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A VISUAL STUDY OF VORTEX RINGS FIRED TRANSVERSELY INTO A CROSS-FLOW

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ABSTRACT

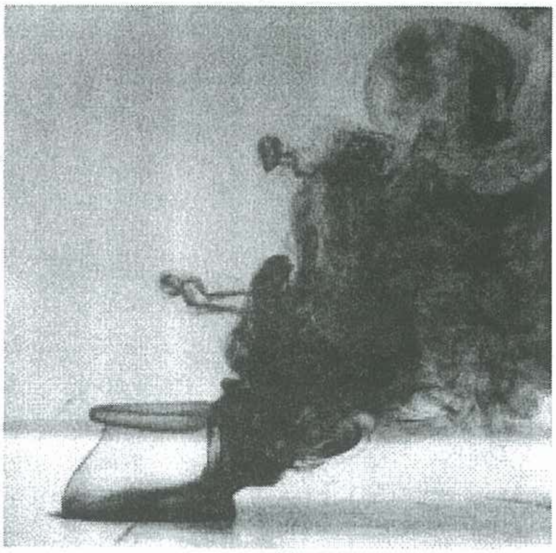
This paper seeks to provide a clearer insight into the mechanism by which the shear layer of a jet in cross-flow rolls up. The results show that a previously proposed model by the present authors may not adequately describe this process. An alternative model is therefore proposed.

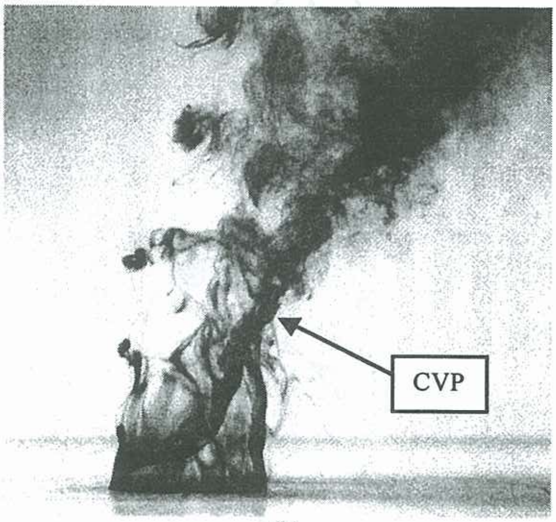
INTRODUCTION

Recently, Kelso, Lim & Perry (1996) reported on a study of round jets in cross-flow at various flow conditions. They observed that when a jet discharges normal to a cross-flow, the shear layer structure near the pipe exit is dominated by ring-like vortices that become distorted with streamwise distance. This process is shown in Fig. 1. The geometry of the corresponding jet apparatus is shown in Fig. 2. Although the overall features of the distorting ring vortices were resolved, the details of this distortion were not fully understood. In the dye visualization the existence of the upstream and downstream parts of the vortex rings was clearly apparent. However, the connection between these parts was obscured by the intermingling of dyes and intertwining of the vortex filaments on the downstream side of the jet. The interpreted flow pattern of Kelso *et al.* (1996) is given in Fig. 3, and implies a substantial tilting of the upstream side of the vortex rings. Brücker (1994), in a PIV investigation of the flow in a T-junction (a jet discharging into a larger, confined cross-flow), observed that ring vortices remain substantially planar. Chang and Vakili (1995) investigated the tilting of vortex rings fired into a cross flow using a pulsed jet, showing little tilting also. Unfortunately this work was unable to clarify the details of the mechanism of the unforced flow due to the wide spacing between the rings. It is therefore clear that further investigation of the shear layer structure is needed. To this end, flow visualization studies were carried out using trains of naturally developing vortex rings fired into the cross-flow. In this paper the results of the investigation will be reported

EXPERIMENTAL METHOD

The experiments were conducted in the same closed-return water channel as used by Kelso *et al.* (1996) and Fig. 2 shows a schematic diagram of the apparatus used. The working section was constructed entirely from plexiglass to allow the flow to be viewed from any angle. In Kelso *et al.*, a continuous jet was issuing from a short tube connected to a 36:1 contraction. Related studies showed that the structure of the jet in cross-flow was visually similar whether


(a)



(b)

Figure 1: Flow patterns obtained when dye is released from a dye injection hole located below the upstream lip of the jet (as shown in Fig. 2) and from a circumferential slot in the pipe. (a) Re=1000 and R = 4.0; (b) Re=1600 and R = 5.5. The Reynolds number Re and velocity ratio R are defined in Fig. 2. The counter-rotating vortex pair (CVP) is present in both photographs, but identified only in (b).

the contraction was present or not, ie. whether the pipe boundary layer was thick or thin. In the new experiments reported here, the pipe (without a contraction) was connected to a piston-cylinder arrangement as shown in Fig. 4. The piston was driven by a stepping motor through a 12 mm diameter lead screw with a pitch of 2.5 mm. The stepping motor was controlled by a signal consisting of a train of square wave pulses. The signal was then gated by a timer which allowed a predetermined number of pulses to be sent to the motor, thus enabling the Reynolds number and pulse duration to be controlled. In order to visualize the vortex rings, dye was released from the dye injection slot as shown in Fig. 3 to mark evenly the boundary layer fluid in the pipe prior to firing. The vortex ring injections were recorded using a Sony Hi-8 video system with the camera's viewing axis aligned normal to the vertical centreplane of the water channel. Thus, the flow was viewed in elevation with the cross-flow from left to right. Selected images were reproduced using a Sony Video Printer.

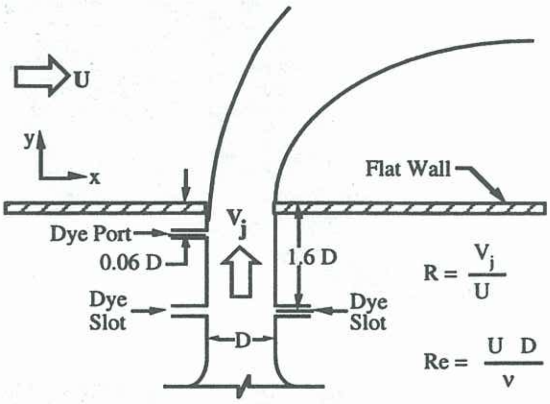


Figure 2: Schematic diagram of jet apparatus used by Kelso *et al.* (1996).

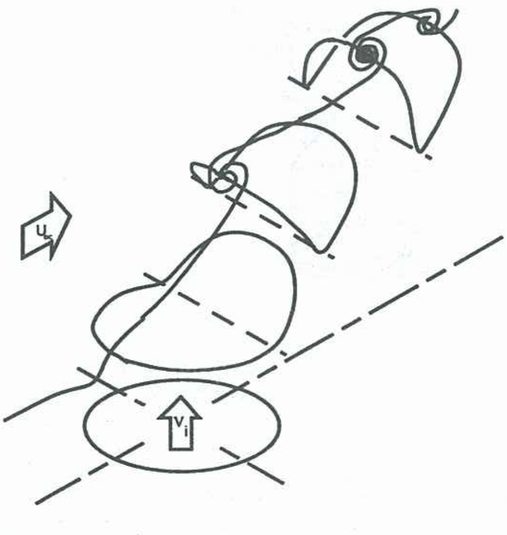


Figure 3: Earlier interpretation of the jet shear layer vortex ring evolution (after Kelso *et al.* 1996).

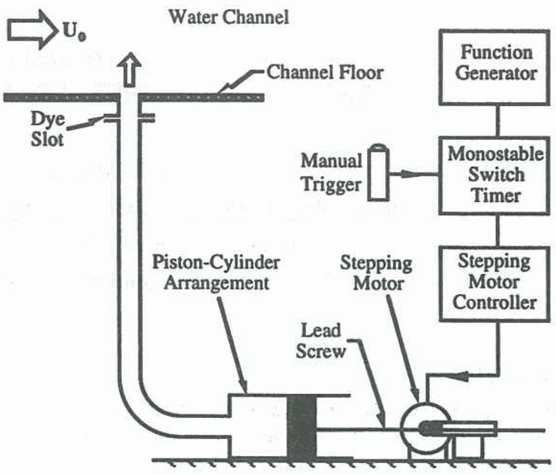


Figure 4: Schematic diagram of the apparatus used to generate the vortex rings in cross-flow.

RESULTS AND DISCUSSION

Figure 5 shows the result of injecting a long-duration slug of fluid into the cross-flow. The view is from the side with the cross-flow from left to right, and less than half of the total injection time is shown. The ring-like roll-ups occur without any deliberate forcing and appear to be due to the natural instability of the shear layer. The Reynolds number is approximately 660 (based on the cross-flow velocity) and the flow case corresponds to a continuous jet case with a velocity ratio of approximately 6. In this sequence the first ring (starting vortex) and second ring are not representative of the continuous jet-in-cross-flow case. The third and subsequent rings are analogous to the jet-in-cross-flow case. Although the flow is transient, the shear layer structure is established rapidly and the roll-up process becomes repeatable and periodic. From Fig. 5 it is clear that the model previously suggested by Kelso *et al.* requires modification. It is also clear that the vortex rings form an interlocking ladder-like network, where each ring interacts with its neighbours.

Similar to the previous model, the ring vortices roll up near the pipe exit, initially with a small upstream tilt angle (ie. the upstream side of the ring's plane is lower than downstream side). The plane of the upstream side of the ring then rotates in the direction of jet curvature (clockwise here). This is shown later in Fig. 7.

The deformation of the downstream side of each vortex ring is far more complex than the previous model would suggest. Figure 6 describes this initial deformation process and defines the angular coordinate θ. The images in Fig. 5 suggest that near $\theta = 120 - 150°$ the rings are lifted and stretched upwards approximately parallel to the mean jet trajectory. The rear-most part of the ring ($\theta = 180°$) undergoes less upward stretching, leading to a "loop" on the downstream side of each ring, as indicated in Fig. 6. As the rings evolve the differential stretching process continues, leading to a substantial folding and elongation of the rings. The loop appears to be pushed through the rear of the ring towards the upstream side of the jet, turning the loop "inside out".

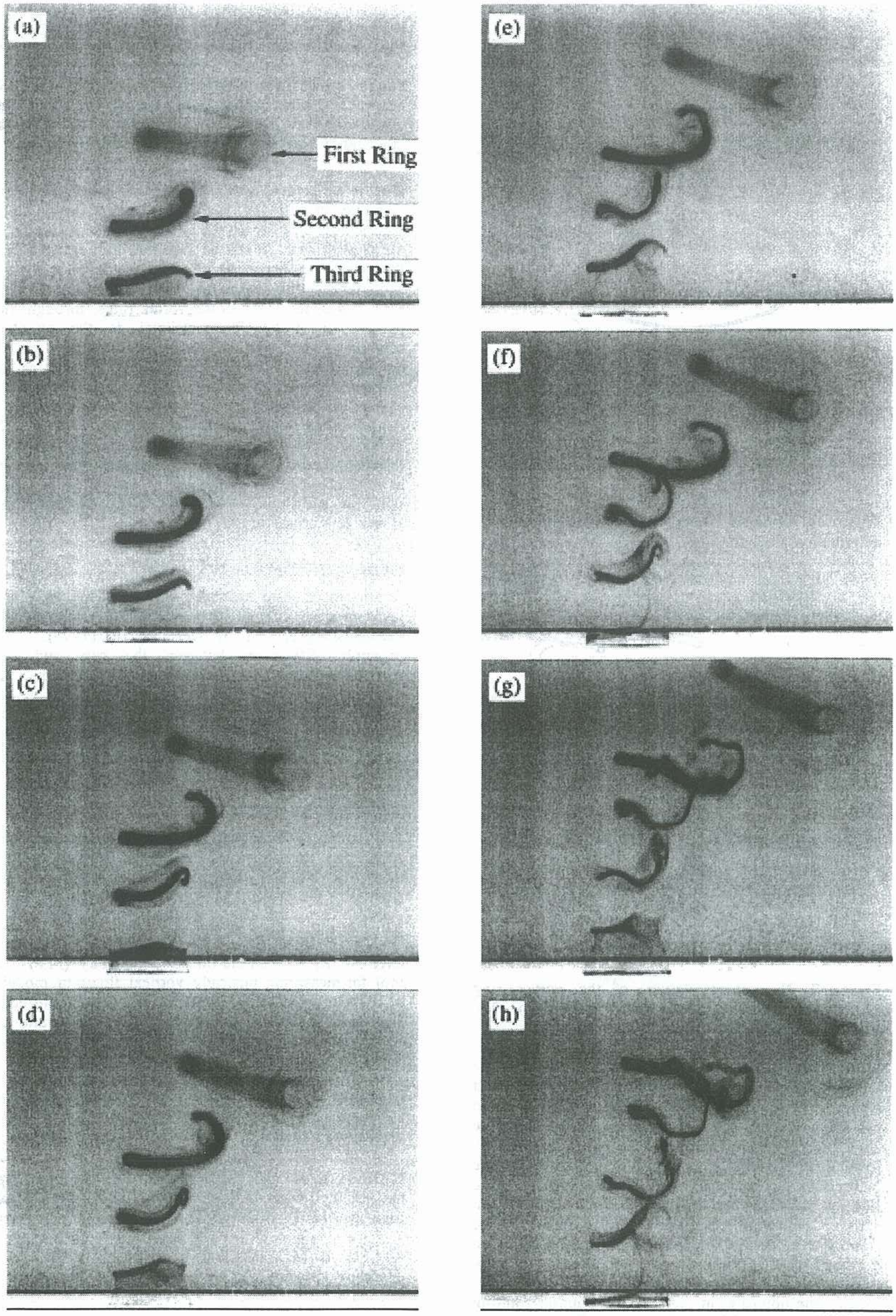


Figure 5: Sequence showing a train of vortex rings fired into the cross-flow, generated by a long-duration slug of fluid ejected from the pipe. The Reynolds number, based on the cross-flow velocity and pipe diameter, is approximately 660. Frame (a) is taken at t = 0; (b) t = 0.12 secs; (c) t = 0.32 secs; (d) t = 0.4 secs; (e) t = 0.52 secs; (f) t = 0.68 secs; (g) t = 0.88 secs; and (h) t = 1.04 secs. The total duration of the slug was 2.78 seconds.

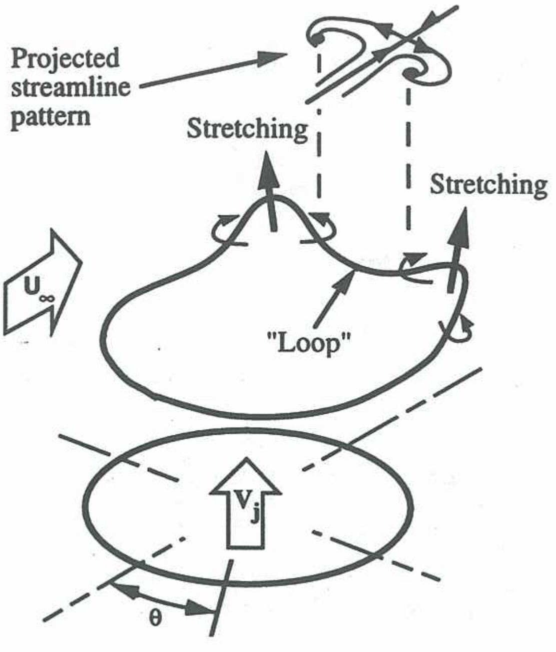


Figure 6: Authors' interpretation of the initial ring deformation process.

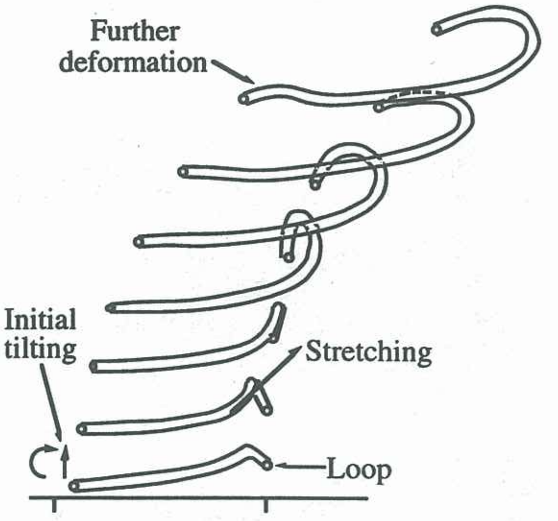


Figure 7: New interpretation of the vortex ring evolution in the shear layer, shown in elevation. The cross-flow is from left to right.

In fact, Fig. 5 suggests that the upstream motion of the loop is quite small and the "turning inside-out" effect is mostly due to the stretching of the adjacent parts of the ring. Finally, after the loop has "turned inside out", it lies close to the plane of the vortex ring above, forming an interlocking, ladder-like structure. Figure 7 describes the complete process schematically. The spacing between the rings has been reduced to improve the detail and clarity. The existence of the loop corresponds well with the observations of Haven & Kurosaka (1997) who observed vorticity components at the downstream side of the shear layer which were opposite in sign to the counter-rotating vortex pair observed in transverse jet. These vorticity components would be associated with the sides of the loop as shown in the projected streamline pattern in Fig. 6. The mechanism proposed by Haven & Kurosaka is based on "warping" of the vortex lines due to reverse flow on the downstream side of the jet. The results shown in Fig. 5 suggest that the stretching of the vortex rings, as depicted in Fig. 7, is the major contributor to this vorticity

How is the present flow related to the continuous jet? Comparison with Fig. 1(b) shows the correspondence with a flow case where the velocity ratio is similar to the present case. It can be seen that the region where the stretching occurs is close to the location of the "counter-rotating vortex pair" in the continuous flow case. Thus, the sides of the vortex rings, through the process of stretching, contribute to the counter-rotating vortex pair, as discussed by Kelso *et al.* among others. Further investigation is required to confirm this correspondence.

An additional effect is also apparent in Figs 1 & 5. This is identified in Fig. 7 as a "further deformation" of the rings on the upstream side of the jet. This effect is, as yet, unexplained, although it may be associated with an additional "warping" effect described by Haven & Kurosaka (1997) .

CONCLUSION

A new mechanism has been proposed for the shear layer structure of a jet in cross-flow, superseding the mechanism proposed by Kelso *et al.* (1996). The principle differences between the new and old mechanisms are the deformation process on the downstream side and the manner in which the vortex rings subsequently interact with one-another. In the new model the vortex rings form an interlocking ladder-like network. In the old model the vortex rings were considered as discrete and separate entities.

ACKNOWLEDGEMENTS

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