Investigation of Flow Past a Cavity using PLIF and MCCDPIV

P. Manovski, D. R. Honnery, J. Soria

Laboratory for Turbulent Research in Aerospace & Combustion, Mechanical Engineering, Monash University, VIC 3800, AUSTRALIA
pmanovski@gmail.com

ABSTRACT

A fundamental study of laminar flow over a two-dimensional rectangular cross section cavity is presented. To further understand the complex flow system an experimental investigation was performed in a small water tunnel. The cavity length (b) was varied, while the cavity depth (d) was kept constant at 10mm. The range of Reynolds numbers (Re) investigated was 90-730. Planar laser induced fluorescence (PLIF) was employed as a flow visualisation method. Pathline flow visualisation using laser sheet illumination of seed particles followed. These two flow visualisation techniques allowed the flow to be characterised into three regimes, after which particle image velocimetry (PIV) provided quantitative measurements of the complex instantaneous and mean velocity flow fields, revealing patterns of velocity, vorticity and streamline topology. Furthermore, only a limited number of cavity flow PIV measurements exist. Geveci et al. [2] performed the first study to provide instantaneous global representations of flow-acoustic coupling in a cavity using PIV. Experiments were completed in a pipeline axisymmetric cavity system, with air as the working fluid. The unsteady flow structure due to a turbulent boundary layer past a rectangular cavity was characterised by Lin & Rockwell [3] using PIV in a large open water tunnel. Patterns of organised small- and large-scale vortical structures were observed. The large scale vortices also induced ordered pressure fluctuations; their magnitude and phase shift were determined using simultaneous imaging and pressure measurements. Both of these investigations employed turbulent inflow conditions, at relatively high Re. Whereas, this study employs laminar inflow conditions, at a much lower Reynolds numbers.

1. INTRODUCTION

The most interesting aspect of cavity flow is the initiation of self-sustained oscillations of the cavity shear layer between the freestream flow and the cavity fluid. These oscillations can cause acoustic waves (noise), increased drag and structural vibrations in many internal and external flows. Flow past a cavity has a wide range of applications, from the aeronautical to the nautical field. Much attention has been given to high speed cavity flow aeronautical applications, with less attention given to the low speed case, such as automobile and marine applications. In order to explain the behaviour of the fluid motion in these systems, there is a need for research on low speed flow past cavities. The aim of this study is to experimentally characterise low Reynolds number (Re) laminar flow over a two-dimensional rectangular cross section cavity (Fig. 1) using both qualitative and quantitative methods.

The primary focus of this experimental study is the self-sustained oscillations of cavity shear layers. Rockwell and Naudascher [1] categorised cavity flow oscillations into three groups. The most relevant here is fluid dynamic oscillations, which arise from inherent instability of the flow, refer to schematic diagram Fig 1. The primary mechanism for excitation is the amplification of unstable disturbances in the cavity shear layer, with oscillations strongly enhanced by the presence of the downstream edge of the cavity creating an effective feedback system. This feedback condition is essentially the upstream propagation of disturbances, enhanced by the presence of the downstream cavity edge. The pressure perturbations emanating from the downstream cavity edge produce vorticity fluctuations near the sensitive shear layer origin, which result in disturbances to be amplified within the shear layer.

The available experimental data on cavity flows consists principally of pointwise instantaneous measurements and mean flow field measurements of pressure and/or velocity, as well as qualitative flow visualisation using dye or smoke. Unlike point-wise measurements a non-intrusive optical velocity measurement technique such as Particle Image Velocimetry (PIV) can yield whole field quantitative measurements of the complex instantaneous and mean velocity flow fields, revealing patterns of velocity, vorticity and streamline topology. Furthermore, only a limited number of cavity flow PIV measurements exist. Geveci et al. [2] performed the first study to provide instantaneous global representations of flow-acoustic coupling in a cavity using PIV. Experiments were completed in a pipeline axis-symmetric cavity system, with air as the working fluid. The unsteady flow structure due to a turbulent boundary layer past a rectangular cavity was characterised by Lin & Rockwell [3] using PIV in a large open water tunnel. Patterns of organised small- and large-scale vortical structures were observed. The large scale vortices also induced ordered pressure fluctuations; their magnitude and phase shift were determined using simultaneous imaging and pressure measurements. Both of these investigations employed turbulent inflow conditions, at relatively high Re. Whereas, this study employs laminar inflow conditions, at a much lower Reynolds numbers.

2. EXPERIMENTAL FACILITY & METHODOLOGY

2.1 Experimental facility

The aims and objectives of this study were met by conducting a series of cavity flow experiments in a small water tunnel facility with a small test section 100x100x800mm². The side and bottom walls are made of 6mm thick glass for imaging, and the top is 12mm thick Perspex. Rails on both sides of the test section, and an optical table below, allow easy mounting of optical components for flow visualization. A gate valve and meter allow the flow rate to be adjusted. The cavity is formed by two Perspex plates that are situated on the tunnel bottom in the main working section of the water tunnel. The length of the cavity (b) can be adjusted up to a maximum value of 100mm by keeping the upstream plate fixed and adjusting the downstream plate. The depth of the cavity (d) is maintained constant at 10mm. The span-to-depth ratio is 10 thus the flow will be considered nominally two dimensional. The overall configuration and dimensions of the two plates that form the cavity can be seen in Fig 2. To visualise the free shear layer, a dye hole was positioned 1mm from the leading edge of the cavity. To capture the recirculation region, another dye hole was located on the cavity wall, centred 3.5mm from the cavity bottom.

![Figure 1. Rectangular cavity configuration](image1)

![Figure 2. Cavity test section dimensions (mm)](image2)
2.2 Flow Visualisation

Planar laser induced fluorescence (PLIF) was the first technique used for qualitative flow visualisation. Sulforhodamine B (Exciton Kiton Red 620 with absorption and emission peak 580-590nm when pumped at 532nm) dye was used as the fluorescing medium. For a variety of flow speeds, the flow structure was investigated for different cavity lengths. The cavity length-to-depth ratio (b/d) was varied from 3 to 10. The following Reₐ based on cavity depth and mean free stream velocity were investigated 90, 180, 280, 370, 460, 550, 640, and 730.

For the PLIF experiments video recording was taken using a Pulnix camera, connected to a desktop computer with image acquisition software. The Pulnix camera uses standard PAL format frame rate; 25 frames per second with a frame size 768 x 576 pixels. The camera is mounted on a three degree of freedom system and a micrometer. A Computar 55mm Telecentric lens was used. To remove scattered and reflected light a red filter was attached to the end of the lens. A continuous Nd:YVO₄ diode pumped solid laser was used, with a power output of 200mW at 532nm and was mounted below the water tunnel. The laser sheet is generated by passing the laser beam through a cylindrical Perspex rod (5mm diameter), this allows divergence of the beam, it is then reflected 90° upwards to the cavity via a 45° orientated mirror.

PLIF is a form of dye flow visualisation which in turn has its own limitations. In steady flow the dye follows the pathlines in the flow to form streaklines from the point of injection. In an unsteady flow the streaklines do not necessarily coincide with the instantaneous streamlines. The transport mechanisms for dye (a passive scalar) and vorticity are slightly different especially in regions of the flow where vortices are substantially stretched. When interpreting the flow visualisation results caution must be exercised to ensure that the streaklines give an accurate representation of the flow. The over-riding advantage of this method is that it can provide the large-scale nature of the flow.

The second flow technique used was pathline flow visualisation using laser sheet illumination. A pathline, or displacement of a particle, is defined by integration of its velocity components. A pathline can be found by a time exposure of single marked particle moving through the flow. The flow was seeded with 11-µm Potter’s hollow glass spheres (specific gravity 1.1±0.02 & particle relaxation time of ~7-µm). The pathline flow visualisation images were obtained by adjusting the exposure time (dt) between successive double exposures images, using a camera control program on a Real Time Linux computer. Cavity lengths investigated were 40mm and 50mm (b/d = 4 & 5). For the pathline flow visualisation and the PIV measurements, a PCO Sensicam camera (1,280 x 1,024 pixel²) coupled to a PC, with image acquisition and timing software was used to acquire pairs of images. A 55-mm Micro Nikkor lens is used for imaging of a capture area (3.024 x 5.22d).

2.4 MCCDPIV

For the PIV measurements the 2D flow plane of interest was illuminated with a Quanta Physics Nd: YAG laser, with a 6ns pulse width. The mass of particles (11-µm Potter’s hollow glass spheres) added to the water tunnel was determined assuming uniform particle mixing and the presence of 5-10 particles in each Interrogation Window (IW). The time interval (Δt) between laser pulses ranged between 1.5-2.5ms, and was based on an average freestream velocity of 74mm/s and a requirement that the maximum displacement of particles had to be less than 25% of the IW size. A Multigrid cross-correlation digital particle image velocimetry (MCCDPIV) algorithm was used in the analysis and was developed in house by Soria [4]. Details of the performance, accuracy and uncertainty of the MCCDPIV algorithm are given in Soria [5].

The PIV measurements present a challenge, because of two dissimilar flow speeds present in the flow system creating a velocity gradient which defines the cavity shear layer between the faster freestream flow and the slower recirculating flow. The underlying assumption in PIV is that all particles within the IWs have a uniform displacement between the laser pulses. Furthermore, the algorithm has no method for handling the motion of particles between IWs. Thus a source of error is the movement of particles in and out of the interrogation window between the laser pulses. It is highly likely that the flow exhibits some 3D behaviour this would mean that particles would move into out of the laser sheet plan thus providing some erroneous data. Data is therefore passed through a filtration and validation process.

3. EXPERIMENTAL RESULTS & DISCUSSION

The PLIF experiments revealed the typical cavity flow structure of the cavity shear layer and recirculation region. The flow was characterised according to the distinct flow structures present. Three distinct regimes were witnessed, namely; regime (1) no oscillations; regime (2) regular oscillations; and regime (3) irregular oscillations. The flow patterns observed for each regime are described in the following sections.

3.1 No Oscillations (Regime 1)

For Reₐ = 90 it was found for all the cavity lengths investigated no oscillation were present, thus defining regime (1). In these cases the shear layer is flat over the cavity, with a large recirculation region encompassing the entire cavity, as shown in Fig. 3.

![Image](image341x294to510x355.png)

**Figure 3.** PLIF image for no oscillations, b/d = 4.0, Reₐ = 90, flow is from left to right in all images.

3.2 Regular Oscillations (Regime 2)

Regime (2) or regular oscillations of the shear layer are characterised by the presence of distinct disturbance waves. These are shed from the cavity leading edge at regular intervals, appearing similar in size (amplitude) and structure. The PLIF flow visualisation recordings for Reₐ of 180, 280, 370 and 460, and for all cavity lengths show regular oscillations of the cavity shear layer. The amplitude of disturbance waves appeared to grow slightly as the cavity length is increased. A typical instantaneous PLIF image of this behaviour is shown in Fig. 4, for Reₐ = 460, and b/d =3, we observe a disturbance wave shed from the cavity leading edge, while another has propagated further downstream just past the mid point of the cavity, a third disturbance further downstream has impinged on the downstream cavity edge and as a result has been severed. Furthermore, on the bottom of the cavity in Fig. 4, subsequent roll up of severed portions of the dye can be seen migrating upstream. When a disturbance wave passes the
downstream edge, a portion of the structure is clipped. This process adds energy to the recirculating region (cavity vortex). This system appears to sustain the regular oscillations of regime (2) for long periods providing that severing of only the trailing portion of the disturbance occurs.

Figure 4. PLIF instantaneous image showing regular oscillations, for b/d = 3, Reₐ = 460.

The pathline flow visualisation gave a much clearer picture of the global flow structures in the complex flow system as seen in the images in Fig. 5. The laser lines distinguish the cavity edges. The Re of the flow and exposure time (dt) is shown on each image.

Figure 5. Pathline flow visualisation sequence.

Common to all pathline images is the faster freestream flow distinguished by the lighter longer pathlines compared to the slower recirculation regions with smaller pathlines. Mixing of particles between the recirculation region and the cavity shear layer is observed. Regular oscillations from the pathline flow visualisation study for both b/d ratios investigated (4.0 & 5.0) show distinct vortical structures, and propagation of these in the sequential images. Figure 5, for Reₐ = 280, typically highlights the flow patterns found in this regime. The sinusoidal, wave nature of the cavity shear layer is observed by the outer rim of the two vortex pairs seen in the images. A notable feature of these images compared to lower Re cases, is the increased width in the lateral direction of the vortices, relating to the increased amplitude of the cavity shear layer disturbances as the Re is increased. In Fig. 5 (a) we see a single large vortex near downstream cavity edge, with another near the upstream edge at a considerable lower speed (smaller pathlines); at a time 0.5s later in (b) we see the same vortex near downstream corner is evident, furthermore a larger vortex has now formed from the leading edge; in (c) we see the two vortices combining into a single large vortex enclosing the entire cavity.

3.3 Irregular Oscillations (Regime 3)
Regime (3) is defined as irregular oscillatory behaviour, it is characterised by non-periodic shedding of different amplitude disturbance waves, flapping of the shear layer and chaotic recirculation regions. It was found that for 550, 640, and 730 and for all cavity lengths oscillations of the cavity shear layer were of this form. Regular oscillations do appear at times but predominantly irregular oscillations, with much greater amplitude variation than regime (2). Figure 6, highlights the intermittent amplitude behaviour of regime (3) with a PLIF flow sequence for Reₐ = 642, b/d = 4.0, with 0.5 seconds between each image; in (a) we see a large amplitude wave ‘escaping’ unimpinged followed by a flat shear layer in successive images (b) to (e); in (f) a portion of shear layer has been swept into the downstream corner vortex; this seems to be the instigator of increased growth of disturbances (g) to (h). The flat shear layer behaviour is a result of destructive interference between the feedback mechanism and the free shear layer shedding characteristics. Furthermore we observed, the propagation rate of shear layer disturbances increased as the flow rate was increased, suggesting that the Re is proportional to the frequency of oscillations.

Figure 6. PLIF flow sequence of irregular oscillations for Reₐ = 640, b/d = 4, 0.5s between images.

Chaotic recirculation regions were observed in the pathline visualisation, a typical image is presented in Fig. 7, for Reₐ = 640, b/d = 5.0 and an exposure time of 250ms. The flow structure inside the cavity is much more chaotic. Single organised vortical structures are not evident, instead smaller vortices. The most distinct vortex is located near downstream cavity edge.

Figure 7. Pathline image of irregular oscillations for Reₐ = 640 and b/d = 5.

By increasing the flow rate, a further instability is introduced. As a result of the instability some disturbances are amplified more than others. The variation of amplitude of the disturbances is due to selective amplification characteristics of free shear layer flow and the additional feedback condition
present in cavity flow. For a constant Re, the amplitude of waves was found to increase as the cavity length was increased. This is due to the growth of disturbance waves as they propagate downstream, and consequently complete impingement (of disturbances) is observed, resulting in an enhanced feedback and consequently larger oscillations.

The typical flow patterns observed from the flow visualisation study of the irregular oscillation regime (3) can be interpreted as follows: The shear layer rolls up and disturbances grow larger as they propagate downstream. If the severing of the disturbance wave at the trailing edge begins to capture excessive fluid it affects the feedback system which drives the oscillations. A critical amplitude of oscillation is reached when the feedback is disrupted enough to cancel the oscillations and consequently a flat shear layer is observed, this was also noted by Neary [6] for greater Re. Otherwise, sufficient cavity fluid motion destroys the shear layer organisation and causes the shear layer to oscillate with an irregular pattern. The large mass transfer rate of fluid in and out of the cavity coupled with increased instability of the shear layer at this higher Re prevents the start of more regular shear layer roll up and vortex shedding. A return to more organised or regular shear layer oscillations is observed when the fluid motion in the cavity begins to move in phase with the shear layer oscillations of the system.

![Figure 8. Comparative interpretation; (a) PLIF flow visualisation; (b) MCCDPIV streamline topology; (c) Pathline flow visualisation, b/d = 5.0, Re = 550.](image)

3.4 Quantitative Description using PIV

The detailed PLIF and pathline analysis enabled the spatial extent of the flow to be analysed, from which an interesting flow case was chosen to perform the initial PIV analysis. Irregular oscillation regime (3), for b/d = 5 was chosen, since some variations in the flow structure was expected. Instantaneous velocity fields are determined directly from the pair of images analysed using PIV. The instantaneous patterns of velocity revealed the propagation of the shear layer instabilities. The instantaneous streamline topology can be compared to the flow visualisation study. Thus the three different visualisation techniques are compared in Fig. 8, for b/d = 5 and Re = 550. Note that these images are grouped due to the presence similar structures they are not necessarily at the same phase in the cycle. In Fig. 8 (a) PLIF image is shown with a fairly large amplitude disturbance wave, a chaotic recirculation region, and a disturbance wave shed from the leading edge; (b) is the streamline topology obtained from MCCDPIV measurements for the same case, we observe three vortices, the largest near the downstream cavity corner; (c) is a pathline image that has three similar structured vortices existing in a similar fashion. In (b) a large amplitude disturbance wave appears to have just been shed downstream of the cavity trailing edge, whereas in the PLIF (a) image a large disturbance wave is approaching the downstream edge, thus indicating that images are slightly out of phase but yet are indicative of the flow structures. As a result of this comparison we conclude for this particular case that the PLIF streakline dye flow visualisation in this highly unsteady flow is in general indicative of the flow structures.

4. CONCLUSIONS

The purpose of this research was to investigate low Re cavity flow. PLIF and pathline flow visualisation enabled characterisation of the flow. Three different regimes were identified; regime (1) no oscillations; regime (2) regular oscillations; and regime (3) irregular oscillations. Organised vortex structures are seen in the pathline flow visualisation for regime (2). As the Re is further increased to regime (3) the flow becomes more chaotic with less organised smaller vortices appearing in the cavity. For the irregular oscillations regime (3) the cavity flow phenomenon was evident, highlighted by the constructive and destructive behaviour of the shear layer oscillations as results of the feedback condition. Complete clipping of disturbances was observed as the cavity length was increased, resulting in an enhanced feedback that initiated larger disturbances. The flow field was examined in a quantitative perspective using PIV. Instantaneous flow fields where presented and found to compare well with the flow visualisation study.

REFERENCES