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Asymmetric Flow about a Chevron-Shaped Cavity

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Abstract

This paper discusses the identification of asymmetric flow about a chevron-shaped cavity. The depth-based Reynolds number was 8,300-10,700 and the effective length-to-depth ratio was varied in the range 1–5. The span-to-depth ratio was two. The upstream boundary layer was laminar. Given the symmetrical nature of the geometry, the asymmetric flow pattern was unexpected. The flow was investigated using hydrogen bubble visualisation and particle image velocimetry (PIV). The pattern is attributed to a net in-flow and out-flow of fluid about either side of the longitudinal centreline of the cavity.

Introduction

Geometric cavities in flat plates are defined as a backwards-facing-step followed by a forward-facing-step. Such flows are characterised by a periodic roll up of the shear layer over the cavity opening. The vortex rollup frequencies may correspond to "Rossiter" modes–due to an aeroacoustic feedback loop between the leading and trailing edges–within a certain range of non-dimensional cavity length [1, 2]. A schematic diagram of three-dimensional cavity flow *for the present chevron geometry*, including the coordinate system used in the present paper, is given in Figure 1.

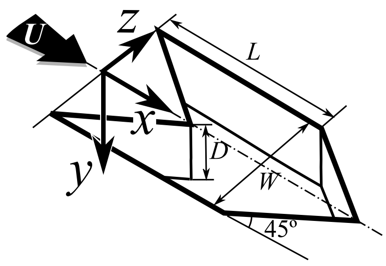


Figure 1: Schematic diagram of chevron cavity configuration, with flow from top-left to bottom-right. The cavity is located in a flat plate (not drawn). L represents the effective length such that L/D is the effective length-to-depth ratio, W is the span of the cavity, while D is the cavity depth. U represents the freestream velocity.

Whilst there is an abundance of literature regarding two-dimensional cavity flows, the literature regarding three-dimensional cavity flows at low-Reynolds-number was relatively limited until the recent publication by Crook, Lau, and Kelso [3] of a detailed investigation on the flow structure about a rectangular three-dimensional cavity at low-Reynolds-number. Crook, Lau and Kelso [3] found that in three-dimensional cavity flows a number of additional flow structures gain importance compared to the two-dimensional case. It was found by Crook [4] that three-dimensional (finite span), narrow (span less than streamwise length) cavities can be subject to a flow asymmetry which was attributed to a twisting mode of the shear layer.

The original motivation behind the present study was the investigation of passive cavity flow noise mitigation techniques. One such technique is modification of the cavity geometry. One of the modified geometries was a 'chevron-like' geometry. Unexpectedly, it was found that, within a certain range of L/D, the flow over this cavity was asymmetric. Therefore, this cavity configuration is investigated further in this paper. This flow pattern is attributed to a net in-flow on one side of the cavity and a net out-flow on the other.

It appears that the shear layer twists such that the in-flow of fluid on one lateral half of the cavity is balanced by the out-flow of fluid at the other lateral half of the cavity. This out-flow thereby forms a wake-like structure, which contains periodic vortex shedding. Conversely on the in-flow side of the cavity the usual vortex roll-up is suppressed due to the 'strong' flow of high velocity fluid into the cavity.

Experimental Method

Experiments were conducted in a recirculating water channel using a flat-plate model containing a three-dimensional cavity cut-out. The span of the plate was 0.5 m, while the developmental length of the boundary layer between the elliptical leading edge and the leading edge of the cavity was 0.334 mm. The working section of the water tunnel has dimensions 0.5×0.5 m. The depth of the cavity was $D = 75$ mm, with length in the range $L/D = 1-5$, and span $W/D = 2$. The chevron cavity configuration, which is symmetric, consists of a chevron-shaped front wall with a double-swept rear wall. This creates a cavity with effectively the same length-to-depth ratio all the way across, but with a sweep angle of 45° applied to each half.

Hydrogen bubble visualisation

Hydrogen bubble visualisation was conducted using energised tungsten wires to visualise the flow structures about the cavity. Two orientations of the tungsten bubble-wires were used: vertical and horizontal. The vertical wire was fixed to a movable support with the vertical wire held between two short horizontal prongs fixed to rigid vertical tube. The horizontal wire, on the other hand, was fixed at a height of 4mm above the flat plate surface (y/D=0.125), and positioned 31mm upstream of the cavity leading edge (x/D=-0.42). The wire height of 4 mm compares to an estimated (laminar) boundary layer momentum thickness of 1.1 mm, and δ_{99} boundary layer thickness of 8.1 mm ($\delta_{99}/D = 0.11$), from Blasius theory, for the primary freestream testing velocity of 144 mm/s. The spanwise width of the horizontal wire was significantly wider than the span of the cavity.

Disadvantages of the hydrogen bubble technique include the buoyancy effect of the bubbles, and the need to achieve suitable lighting so that the bubbles can be observed clearly. This has necessitated the use of an oblique camera angle in most cases.

Particle image velocimetry

Particle image velocimetry (PIV) was conducted in a plane parallel to the flat plate, in an attempt to measure shear layer structure. A Nd:YAG twin laser was used. Image pairs were captured at a rate of 2.5 Hz. The images were triple-pass processed using a window resolution of 128 x 128 pixels with 50% overlap, and the Hart [5] multiplication technique was used. The worst-case total error in the PIV measurements was estimated to be approximately 10%.

Results and Discussion

Flow over the chevron-shaped cavity configuration was found, unexpectedly, to produce an asymmetric flow pattern, as shown in figure 2. This pattern was found to exist across a range of Reynolds numbers, and with increasing L/D was found to come into existence from a symmetric pattern before losing the asymmetry as L/D was increased further. The most pronounced asymmetric behaviour was identified within an effective L/D range of 2 to 3.84. It is believed the pattern can be attributed to a net inflow of fluid on one-side of the cavity, balanced by a net outflow of fluid from the other.

The asymmetry would occasionally have an opposite direction of preference which suggests that it *cannot* be solely explained by some bias in the water tunnel or experimental model. Figure 2(a) shows one direction of preference, while figure 2(b) shows the other. Unfortunately the changeover itself was not observed. Occasionally, the flow pattern changed preference upon stopping and restarting the water tunnel flow.

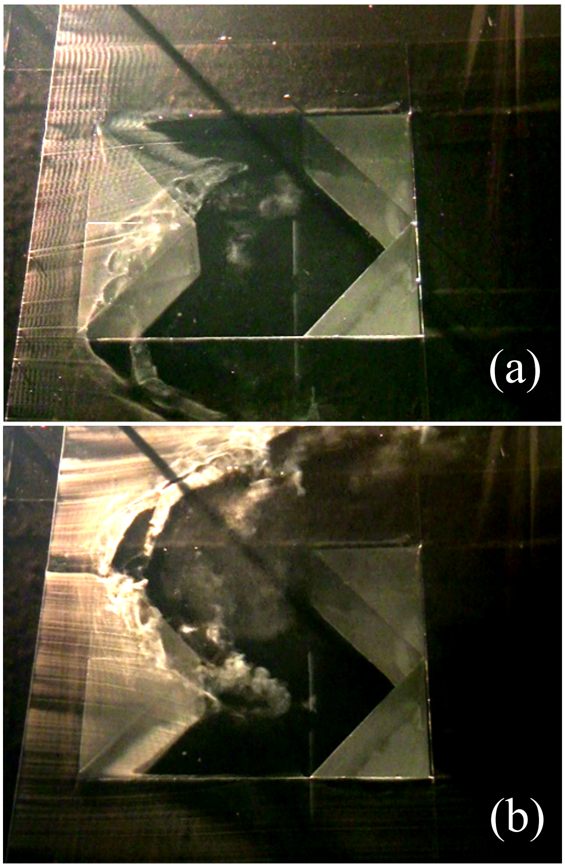
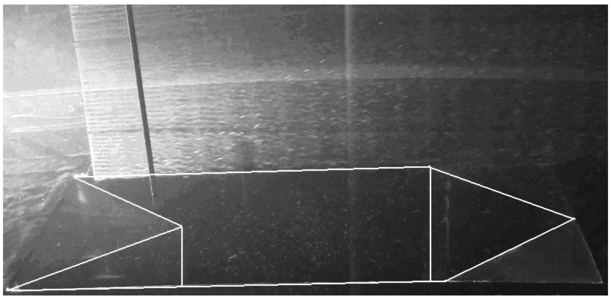


Figure 2: Flow patterns produced by flow over "chevron"-cavity: (a) first pattern, and (b) second pattern. $U = 111$ mm/s, $Re_D = 8,250$ and $L/D = 2$. Flow from left to right.

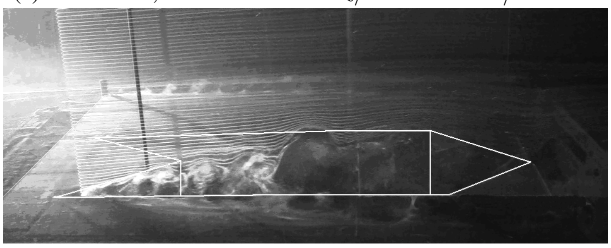
With regards to the period of the asymmetry, in the present experiment it could not be determined. With regards to the period of a different asymmetry over a shallow, narrow, *rectangular* cavity, Crook, Lau, and Kelso (2013) state "this process, which may be periodic or random, is postulated to occur on time scales which are much larger than the sampling times of the current experiment..." The sampling times of their experiment were of the order of minutes for each imaging region (Crook, 2011, p. 72).

The proposed explanation for the asymmetry in the present case is that flow is entering the cavity on one side, which is thereby balanced by an outwards flow on the other side. On the outflow side of the cavity, a wake-like pattern appears to form, as low momentum fluid flows out of the cavity and interacts with the freestream flow. Around the outflow side of the cavity, there is a standing vortex and other vortices owing to the wake. Conversely on the other side where the fluid preferentially flows into the cavity, the flow is very smooth. It appears that the high momentum flow into the cavity suppresses the usual shear layer instabilities, on that side of the cavity.

Comparing figure 3(a) to figure 3(b), it can be seen that the flow pattern on the inflow side of the cavity is dramatically different to that of the outflow side. Therefore on the inflow side of the cavity, smooth streaklines are observed, which are deflected downwards into the cavity slightly. For an equivalent location of the vertical bubble wire on the outflow side of the cavity, the streaklines are clearly deflected upwards with the presence of multiple vortices both about the shear layer and over the side plate next to the cavity.



(a) Inflow side, vert. wire location $z/D = -0.9$ & $x/D = 0.1$.

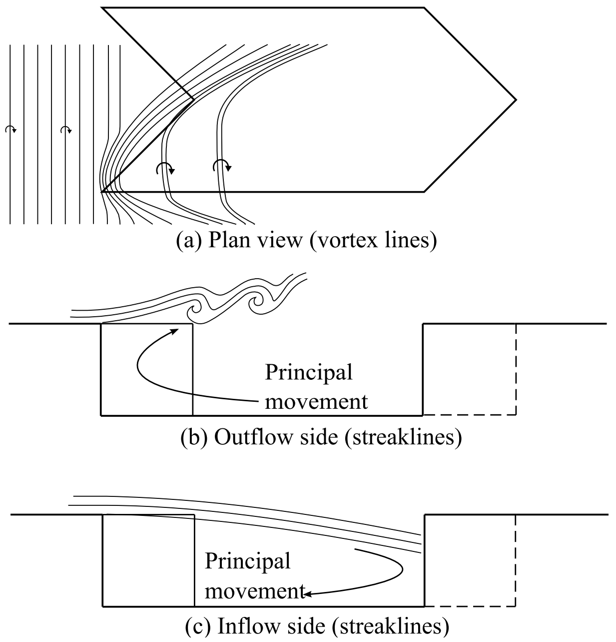


(b) Outflow side, vertical wire location $z/D = 0.9$ & $x/D = 0.1$.

Figure 3: Hydrogen bubble patterns produced by vertical wire within chevron-shaped cavity at $L/D = 2.84$ and $Re_D = 10,700$. The white outlines represent the top edges of the cavity. Flow is from left to right. Location of the vertical bubble wire is indicated in the caption. (a) Vertical wire on the inflow side. (b) Vertical wire on the outflow side.

In figure 3(b), the flow upwards from the "outflow" side of the cavity can be seen. There are multiple vortices clearly visible in the shear layer, which convect downstream with the flow. The spanwise structure of these vortices can be more clearly seen in figures 2. Interestingly these vortices extend beyond the side edge of the cavity, and are also present above the side plate. Around the front of the shed vortices, a standing vortex can be seen. This is most evident in figures **??** & **??**. This vortex is mostly located over the side-plate and above the chevron front wall insert, rather than being located over the cavity itself.

Figure 4 shows sketches of the fluid movement about the chevron-shaped cavity based on the observations described above. Part (a) shows a preliminary vortex line model. Around



(a) Plan view (vortex lines)
(b) Outflow side (streaklines)
(c) Inflow side (streaklines)

Figure 4: Sketch of flow patterns about the chevron-shaped cavity. Flow from left to right.

the front of the region of outflow there is a standing vortex. In part (a), the outflow side of the cavity is shown in the lower half of the sketch. Part (b) shows streaklines which indicate the shear layer vortices on the outflow side of the cavity. Part (c) shows streaklines which indicate the smooth movement of fluid on the inflow side of the cavity.

With respect to the shear layer, the asymmetric behaviour in figure 4 can be explained by a twisting mode of the shear layer. The shear layer twists such that high-momentum free-stream fluid preferentially flows into the inflow "half" of the cavity. This inflow is balanced by an outwards flow of low-momentum fluid on the alternate side, which therefore forms a wake in cross-flow like structure. The period of this twisting mode is unknown.

Varying effective *L/D*

The effect of the length-to-depth ratio was investigated by varying L/D in the range 1 through 5. The depth-based Reynolds number was 10,700.

The asymmetric flow pattern was found to occur over a specific range of length-to-depth ratio. Figure 5(a) shows that at $L/D = 1$, the flow pattern is symmetrical. When L/D is increased to 2, a strongly asymmetric pattern develops which can be seen in figure 5(b). In that instance, the outflow side appears on the far-side (top) of the picture. When L/D is increased further 2.84, the asymmetric flow pattern is still found. In the instance of figure 5(c) the asymmetry has switched to the other side, but this is not related to the L/D ratio in itself. As the L/D is increased further to 3.84, an asymmetric pattern is still found. *However*, when L/D is increased again to five [figure 5(e)], it can be observed that the *strongly* asymmetric pattern is no longer evident. Instead, while the pattern is still slightly asymmetric, it is quite a different pattern to that observed in the range $L/D = 2$–3.84, and the pattern is much closer to symmetrical.

Particle image velocimetry

The results of flow measurements taken in a plane parallel to the flat plate, over the chevron-shaped cavity are now presented. For $z/D < 0$, there is a region where the flow diverges from parallel downstream of the leading edge of the cavity.

Figure 6 shows the streamlines calculated from time-average velocity vectors over the chevron shaped cavity with effective $L/D = 2$ for $Re_D = 10,700$ ($U = 144$ mm/s) at $z/D \approx -0.35$ (above the flat plate). It can be observed that the flow upstream of the cavity is quite uniform in direction. On the negative Z region of the cavity (from the given viewpoint), the flow pattern indicates the emergence of fluid out-of-the-page from within the cavity. The divergence of the free stream fluid around this structure can be seen clearly.

Figure 7 shows the velocity magnitude over the chevron-shaped cavity. There is a large low velocity region on only one side of the cavity corresponding to the outflow region where vortex shedding occurs.

Figure 8 shows the time-average vorticity field about the y-axis (out-of-page). From the bottom to the top of the figure, a region of counter-clockwise vorticity is found between z/D=-1.5 and -0.7. Conversely a region of clockwise vorticity is found between z/D=-0.7 and 0. This is consistent with the existence of a wake-like structure that forms due to the interaction between the freestream and the slow-moving fluid on the outflow side of the cavity. Erroneous vorticity is found near the top of the figure $z/D > 0.5$ which is due to reflection of light from the flat plate and edge of the cavity.

Conclusions

The present 'chevron' cavity geometry (at the given Reynolds range, and within a certain range of L/D) appears to induce a twisting mode of the shear layer. This twisting mode causes high-momentum free-stream fluid to preferentially flow into one lateral half of the cavity. This is balanced by an outwards flow on the other side, which forms a wake in cross-flow like structure.

Acknowledgements

Helpful discussions with Dr. P. V. Lanspeary are greatly appreciated.

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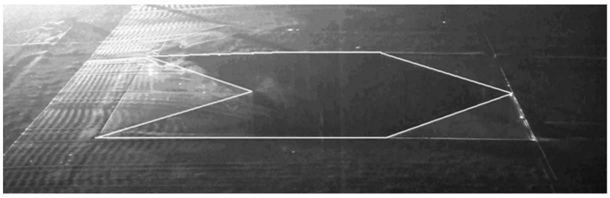
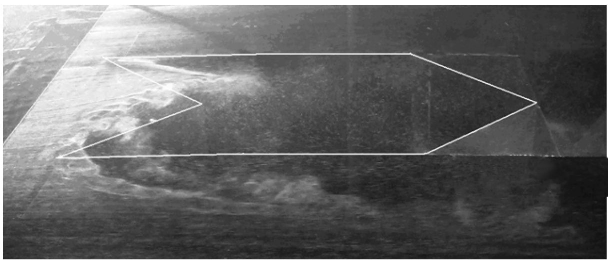
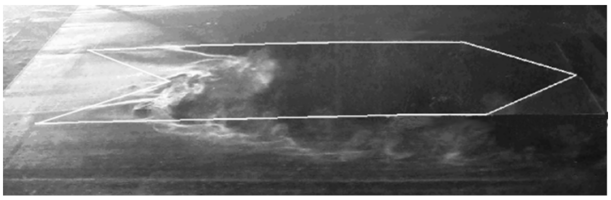
(a) $L/D = 1$



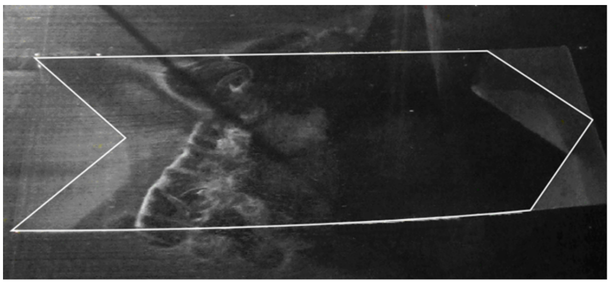
(b) $L/D = 2$



(c) $L/D = 2.84$



(d) $L/D = 3.84$



(e) $L/D = 5$

Figure 5: Hydrogen bubble flow pattern produced by the chevron-shaped-cavity for different effective L/D ratios. Flow from left to right. Depth-based Reynolds number of 10,700. The white outline represents the top edge of the cavity.

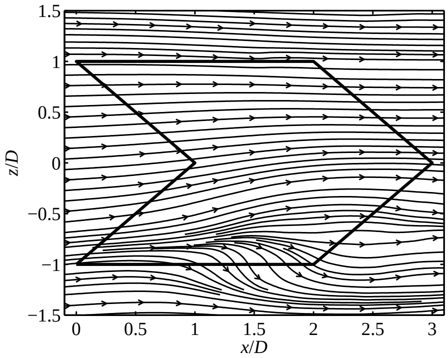


Figure 6: Streamlines calculated from time-average velocity vectors over the chevron shaped cavity with effective $L/D = 2$. The depth-based Reynolds number was 10,700. Flow from left to right. This is a top-down view. The height of the sheet was 26mm (is this correct) giving $y/D = -0.35$ (i.e., above the flat plate).

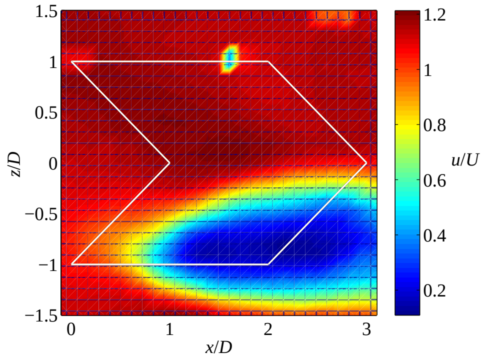


Figure 7: Mean velocity magnitude calculated from time-average velocity vectors over the chevron shaped cavity with effective $L/D = 2$. The depth-based Reynolds number was 10,700. Flow from left to right. This is a top-down view. The height of the sheet was $y/D = -0.35$ (i.e., above the flat plate).

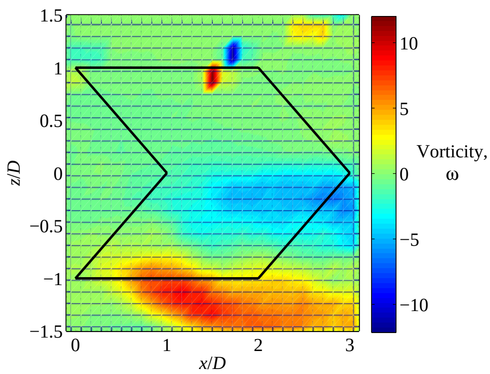


Figure 8: Time-average vorticity over the chevron shaped cavity with effective $L/D = 2$. The depth-based Reynolds number was 10,700. Flow from left to right. This is a top-down view. The height of the sheet was $y/D = -0.35$ (i.e., above the flat plate).