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A NOTE ON THE CAUSE OF REBOUND IN VORTEX RING/WALL INTERACTIONS

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Abstract

A comparison of a vortex ring/wall interaction with the head-on collision of two identical vortex rings was made in order to assess the importance of the no-slip condition at the wall in causing vortex ring rebound.

Introduction

It is well known that when a vortex ring approaches a plane rigid surface, normal to the axis of the ring (henceforth referred to as a ring/wall interaction), its diameter increases and its axial velocity decreases. At some stage, the axial velocity changes direction and the ring moves away from the surface (for example, see Magarvey & MacLatchy (1964), Boldes & Ferreri (1973), Yamada et al. (1982), Cerra & Smith (1983) and more recently Walker et al (1987)). This reversal of the axial velocity is commonly referred to as **rebound.** It has been suggested by many workers including Yamada et al. and Cerra & Smith that rebound is caused by the mutual interaction of the original vortex ring and a secondary vortex which is generated as a result of the rolling up of the separated shear layer at the boundary.

The origin of the above interpretation of rebound can be traced to work of Harvey & Perry (1971), who made an investigation of the observed rebound of trailing wing-tip vortices from a ground plane. They concluded that when trailing vortices are in the vicinity of the ground, the local adverse pressure gradient which occurs below the vortex core causes the boundary layer to separate outboard of the vortex core. This separated boundary layer eventually rolls up to form a secondary vortex with opposite vorticity to that of the trailing vortex. They demonstrated how the secondary vortex caused the trailing vortex to rebound from the ground. This explanation was later extended by Cerra & Smith to include the rebound of a vortex ring from a wall.

The foregoing discussion essentially suggests that the secondary vortex is instrumental in causing the rebound of trailing vortices and vortex rings from a wall. The authors contend that it is the effect of the no-slip condition at the boundary which leads to the generation of the secondary vortex (see also Lighthill (1963)).

However, not everyone agrees with the interpretation of Harvey & Perry. Barker & Crow (1977) attributed the cause of rebound to the inviscid effect of finite vortex core size and core distortion. Saffman (1979) disputed this, and in his numerical analysis showed that rebound cannot be explained by finite core size.

The aim of this project was therefore to assess **experimentally** the validity of the interpretation of Barker & Crow. To achieve this, an experiment was proposed in which two identical vortex rings were made to collide 'head on' (henceforth referred to as a ring/image interaction). This experiment mimics the inviscid case by using a real "image" vortex ring, to simulate the effect of the boundary. Since no rigid boundary is involved, slip is allowed between the two rings. It was reasoned that if rebound is in fact caused by the no-slip condition, as put forward by Harvey & Perry, then it should not occur in the case of the ring/image interaction. If, however, rebound in the ring/wall interaction is caused by finite core-size effects, then it should also be observed in the ring/image interaction.

Experimental Apparatus and Procedure

The experiments were conducted in water in a glass tank with dimensions of 1222 x 472 x 360 mm. The experimental facility used was essentially the same as that described by Lim (1989), but suitably modified for this investigation (see figure 1). The nozzles were spaced 220 mm apart and one of them could be traversed, both horizontally and vertically, to allow for fine adjustment of the alignment. Vortex rings were produced when the piston was advanced by a lead screw, driven by a high torque stepping motor. The stepping motor was controlled by a signal generator which provided an accurate, fixed frequency of pulses. This signal was gated by a monostable timer which passed a fixed number of pulses to the motor, thus enabling the Reynolds number to be determined. In order to visualize the vortex rings, dye was mixed with alcohol to give a specific gravity of 1.0, and was released from annuli surrounding the nozzles (see Lim (1989) for a detailed description). In the ring/wall interaction, a plane perspex surface was located half way between the two nozzles. The motion of the vortex rings was recorded using a Sony U-matic video recorder. Unless otherwise stated, all the pictures which appear in this paper are taken from the video monitor using Mamiya RB 67 camera.

Results and Discussion

Figure 2[A] is a sequence of photographs showing the

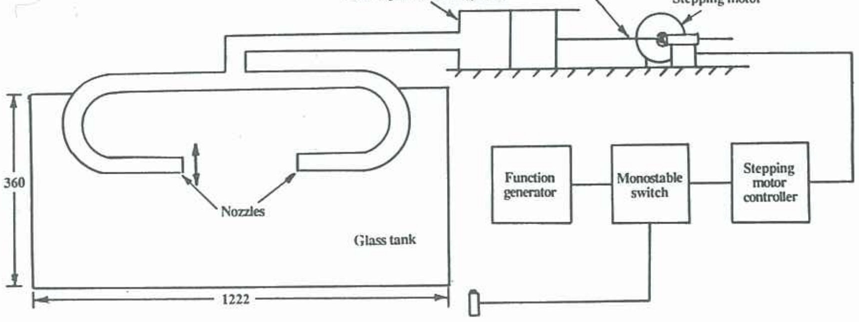


Figure 1. Schematic layout of apparatus

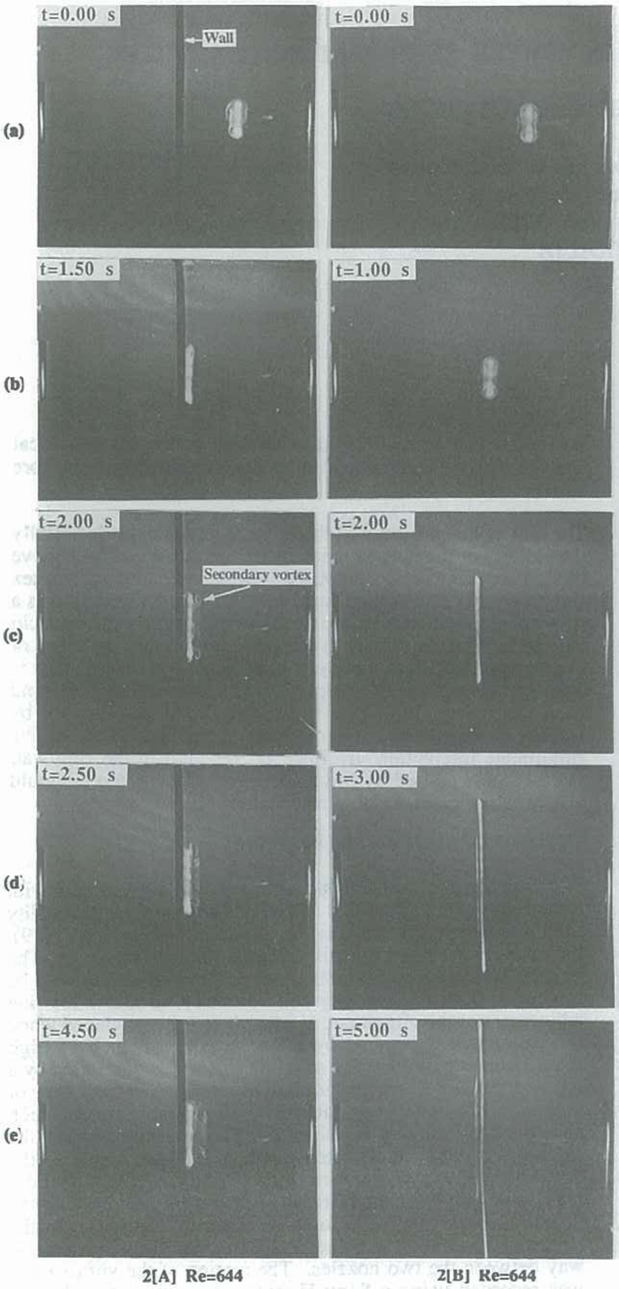


Figure 2. Comparison of ring/wall (series 2[A]) vs ring/image (series 2[B]) interactions at Re=644.

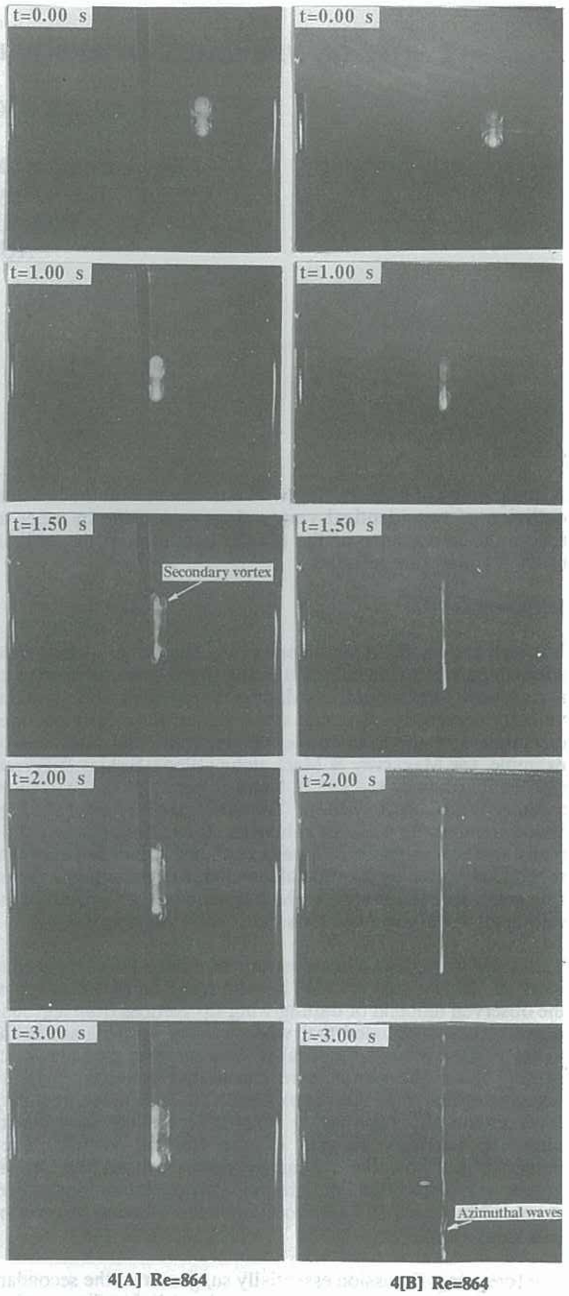


Figure 4. Comparison of ring/wall (series 4[A]) vs ring/image (series 4[B]) interactions at Re=864.

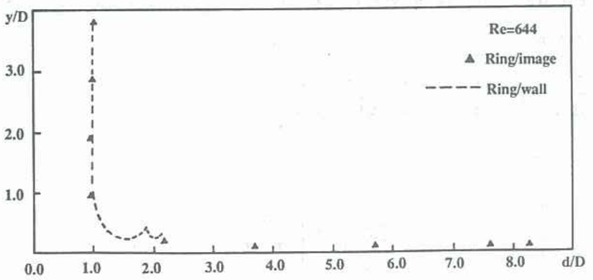


Figure 3. Trajectories of vortex cores in the plane of symmetry - ring/wall vs ring/image at Re=644.

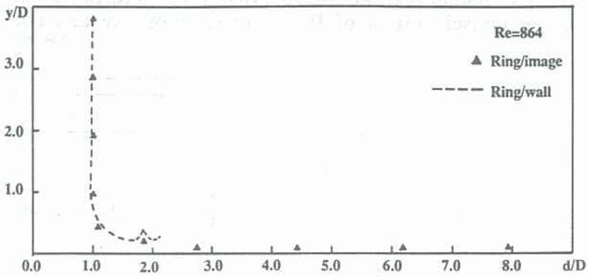
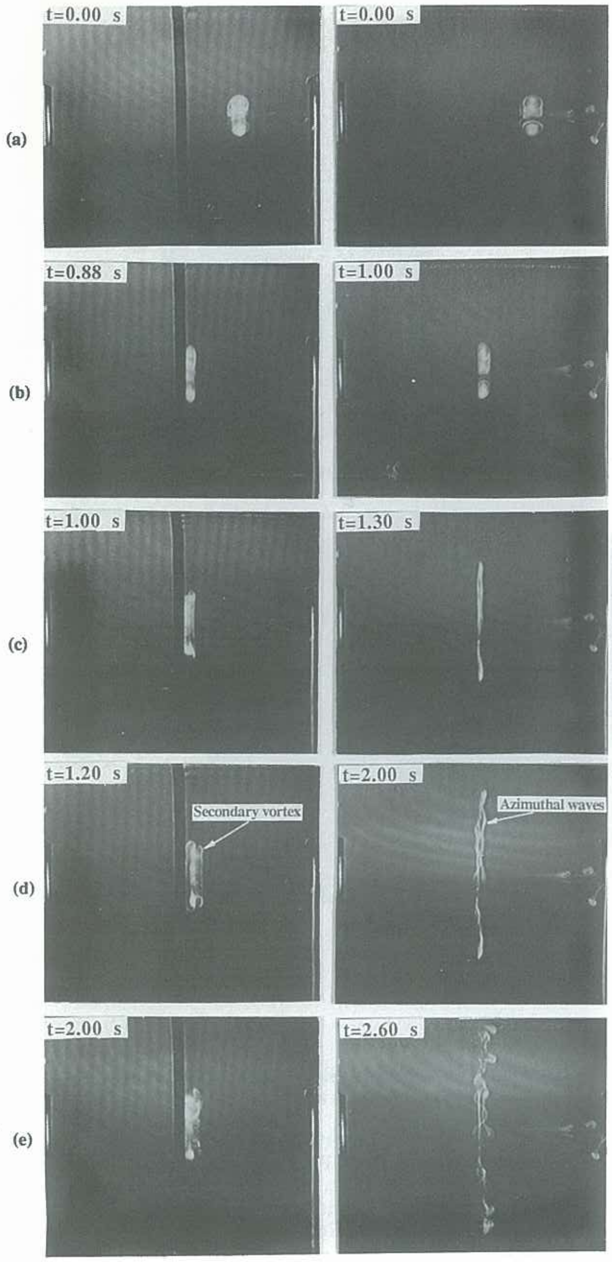


Figure 5. Trajectories of vortex cores in the plane of symmetry - ring/wall vs ring/image at Re=864.



6[A] Re=1000 **6[B] Re=1000**

Figure 6. Comparison of ring/wall (series 6[A]) vs ring/image (series 6[B]) interactions at Re=1000.

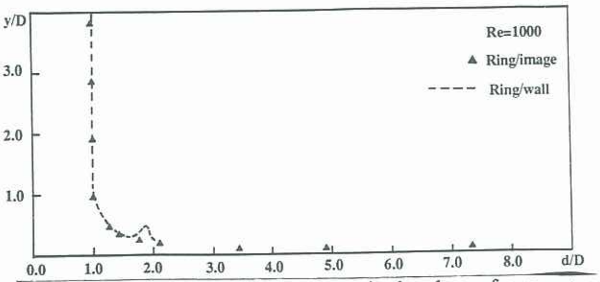


Figure 7. Trajectories of vortex cores in the plane of symmetry - ring/wall vs ring/image at Re=1000.

interaction of a vortex ring with a wall, and figure 2[B] shows a similar vortex ring during its head-on collision with another identical ring. The Reynolds number, based on the nozzle diameter and the ejection velocity, is approximately 644. For clarity, only one of the rings in the ring/image interaction is coloured with dye. The elapsed time interval from t=0.0 is shown on each of the photographs. It should be noted that the different time intervals have been chosen so as to illustrate the most significant features of the flows. The first photograph in each sequence has been arbitrarily assigned as t=0.0. This corresponds to the location where the vortex ring is about two diameters away from the wall or from the plane of collision. It can be seen from figure 2[A] that as the vortex ring approaches the rigid surface, its diameter increases due to the velocity induced by its image (see figure2[A]-(b)). The presence of the ring also induces a velocity at the wall which causes a boundary layer to form. Owing to the local adverse pressure gradient beneath the ring, the boundary layer eventually separates from the wall and later rolls up to form a secondary vortex as shown in figure 2[A](c)-(e) (see also Harvey & Perry). Figure 2[A](c) also illustrates clearly that the vorticity of the secondary vortex is opposite to that of the original vortex ring. Using the Biot-Savart law, one can show that this secondary vortex causes the original vortex ring to lift away or "rebound" from the wall (see Cerra & Smith (1983) and Walker et al. (1987)). Although the rebound is not obvious from the photographs, it can be seen convincingly in both the video replay of the interaction, and the plot of the vortex core trajectories in figure 3.

The flow case shown in figure 2[B] is essentially the same as figure 2[A] except for the slip at the boundary (i.e the plane of collision). A comparison of the photographs in figure 2[B] with those of figure 2[A] indicates that the two flows behave quite differently. The most obvious difference is in the extent of the increase of the vortex ring diameter. In the ring/wall interaction the ring expands to about three times its initial diameter, as compared to more than seven times in the ring/image interaction (see figure 3). In the ring/wall interaction this expansion is arrested rapidly by the production of a secondary vortex at the boundary (see figure2[A] (c)-((e)). However, in the ring/image interaction the expansion does not appear to be checked at all until the rings finally "die" due to the diffusion of the vorticity to the surrounding fluid. Also, there is no evidence of secondary vortex formation in the photographs of the ring/image interactions.

Figures 4 and 6 show similar flow cases as figure 2 with Re=864 and Re=1000 respectively. It can be seen that the basic flow structures during the ring/wall interaction at higher Reynolds number are fundamentally the same as those in figure 2. The production of the secondary vortex is followed by the rebound of the vortex ring and the arrest of the expansion of the ring diameter when it is about three times its original size(see also figures 5 & 7). In the case of the ring/image interaction, even at higher Reynolds numbers, there is no evidence of the formation of a secondary vortex, and the ring does not appear to rebound. In addition, the ring increases its diameter to a much greater extent than in the ring/wall interactions (see figures 5 & 7). From the above experimental evidence, it seems reasonable to argue that the rebound of the vortex ring is related to the influence of the secondary vortex which is formed due to the no-slip condition at the wall. This study thus provides further support for the model suggested by Harvey & Perry. In figure 8 the trajectories of the vortex cores in the ring/image interactions, for all three Reynolds numbers, are compared to trajectories calculated from Dyson's (1893) inviscid analysis. It is of interest to note that the experimental trajectories closely approximate the inviscid case for an ε/D ratio of 5.0 (where ε is the core diameter and D is the diameter of the ring). This would seem to imply that the effect of viscosity in this interaction is small, and thus it is a good approximation of the inviscid case. A further observation at high Reynolds number in the ring/image interaction is the appearance of an instability in the form of azimuthal waviness (as shown in figures 4 & 6). This instability can lead to the formation of smaller rings around the circumferential axes of the original vortex rings, through cross-linking of the vortex filaments (see figure 9). It appears to be an axisymmetric case of the instability observed by Crow (1970) for trailing vortex pairs, and has also been observed, but in less detail, by Oshima (1978).

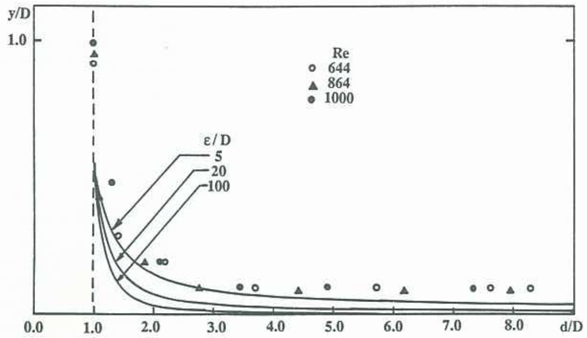


Figure 8. Comparison of ring/image interactions with the inviscid analysis of Dyson.

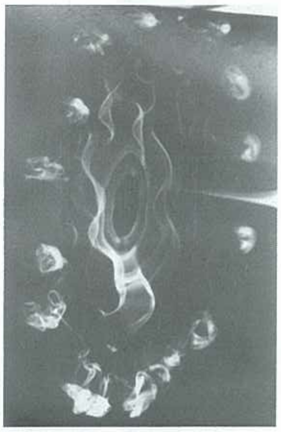


Figure 9. Formation of smaller rings due to cross-linking of vortex filaments.

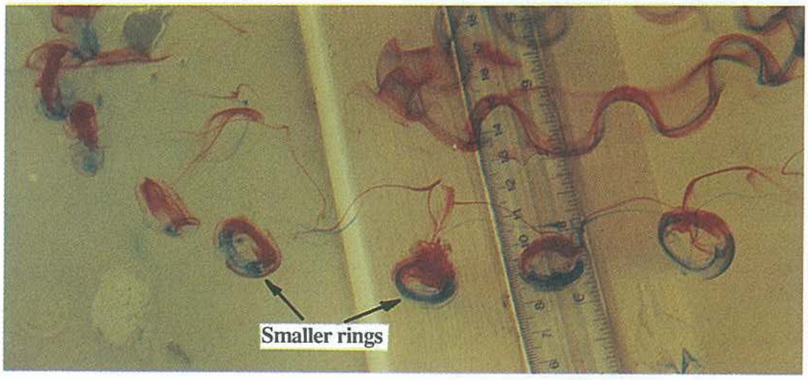


Figure 10. Photograph showing showing detailed features of smaller rings.

A further observation is that when one of the vortex rings is originally marked with blue dye and the other with red dye, the resultant smaller rings are half blue and half red and convect away from each other in the radial direction (see figure 10). This result demonstrates quite clearly the contribution of each of the original "parent" rings to the formation of their "offspring". It also shows one mechanism by which smaller scales of eddies can be produced from the breakdown of larger scales. Further investigation of this phenomenon may be worthwhile.

Conclusions

This work strongly supports the contention that the rebound of a vortex ring from a wall, and the arrest of the expansion of its diameter, is caused by the formation of a secondary vortex at the boundary due to the no-slip condition. Secondary vortex formation was not observed in any of the ring/image interactions, where free-slip conditions existed. Consequently, no rebound was observed and the expansion of the ring diameter was not checked. The findings of this study therefore do not appear to support the interpretation of rebound put forward by Barker & Crow.

Another interesting observation emerging from this study is the formation of smaller rings from the interaction of wave-like instabilities on each of the original vortex rings in a head-on collision. The experiments with differently coloured dye clearly show how each of the original vortex rings contribute to the formation of the resulting smaller rings.

Acknowledgements

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