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# PIV measurements in a forced separated shear layer from a blunt leading edge.

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### Abstract

We report results from an experimental investigation of the separated flow from a square blunt leading edge. Earlier flow visualization studies have indicated that forcing a shear layer such as this with amplitude ratios of the order of 0.3 referred to the free stream velocity significantly modifies the flow structure in the separated region. The present study characterizes the effects of these high amplitude ratios and the excitation frequency using particle image velocimetry. The study was conducted in a water tunnel of section size 500 mm by 500 mm with a blunt leading edge model of 25 mm thickness at a Reynolds number of about 1000. The forcing flow was imposed through a slit of 0.5 mm width located close to the separation corner. The results indicate that higher amplitudes produce additional coherent structures in the shear layer which modify the interaction between the free stream and the separated flow region.

### Introduction

The region near the point where the flow separates from an adjacent surface has high gradients of flow variables and is a receptive region for growth of disturbances. One way to minimize the deleterious effects of separation is to artificially introduce control disturbances in the vicinity of this region. The complexity of real separated flows in technological devices necessitates the study of canonical separated flows of simple geometries before trying to understand flows in more realistic geometries. One such canonical configuration is the separated flow from a blunt square leading edge with a fixed location of separation and a well defined shear layer near the separation point produced by a uniform steady laminar approaching flow.

The unforced flow past a blunt leading edge has been studied extensively and the statistical structure of the flow variables is well documented in numerous studies, see, for example, Kiya and Sasaki [3]. Control disturbances can be applied either globally (for an example see Soria et. al. [8]) or locally through a small slit close to the separation corner (typically with acoustic pulsations in wind tunnels). Though the flow past a blunt leading edge has not been investigated with local forcing by many studies, quite a few studies of related geometries are available - Sigurdson (blunt cylinder) [5], Hasan (backward facing step) [9], Fiedler and Mensing (plane turbulent one stream shear layer)[2]. In general, these studies have limited themselves to small amplitude forcing.

Chun and Sung [1] performed a flow visualization study with large amplitude perturbations of a flow over a backward facing step. An earlier study by us ([4]) presented a flow visualization investigation of the present flow configuration. These two studies indicate that large amplitude forcing of the shear layers give rise to additional structures in the flow which alter the dynamics significantly and are beneficial from a flow control perspective. For example, it was reported ([1]) that the reattachment length diminished to 1/3 of that for the unforced case. In this paper we report some particle image velocimetry (PIV) measurements of the velocity field near the separation corner to supplement the visualizations to aid understanding of the dynamics.

### Experimental equipment and procedure

The experimental work was conducted in the water tunnel of the Laboratory for Turbulence Research in Aerospace & Combustion at Monash University. The section of the tunnel was 0.5 m x 0.5 m. The blunt leading edge plate model of width 25 mm (denoted hereafter by H) was placed in the middle of a 5 m long test section as indicated in Fig. 1. The trailing edge of the plate was supplemented by a section of an airfoil to minimize the formation of a wake. The plate thickness was 25 mm. A 100 mm long slit with a width of 0.5 mm was provided right at the separation corner on the front face of the plate for the forcing flow. The knife edge that made up the wall of the slit was 0.2 mm thickness on the front face. The forcing flow was provided by a hydraulic cylinder actuated by a scotch yoke mechanism driven by a computer controlled stepper motor. This provided a pure harmonic forcing of the desired frequency and amplitude.

A pair of New Wave Research - Gemini lasers and a PCO Camera (from PCO Computer Optics GMBH) formed the basis of the PIV measurement system. The timing of the lasers were achieved with a computer managed by a Real Time Linux operating system. The water tunnel flow was seeded with Vestosint 11 $\mu$ particles. A small circular hole of 2 mm dia. on the front face midway between the centerline (stagnation point) and the separation corner was used to introduce a oozing flow with a higher concentration of seeding particles. This served to mark the shear layer much like a dye flow. The single exposed PIV images were analysed using multigrid cross-correlation digital PIV (MCCDPIV) analysis. The MCCDPIV analysis algorithm, its performace and accuracy are documented in [6],[7]. The image area in pixels was 1280 by 1024 (w x h).

The experiments were conducted at a Reynolds number of about 1000 based on tunnel reference speed ($U_\infty$) and the plate width (H). The tunnel reference speed ($U_\infty$) was 35 mm/s. The forced flow experiments were done with perturbations of 1 Hz frequency. The scotch yoke amplitude for forcing was 0.1 mm and was measured with a dial gauge. The nominal internal diameter of the hydraulic cylinder was 20 mm. The corresponding velocity amplitude at the forcing slit (of size 100 mm x 0.5 mm) at the separation corner is estimated to be 4 mm/s. This gives a velocity amplitude ratio of approximately 0.11.

### Results

The reference flow past the plate without any forcing is shown in figure 2. This picture is composed from four separate vector fields calculated from PIV images taken at adjacent locations along the plate and in front of the plate. These are individual realizations of the vector field, not averages. The separation corner is at the origin. Flow visualization had indicated that average of the images of the unperturbed shear layer did not smear and did not develop any vortical structures until after about X/H = 3. Velocity field measurements with PIV in the present study confirm this and repeat measurements of velocity fields are al-

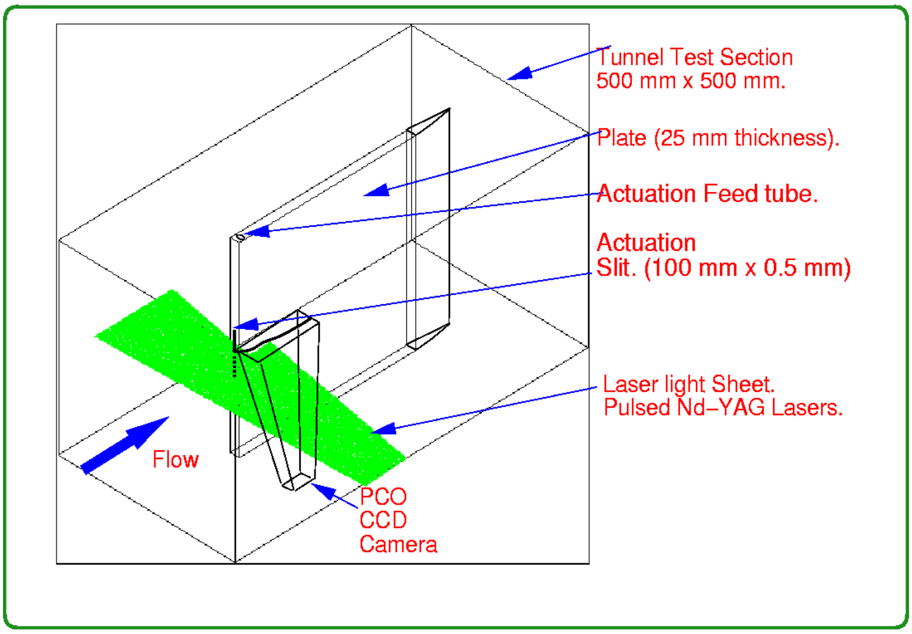


Figure 1: Water tunnel test Section set-up.

most identical with very little variance. The streamtraces generated by the computer software from the vector fields for the different zones are also shown. The location of the stagnation point on the front face of the plate has a significant effect on the physical size of the separation bubble. Hence it is essential to align the plate orientation to the oncoming flow, that this was done can be seen in the velocity field measurement.

The recirculating flow in the separation bubble close to the corner was found to be very steady as can be seen from the streamtraces. But the reverse flow in the bubble in the next zone was a little more unsteady from random vortical structure formation further downstream. The shear layer thickness at the farthest location, i.e. at X/H = 2.5 is of the order of 0.4H. This lateral location is expected to be the location of the maximum height of the bubble and the midpoint of the bubble. This assumes that the re-attachment length is about 5H, a value reported in many studies. Thus the middle vector field area covers the first quarter of the bubble.

We consider the response of the shear layer to imposed perturbations. This is depicted in figure 3. Four images of the shear layer corresponding to the first quarter of the bubble at equal phase angle intervals of $90^o$ are shown. The period of the forcing cycle was 1 Hz. The images, thus, are separated by 250 ms time intervals. They were selected from a sequence of images taken 50 ms apart. The speed of the image acquisition system was insufficient to acquire this sequence from a single forcing cycle. The images, hence, come from triggered acquisition from successive forcing cycles with respect to a reference trigger signal generated once per cycle.

The picture shown is generated from two layers - the actual PIV image and the vector field generated from that image. The contrast of the PIV image was adjusted to make the higher seeding density used to mark the shear layer visible. The top frame shows the shear layer at an arbitrary phase angle indicated by $\phi$. Three features can be seen in the flow visualization of the shear layer and these are marked A, B and V-1. A vortical structure corresponding to V-1 can be seen in the velocity vector field. The corresponding structure of the previous cycle can be seen in the right extreme of the frame. The saddle point between these two vortical structures and the corresponding 'braid region' of the visualization can also be seen.

The evolution of the structure marked A through the four frames can be seen to be under the influence of the strain field of a saddle point in the vector field. The flow visualization structure V-2 can be clearly seen in the final frame at the bottom. Thus we can conclude that the birth of the vortical structure in the velocity field takes place right at the separation corner. PIV measurements with higher magnification confirm this. These vortical structures in the velocity field grow continuously and seem to span the entire section of the bubble, i.e. from the wall to the shear layer at that location. Though not clear in the images shown here, larger images show that the free stream outside the shear layer flow 'around' these structures for about two to three structure sizes.

The need for caution in interpreting flow visualiztions in time dependent flows has been emphasized in the literature many many times. This image affirms that caution. The vortical structure seen in the flow visualization is clearly a consequence of the history of the motion of a particular section of the shear layer filament. This motion is under the influence of a small section of the much larger structure seen in the velocity field. The relation between what is seen in the flow visualization and what is seen in the velocity field is not a simple one. Ascribing dynamical significance to structures seen in traditional flow visualizations and deducing dynamical events from them thus runs the risk of treating the Lagrangian-Eulerian connection simplistically.

Our earlier dye flow visualization study reported in [4] was done with a range of forcing amplitudes. For very small excitation levels four distinct structures were seen in the visualizations. It was surmised that these result from the four different phases of the harmonic excitation cycle, the regions around the maximum and the minimum and the two linear regions between these. For higher excitation levels the different structures behaved differently with some travelling faster than others and merging to form three structures. The average dye intensity distribution showed marked difference for different amplitude levels with

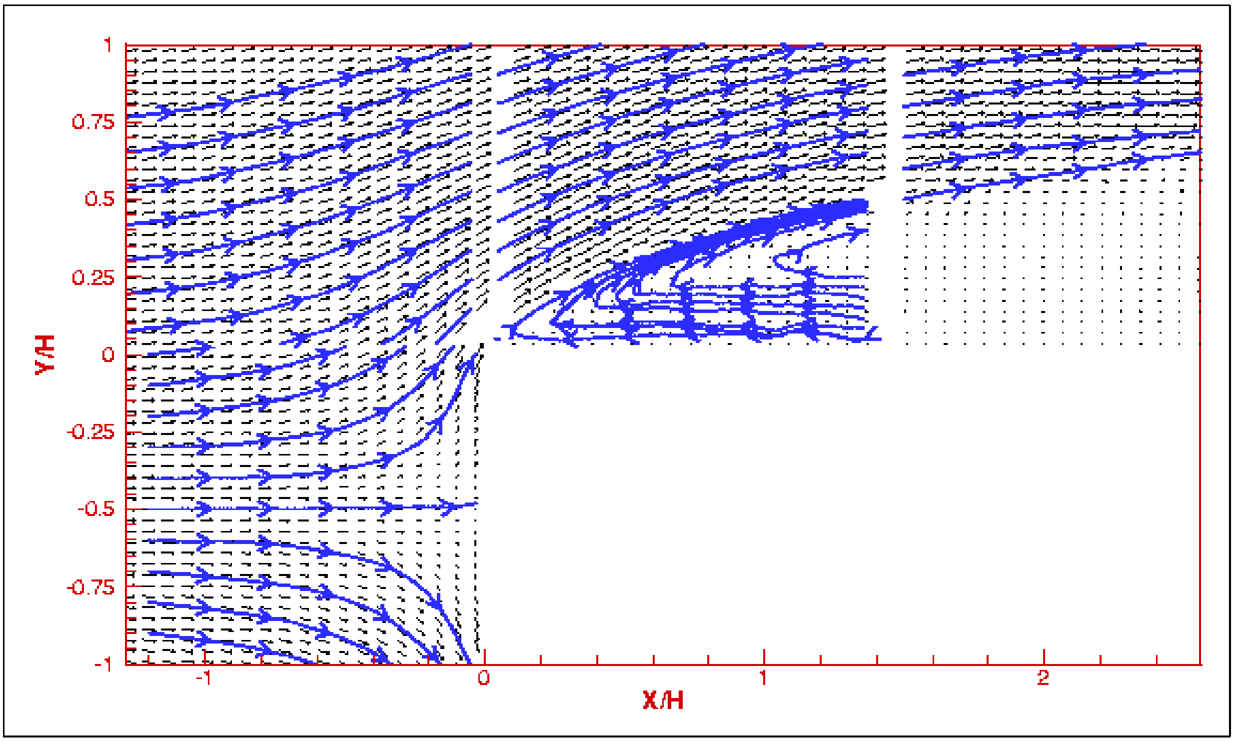


Figure 2: Unperturbed flow. Reynolds number ≈ 1000. Plate thickness H = 25 mm.

higher excitation levels seeming to mix the recirculation zone much more.

We find that the details of the flow visualization shown here and the comparable one of the earlier study are identical. PIV data acquisition for a range of amplitudes have been completed. Preliminary inspecton of these results show that the additional structures seen in the flow visualization in each cycle are intensified at higher excitation levels and at particular excitation levels seem to induce vortex amalgamation. We are currently working on establishing the connection between the different phases of the excitation cycle and the structures seen at different amplitudes in the flow visualization and the structure of the velocity field.

## Conclusions

Simultaneous flow visualization of the shear layer and vector field measurement with particle image velocimetry technique was applied to the flow close to the separation corner of a square blunt leading edge. A vortical strucure for each forcing cycle is generated close to the corner, well before any structure is seen in flow visualization. The interaction of the receptive region close to the corner with higher amplitude excitations of the forcing seem to introduce additional structure to the motion. On the basis of an earlier flow visualization study we feel that these structures play an important role in enhancing the mixing of the free stream with the recirculating flow. Flow control applications may need to look at large amplitude forcing for effective control.

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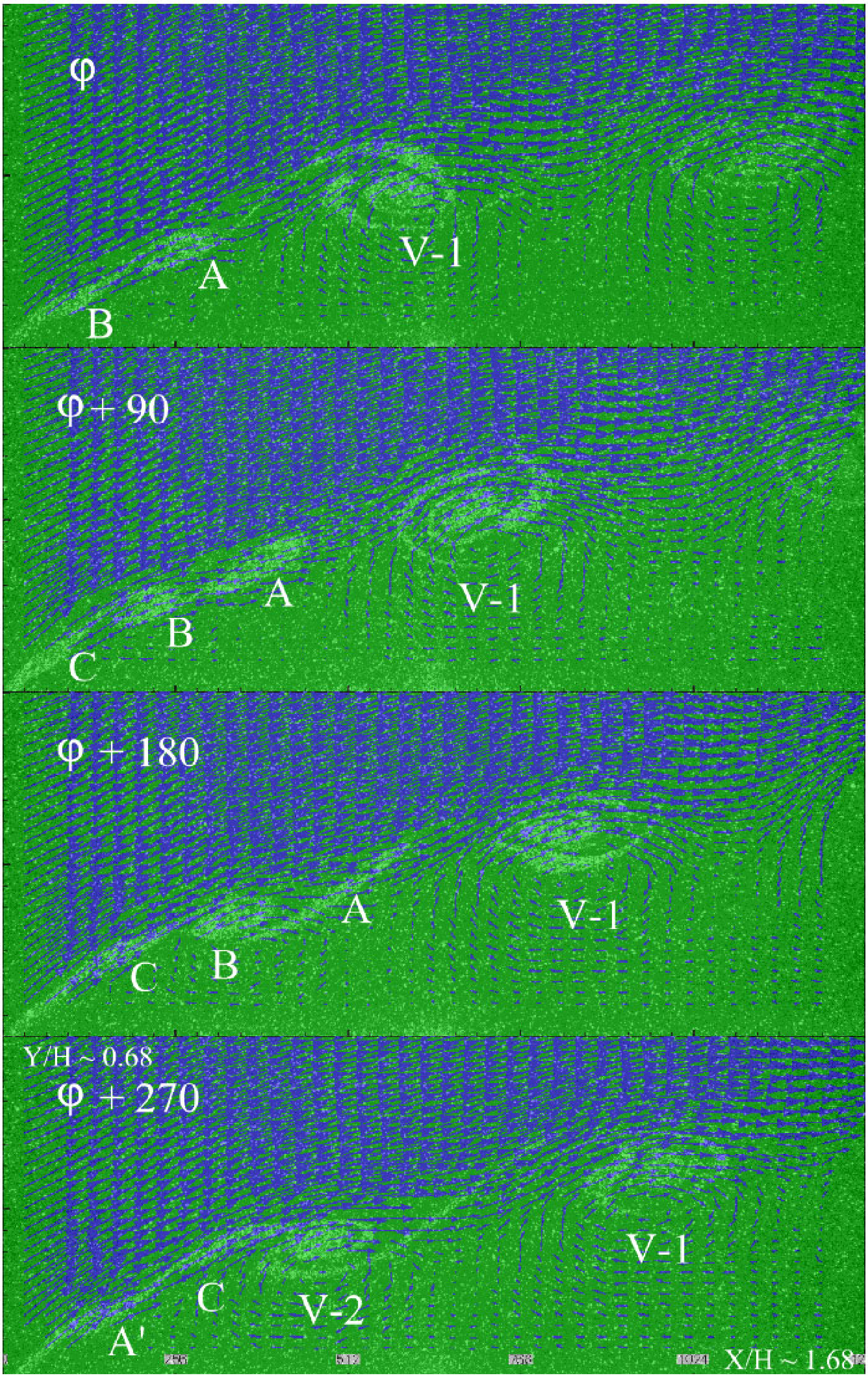


Figure 3: Perturbed flow. Re $\approx$ 1000. Frequency of forcing = 1 Hz. Velocity amplitude ratio $\approx$ 0.11.