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Interaction of Two Vortex Rings Moving Side by Side

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Experimental studies were carried out on the interaction of two vortex rings moving parallel side by side in a water tank. In order to investigate the process of interaction clearly, two rings were colored by different dyes. Three typical patterns of interaction were observed according to initial conditions at ejecting vortex rings. (1) Under the most favorable condition, two rings contact at two points successively and there occur the cross-linkings of vortex filaments. Thus a distorted vortex ring is formed and then it splits into two vortex rings again. (2) Two rings contact and form a ring, but it does not split and moves with intermittent deformations. (3) Two rings join into a distorted ring, which splits into two small rings and a merged body of the two initial rings. Soon after they fuse into a mass of vorticity and diffuse away.

§ 1. Introduction

Motions of vortex rings are the most familiar examples of fluid flows with vorticity. They are analysed and predicted even on the ideal-fluid theory. According to this theory, in unbounded fluid at rest at infinity, a circular vortex ring moves along the axis perpendicular to its plane with constant speed due to its own induced velocity.

When more than two vortex rings come nearer with each other, they interact and change their shapes, sizes and speeds. Among these interaction phenomena, the most interesting one is that of two vortex rings moving along a common axis of symmetry in the same direction. Owing to their mutual interaction, the front vortex becomes larger and slower while the rear vortex becomes smaller and faster. Under the favorable condition the rear vortex ring ultimately passes through the front, thereafter their roles are reversed and thus the game of passing through each other between two vortex rings happens and repeats itself.

Since real fluids have always more or less viscosity and there occur diffusion and decay of vorticity, actual motions of vortex rings in real fluids are to be modified from those predicted on the ideal-fluid theory. Behaviors of vortex rings in real fluids have recently been investigated by several researchers. Saffman[1] analysed the motion and decay of vortex ring in viscous fluids. Maxworthy[2] investigated experimentally the formation and structure of vortex ring in water and presented a simple theoretical model. Further he discussed about interactions of two vortex rings and said that he was unable to observe the game of passing through between two vortex rings. He also described the interaction phenomena of two vortex rings moving along parallel axes side by side, by quoting Fohl's experiment. Leonard[3] carried out numerical computations for the cases of interactions of vortex rings moving along an axis in tandem or along parallel axes side by side.

For these several years we have been engaged in studies on the motions and interactions of vortex rings. Oshima[4] observed the motion, decay and deformation of a circular or non-circular vortex ring in water. Further she investigated the motion of a vortex ring moving in water toward its free surface[5]. The motions of the ring together with its image due to the water surface simulate those of rings in a head-on collision along an axis. Kambe and Oshima[6] analysed the motion and decay of vortex ring in unbounded viscous fluid at rest at infinity. They also calculated the generation and development of a vortex ring numerically and verified these results by experiments in water. Oshima, Kambe and Asaka[7] investigated the interaction phenomena of two vortex rings moving along a common axis of symmetry by numerical analyses and experiments in water. It has been found that both results of analyses and experiments are in good agreement and that the repetition of games between two vortex rings passing through each other don't happen in real fluid at least over the range of Reynolds number from 100 to 150.

Moreover we carried out the experimental studies on the interaction of two vortex rings moving along parallel axes side by side in water. Two rings were colored with different dyes in order to observe clearly the process of interaction. Very conspicuous phenomena were confirmed, that is, two vortex rings fuse into a distorted ring, thereafter it splits into two vortex rings again, each of them consists of two components of both initial rings and moves away in the direction perpendicular to the line on which the initial rings have stood.*

In following sections we report our investigations in detail on the interactions of two vortex rings moving along parallel axes side by side.

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* We have presented and read a paper concerning the above-mentioned investigations at Coloquium on Cohelent Structures in Turbulence held at University of Southampton from 25th to 29th March, 1974. On the way from the Coloquium, Kambe and Oshima visited the University of Cambridge and met Dr. Turner. He told them about his experimental researches, in which he examined the collisions of two vortex rings at various angles between the axes of two rings and observed quite similar phenomena to those we have found.

§ 2. Experimental Apparatus and Method

All experiments were carried out in a water tank with the size of 20 cm×20 cm×55 cm made of acrylic plates 1 cm thick. A circular cylinder is placed at the center of bottom of the water tank. The cylinder is 7.0 cm in diameter and 8.0 cm in length and divided into two chambers by a thin vertical acrylic plate. Two circular holes of diameter 1.6 cm are bored through the upper end plate of the cylinder with a space 3.2 cm between their centers. Vortex rings are produced by ejecting colored water through these two holes. The space between two holes are thus chosen because our previous experiments suggest that effects of a vortex ring are remarkable within distances of one or two diameters from its center. The lower ends of two chambers are communicated with each other and connected through a glass tube and a cock with an air reservoir, which is kept at a certain pressure slightly higher than the atmospheric pressure. The schematic diagram of the experimental apparatus is shown in Fig. 1.

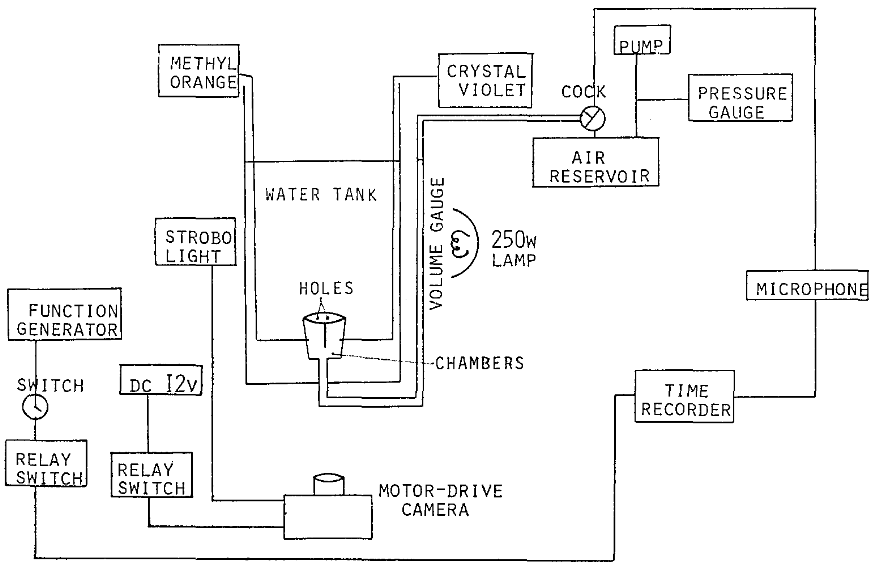

Fig. 1. Schematic diagram of the apparatus.

First the tank is filled with city water up to 50 cm in depth. Two kinds of dyes, methyl orange and crystal violet, are supplied through fine vinyl pipes into two chambers in the cylinder, and waters in the chambers are colored in orange and in violet, respectively. The solution of methyl orange is a little heavier than the water and that of the crystal violet is a little lighter than the water, so one or two drops of the ethyl alchol are added to the former solution and those of the salt solution are added to the latter one in order to avoid the effect of buoyancy on the vortex motion.

When the cock is opened in a short time, excess pressure in the air reservoir is applied on the water chamber and masses of colored waters are puffed out simultaneously through two holes into the water in the tank and soon two vortex rings, orange and violet, are formed from these masses. They move parallel side by side and eventually interact with each other. As is shown later, the interaction pattern changes according to the strength of fluid impulse at the initial ejection, which is controlled by the pressure of the air reservoir and the time in which the cock is opened. The processes of interactions are photographed in color films. Tungsten lamp and stroboflash are used to illuminate vortex rings. The color pictures are taken successively at some time interval using a moter-drive camera and also by a 16 mm cine-camera. The times when the cock is opened and the photographs are taken are marked in a time recorder by means of a microphone and a relay device, respectively.

The Reynolds number $R=\frac{rU_0}{\nu}$ of the experiment is about 100, where r is the radius of the hole of ejection, U_0 is the initial speed of the vortex ring and ν is the kinematic viscosity of water.

§ 3. Experimental Results and Discussions

From a great number of observations, it is found that the interaction processes of the two vortex rings ejected from different holes and moving parallel side by side are divided into three typical patterns according to the initial conditions, or impulses of ejecting fluids. These are as follows:

Case I. This is the case when the impulse of ejection is the most favorable. Two rings join into one distorted ring, which splits into two rings again.

Figure 2 shows an example of a series of front views of the interaction of this type. Schematic illustrations of the processes of fusion and fission of vortex rings are shown in Fig. 3. The figures on the left hand side show the front views and those on the right hand side the perspective views from the side and above of each stage of the interaction, which proceed from bottom to top in this figure.

1. Two circular vortex rings are formed in the same horizontal plane simultaneously, and travelling upwards along parallel axes side by side.

2. The inner portions of each vortex ring (the portions near to the other ring) are retarded more strongly than the outer portions (the portions far from the other ring) owing to the induced velocity of the other ring, the travelling direction and the plane of each ring turn toward the other, and two rings approach each other.

3. Then the inner portions of the two rings come in contact. At the point of contact A, vorticities of these portions are cancelled out with each other due to the opposite direction of circulation. There

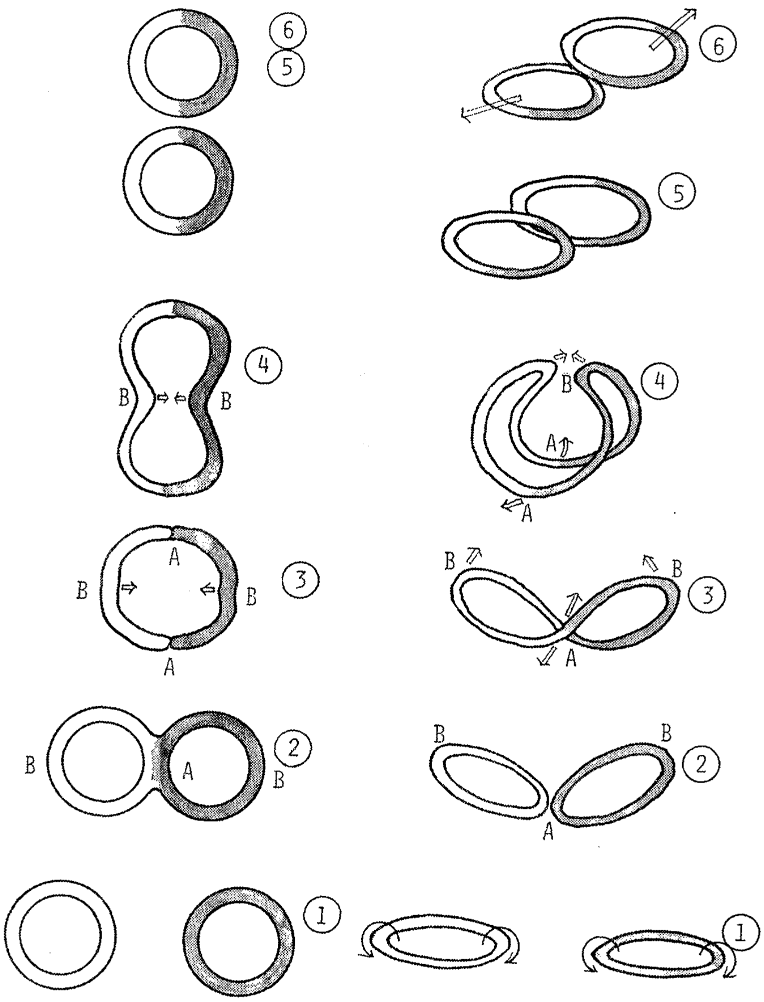

Fig. 3. Schematic diagrams of the interaction of *Case I*. Figures on the left hand side show the front views and those on the right hand side show the perspective views, and they proceed from bottom to top.

happen cross-linkings of vortex filaments of two rings and a distorted ring, of which one half is orange and the other half is violet, is formed.

4. In the newly-made ring, the portions near A move away from each other, while the portions near B approach each other until they contact at B.

5. Here again the cross-linkings of vortex filaments occur and one distorted vortex ring splits into two rings. Each of them is composed of two components of both initial rings, i. e. orange and violet components.

6. The two new rings are separated from each other and move away in the direction perpendicular to the line on which the initial two rings have stood.

Case II. When the impulse of ejection is smaller than in *Case I*, two rings join into one distored ring, which continues its motion without splitting into two rings. An example of interaction process of this type is presented in Fig. 4. Schematic diagrams are shown in

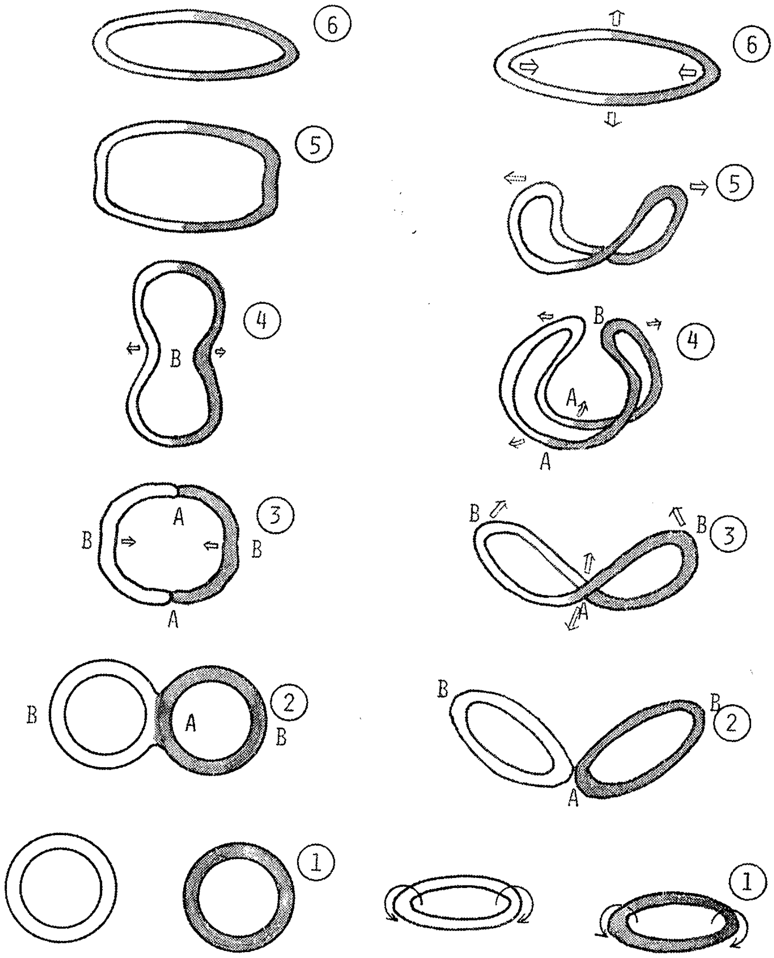

Fig. 5. Schematic diagrams of the interaction of *Case II.*

Fig. 5. Stages 1 to 3 are almost the same as in *Case I,* and a distorted vortex ring composed of orange and violet filaments is formed.

4. The portions near B of the newly-made ring once approach each other, but they don't cross over each other because of the weak impulse of ejection even if they seem to contact. Thereafter these portions recede rather rapidly from each other.

5. The deformed ring develops into a non-circular ring almost in a plane and moves normally to this plane.

6. This non-circular vortex ring continues its motion changing the shape. The largest diameter becomes shorter and the smallest diameter becomes longer until they interchange their magnitudes. Then the deformation occurs in the reversed direction and this process is repeated. Together with this intermittent deformation, the plane of the ring bends forward and backward as the ring travels. This motion and deformation of the ring are quite similar to those of a lenticular vortex ring[4].

Case III. When the impulse of ejection is strong enough also, the first two rings join into a distorted ring as in *Case I* and *Case II.* Owing to the strong impulse of ejection, the outer portions of two initial rings contact very closely over a wide range and are merged into a body of water of mixed colors. Remaining portions of the distorted ring split into two small and unstable rings. Then these two rings together with the body of colored water fuse into a mass of vorticity and gradually diffuse away.

Patterns of the interactions in these cases are determined mainly by the strength of fluid impulse at the initial ejection. In these experiments, the strength of fluid impulse is controlled by the volume of ejected fluid and the time taken to eject this volume of fluid. They are shown in Fig. 6, correlating with three patterns of interaction. As is shown in this figure, these conditions are restricted in the very narrow ranges in order to perform the fusion and fission of two vortex rings, especially for *Case I*.

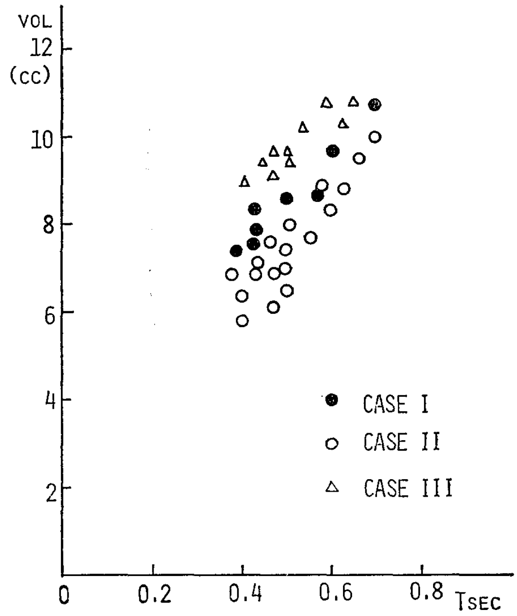

Fig. 6. Relation between volume and time of ejection for interaction.

Though the interaction patterns mentioned above seem very peculiar, they are supposed to be fundamental types of complicated motions of vortex system, also in turbulent motion.

Acknowledgements

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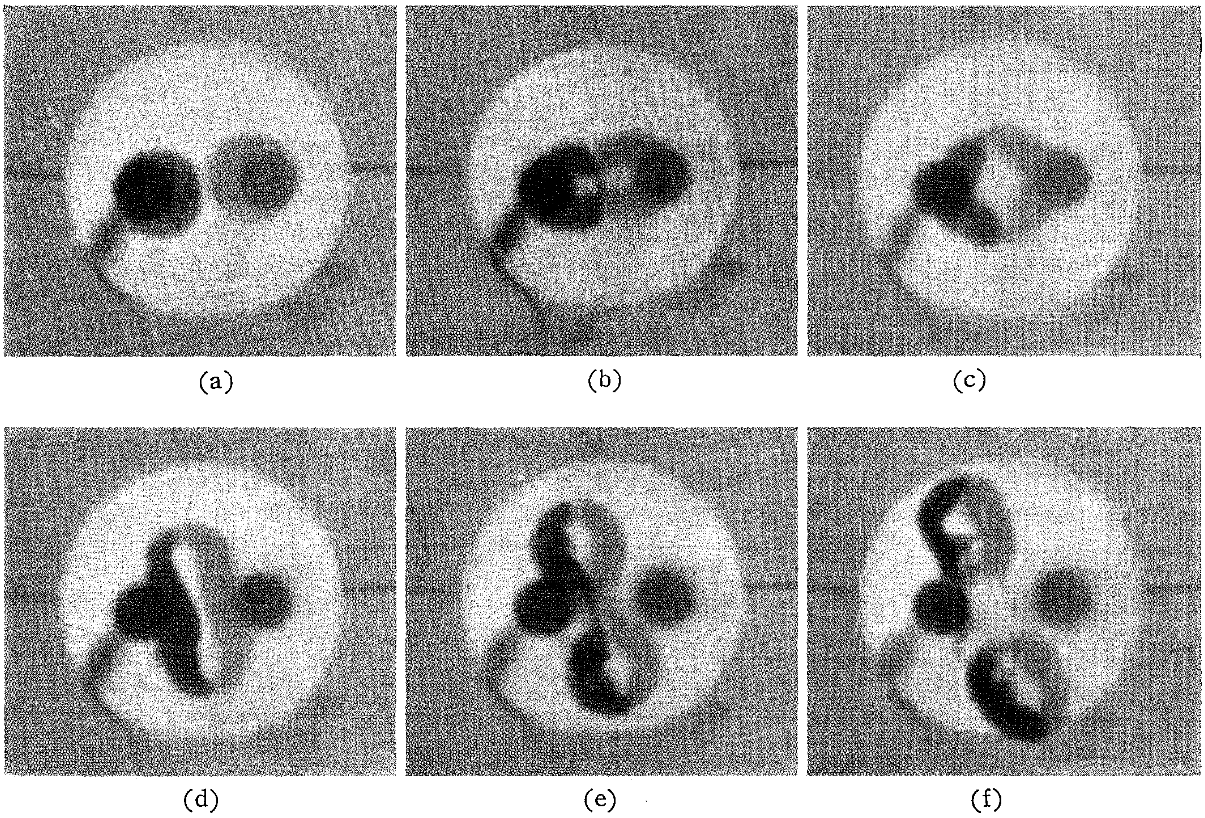

Fig. 2. A series of photographs of the interaction of *Case I*.
(a) t=0.5 sec, (b) 1.0 sec, (c) 1.5 sec, (d) 2.5 sec, (e) 4.0 sec, (f) 6.0 sec,
t, time after the ejection.

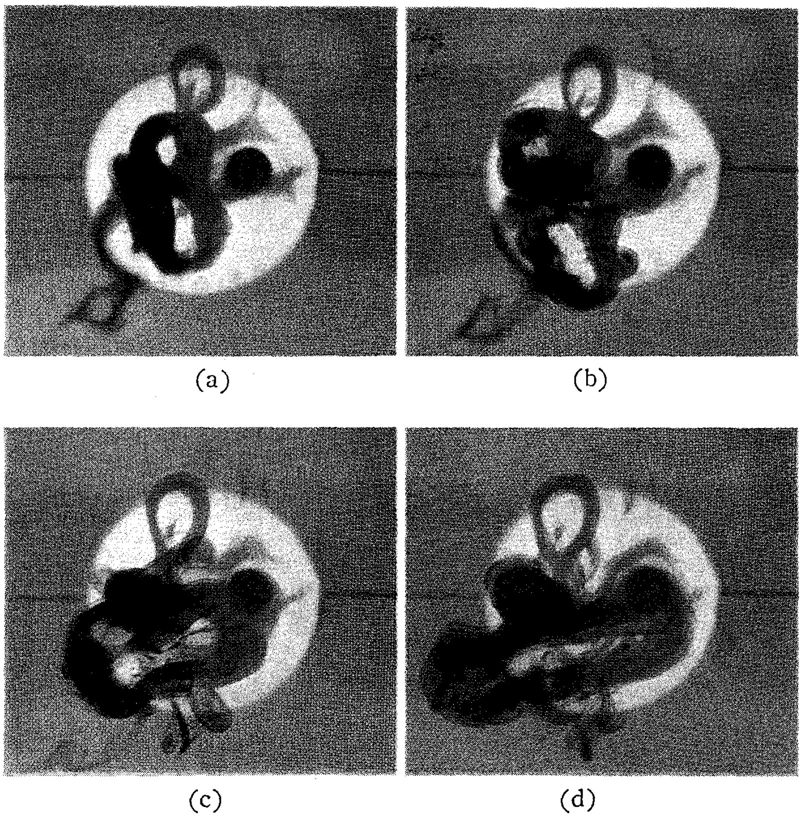

Fig. 4. A series of Photographs of the interaction of *Case II*.
(a) t=4.2 sec, (b) 7.7 sec, (c) 12.6 sec, (d) 17.5 sec.