was deemed possible to determine the shear stress values. Although it is possible to assign shear stress values to the Hue using the calibration in figure 4, their values would only be correct for the condition when the surface shear flow was in the direction of the freestream flow. However, for angles between 0^0 and 30^0 as well as angles between 75^0 and 90^0, the pathlines provided by the movement of the liquid crystals show the flow is essentially in this direction. This is not the case for the intermediate angles nor for reversed flow regions where interpretation of the shear stress values would be difficult.

The surface shear flow surrounding the cavity was visualised with the CN/R7 crystal. However, this crystal quickly reached its maximum Hue value and became out of range throughout most of the test. The redeeming feature of this crystal was that it showed a clear uniformity of Hue throughout the test run period, thus providing evidence of a uniform surface shear stress over the model surface that surrounded the cavity.

With the cavity set at a yaw angle of 0^0 the liquid crystals (CN/R2) appear uniform along its major axis (see Fig 5). Note that the locations of the pressure transducer plugs are shown white in this figure. It should also be noted that the flow for all the ensuing images is from right to left, with some images showing a small shadow cast in the upstream edge of the cavity. This image shows that some crystal is accumulating at a position approximately 25% of the chord from the upstream corner. Here, the stress would be close to zero and is depicted as small white points along a line running the length of the cavity. The low value in Hue of between 0 and 0.11 when converted to shear stress using the calibration curve in Fig 5 gives values of between 0 and 180 N/m^2. For this cavity orientation (open type) the flow would separate from the upstream cavity wall and create a recirculation within the cavity, giving rise to a flow from the downstream corner towards the upstream corner until it reaches the zero stress region. Measurements of Hue also show the reduction in value towards the upstream corner with zero at a similar location as that visualised (see Fig. 12a). This would suggest that a large vortical motion dominates the flow in this corner.

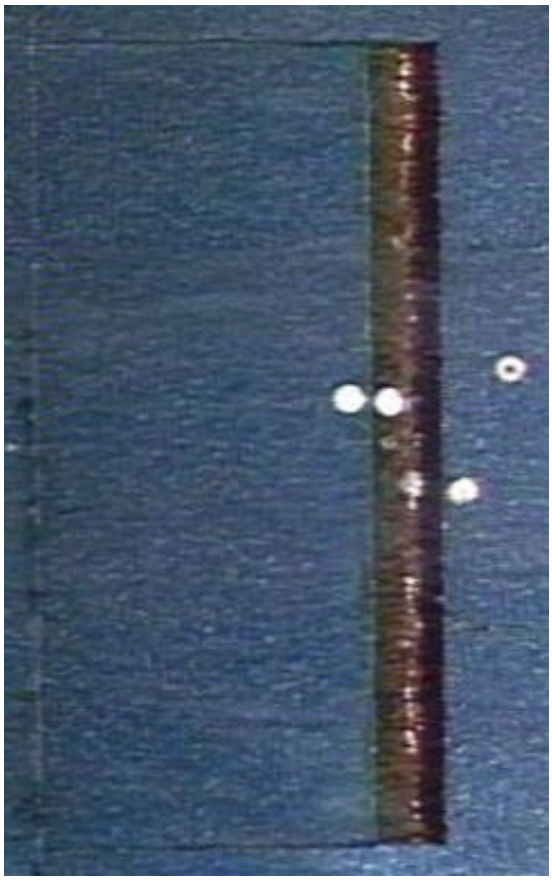


Fig. 5 Cavity at 0^0 yaw angle

Further examination of the video images between yaw angles of 0^0 and 20^0 showed little change in the flow behaviour. Throughout this range the flow in the cavity appeared as though it was normal to the downstream corner, flowing towards the upstream wall and culminating in an accumulation of crystals at the zero stress location. This would suggest that the flow in the cavity remains essentially the same as that for 0^0 yaw, giving a RSPL of similar magnitude (see Fig. 3).

At a yaw angle of 30^0, there is a noticeable change in the flow structure within the cavity and this coincides with the reduction in the RSPL (see Figs. 3 & 6). It is anticipated that the flow separates from the edges of the upstream corner and interferes with the flow in the immediate area producing some high shear stresses giving high Hue values (see Fig. 12b).

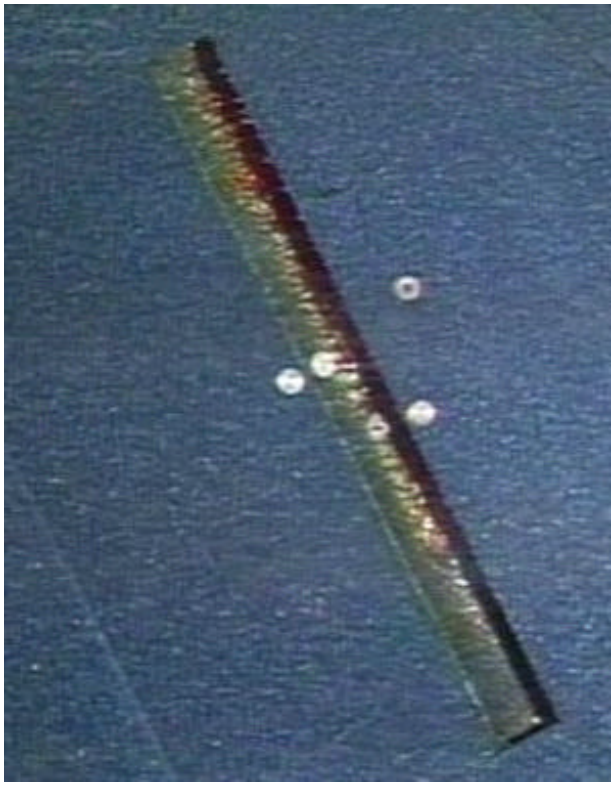


Fig. 6 Cavity at 30^0 yaw angle

Also in evidence is a green tinge of colour along the downstream wall (see Fig. 6 & 12b). This is possibly due to the separating shear layer impinging onto the downstream wall, flowing vertically downwards, and then moving away from this corner on the cavity floor towards the upstream direction. In addition, there is a reduction in the Hue value at the downstream corner progressing towards the upstream wall (see Fig. 12b). This implies that the cavity is no longer operating as a typical open type geometry but is becoming more of an open-transitional type of flow field.

This may also be supported by the changes in the dominant frequency as the cavity is yawed, Fig 7, in which the frequency of the dominant mode, as measured from the pressure transducer spectra, is shown to be approximately constant at 22.5 kHz between 0^0 and about 35^0 . Above this angle clear switching is observed suggesting that the cause for the pressure oscillations changes from an acoustic mechanism to a fluid dynamic one.

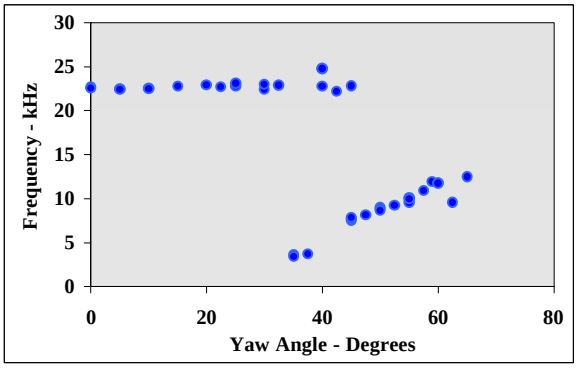


Fig. 7 Variation of dominant frequency with yaw angle

With increasing yaw angle to 45^0 the flow changes continue, with a larger area of high shear (blue colour) occurring in the upstream corner (see Fig. 8 & 12c). In the downstream corner there is a predominance of low shear (red colour).



Fig. 8 Cavity at 45^0 yaw angle

Along the downstream wall there is an overall area of green colour on the cavity floor reducing towards a lower shear (red colour) in the upstream direction. This is occurring especially near the positions where the pressure spectrum levels were measured.

This change in flow pattern perhaps indicates why the RSPL is lower in magnitude compared to an open cavity case (see Fig. 3). Here, the flow no longer simply spans the cavity but some of the separating shear layer enters the cavity, changing the oscillation mode from one of mainly acoustic to a more mixed resonance type, namely acoustic and fluid dynamic fluctuations. This argument is again supported in Fig 7 by observing that the dominant frequency at this angle corresponds to fluid mechanic behaviour and not the transverse acoustic mode.

At 60^0 the flow is now developing along the cavity in the direction of the major axis (see Fig. 9). There appears to be a larger recirculation region at the upstream end of the cavity (see Fig. 12d). However, the flow is far from easy to describe at this angle since it appears to be separated into several zones within the cavity. It should be noted that, from a study of the flow in a rectangular cavity under subsonic conditions, this angle was associated with the largest drag [10]. This drag increase appears to be due to an increase in one particular frequency of oscillation within the cavity [11]. In the present work, at the downstream end of the cavity the fluid was observed to leave the cavity as two contra-rotating vortices at the two corners. In addition, the flow along the cavity floor towards the downstream end is turned towards the upstream edge where a secondary reversed flow region develops.

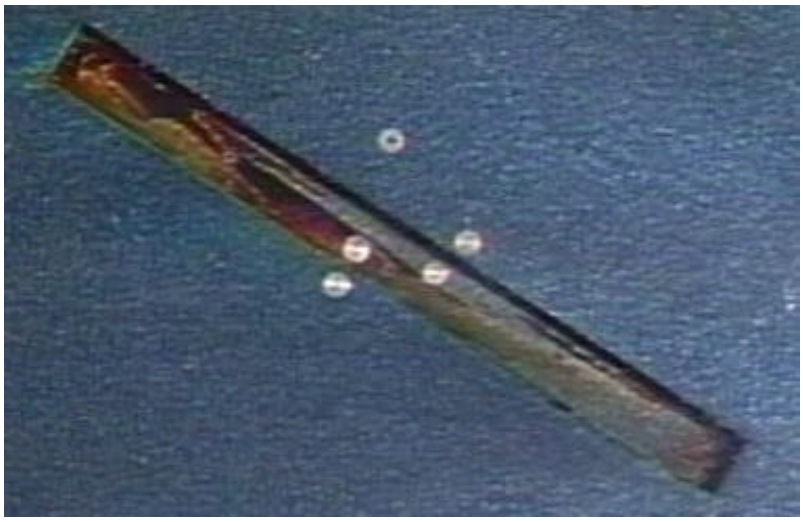


Fig. 9 Cavity at 60^0 yaw angle

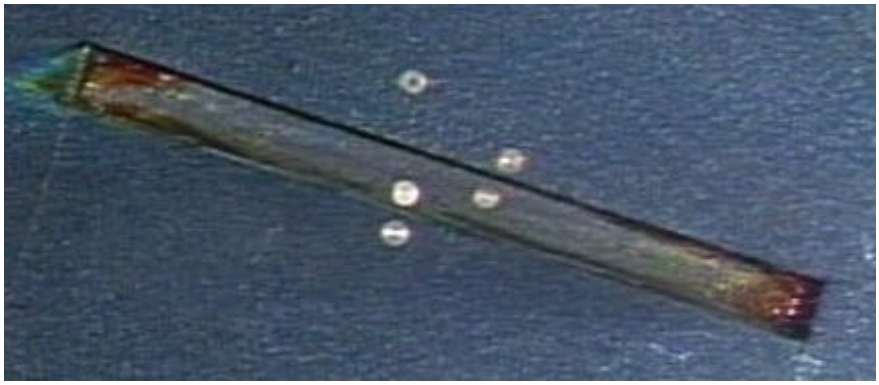


Fig. 10 Cavity at 75^0 yaw angle

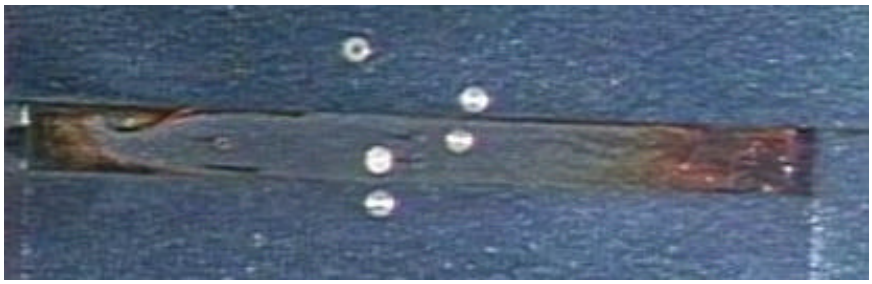


Fig. 11 Cavity at 88^0 yaw angle

As the yaw angle is changed from 60^0 to 75^0 there is only a small reduction in the RSPL and this may be explained by considering the liquid crystal images (see Fig. 3 & 10). At 75^0 the cavity is changing from a transitional-closed type to that of a typical closed cavity. Much of the flow is along the cavity floor in the direction of the major axis (see Fig. 10). Here the cavity floor boundary layer is very thin and the pressure transducers would, undoubtedly, be measuring the dynamic resonance of this thin boundary layer. This is clearly shown in Fig. 12e where a constant Hue of 0.55 (blue colour) is predominant across most of the cavity. Only in the upstream and downstream corners is there a movement of crystals at low shear. Again, two contra-rotating vortices are leaving the two downstream corners, with the flow on the floor of the cavity at this end developing as a contorted 'mushroom' shape. One half of this structure is compressed into the furthest downstream corner and the other half is being driven around towards the upstream edge of the cavity. Here, the flow continues to build and the crystals provide evidence that the fluid motion is allowed to develop as a vortex, such that fluid spirals out of the cavity at a location within L/8 of the cavity length from the downstream end. The crystals also depicts the wake area of the cavity.

The last image showing that the cavity is behaving as a closed type was taken at 88^0 rather than at 90^0, Fig 11. This angle was chosen to indicate the sensitivity of the liquid crystals to such a small angular distortion to the flow. In this case, the recirculation region at the upstream end is well-illustrated (see Fig. 12f). Along the cavity floor a thin boundary layer is developing and this passes over the locations where the RSPL was measured, thus detecting the local fluid dynamic oscillations. Throughout most of this centre region the crystals have a Hue value of approximately 0.55 and, when used in conjunction with Fig 5, this shows that the shear stress along the floor

has a value of approximately 2000 N/m^2. At the downstream end of the cavity a different picture emerges. Here, the flow is developed into a mushroom shape, with a vortical motion allowing fluid to escape from the cavity, not only at the two corners, but also at a location some L/8 along the cavity length from the downstream end (see Fig. 11). This may be further shown by observing the lines of constant Hue (see Fig. 12f). This figure shows a compact area of what appears to be a low stress region close to the upstream edge of the downstream end of the cavity.

5 Conclusions

Liquid crystals of the cholesteric type CN/R2 have been used successfully within a cavity at a freestream Mach number of 2. Since the surface flow field within the cavity was not always in one particular direction the incident lighting angles varied throughout. Due to this variation in lighting and viewing angles the shear stress was not determined for all angles. However, it was found that the shear stress in the cavity for the 90^0 case (closed) was more than 10 times greater than that for 0^0 yaw (open). The results for the visualisation of the crystals within the cavity have been plotted as lines of constant Hue (colour), with the highest shear stress areas having the highest value in Hue (blue), and the lower stress areas shown by the lower values in Hue (red). These lines of constant Hue, together with the colour images, provide an explanation for the change in the measured pressure spectrum level as the cavity is yawed.

It is shown that as the cavity is yawed from 0^0 to 30^0 the flow regime changes from an open to an open-transitional case. Furthermore, as the cavity is yawed from 45^0 through 60^0 and onto 90^0, the flow undergoes further changes from the transitional-closed to the closed condition. In the open condition the spectrum responds more to the acoustic resonance whereas, in the closed case, the spectrum responds to the oscillations due to the fluid dynamics within the shear layer on the floor of the cavity.

At the large angles of yaw, there is a great deal of fluid motion at the downstream end of the cavity, with an asymmetrical ‘mushroom’ structure being observed. This allows fluid to be entrained within a vortical flow regime and provides an escape route for the excess fluid that has been brought into the cavity due to its closed condition. In addition, a strong wake area develops at the downstream end of the cavity from a yaw angle of about 60^0 through to its closed condition of 90^0. Fluid was also observed to leave the corners of the downstream end of the cavity as two contra-rotating vortices.

Since the pressure transducers were only located near the centre-line of the cavity model no information concerning the spectrum is available near the two ends. Further experimental results are needed in order to fully understand the complex flows that occur within a cavity at a supersonic speed of Mach 2. However, liquid crystals have successfully indicated the likely flow scenario and further work on cavities with different aspect ratios is being carried out.

5 Acknowledgements

Many thanks are due to Mr R G DiMicco and Mr C Fox for their help and enthusiasm throughout the testing programme, as well as to Hallcrest for the use of their crystals.

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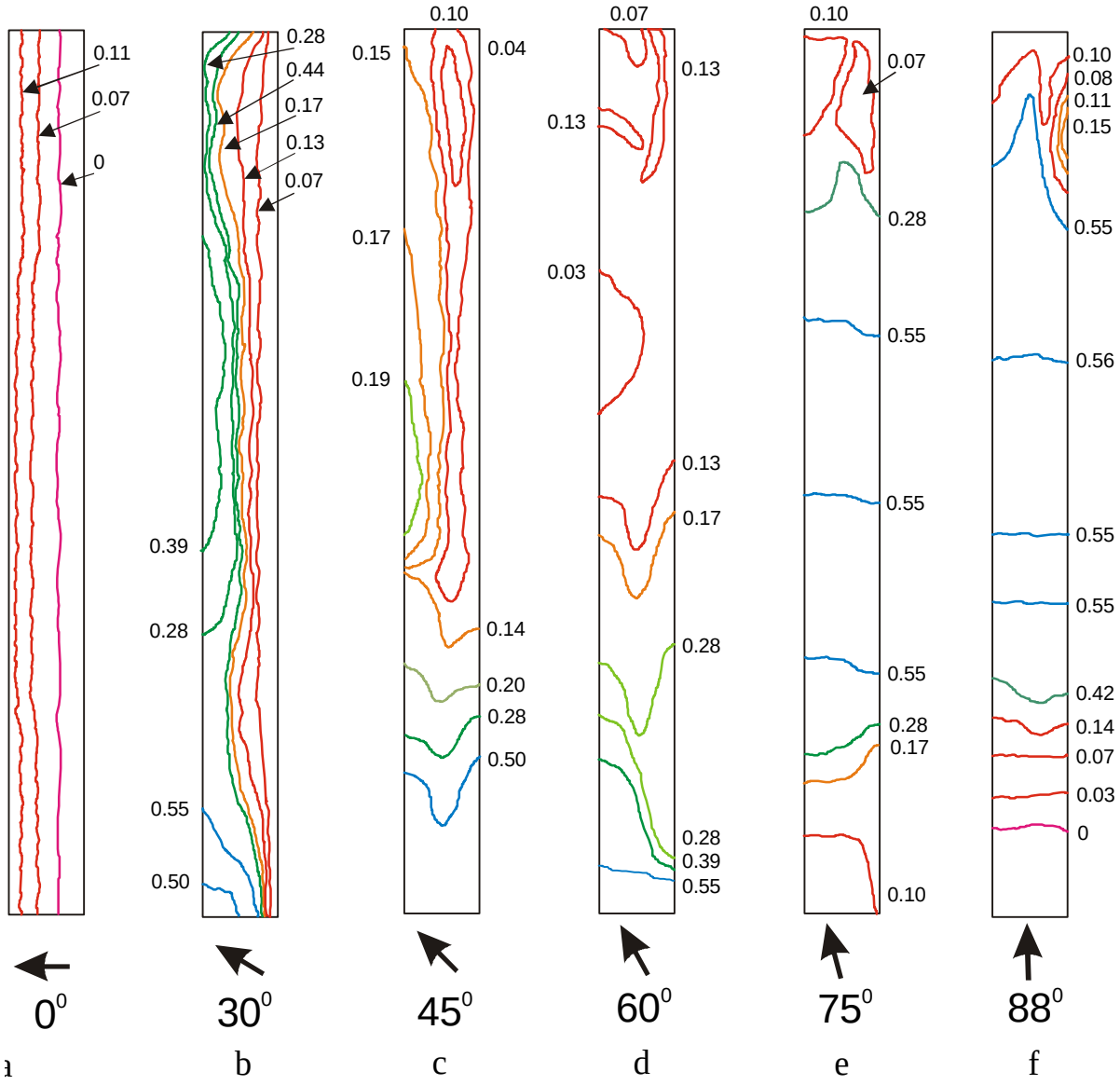


Fig. 12 Variation in the Hue in the cavity for different yaw angles