Crosslinking of Two Vortex Rings Side by Side

By

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Summary: Mechanism of crosslinking of two vortex rings has been investigated experimentally. Phase locked measurements of velocity using x-type hot wire were carried out over the whole flow field at point by point, and time dependent vorticity fields were educed. Also, the flow field were visualized by Schlieren method. It is found that a new pair of vortex tube are created connecting the interacting vortex rings and they grow up gradually while the vorticity intensities of the main rings decreases. This is considered as kind of bridging phenomenon of the vortex tubes, proposed by Kida and Takaoka in their numerical simulations.

1. INTRODUCTION

Motion and mutual interaction of the vortex rings have been studied extensively by many researchers, stimulated by their fundamental role in turbulent flow. That is, as turbulence is a tangle of vortex filament, the study of the interactions of vortex constitutes the most fundamental approach to understanding turbulence. Also vortex rings are easily realized in laboratory. Among them, crosslinking of the vortex filaments is one of the most fascinating phenomena on the point of view of physical and topological aspects [*1*, *2*].

On the history of vortex ring study, flow visualization has played the major role for the phenomenological understanding. The motion and decay of vortex rings and the mutual interaction between them have been extensively studied and the various classes of these interaction phenomena were found through flow visualization study [*2*, *3*, *4*]. Recently, a time dependent measuring system of vortical flow field has been established [*5*] for the cases in which the phenomenon has good reproducibility. Data processing system utilizing microcomputers is used to educe the physical quantities such as vorticity. Using this system, quantitative measurements were carried out to investigate closslinking phenomena of two vortex rings proceeding side by side.

2. EXPERIMENTAL SETUP

Two vortex rings are generated by pushing out a mass of air through two circular orifices drilled on a buffer plate in front of the speaker with low frequency response, which is intermittently driven by electric pulses. The structure of the vortex rings is controlled by the amplitude and the duration of the driving pulse. Due to the mutual

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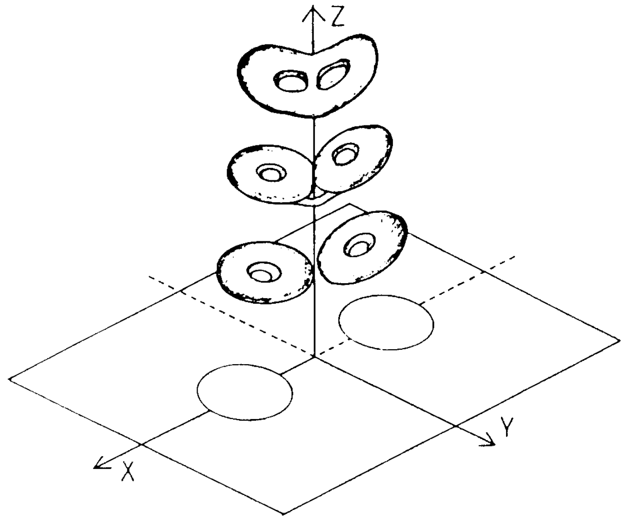

Fig. 1. General view of vortex deformation and the coordinate system.

interaction of these vortex filaments, near parts of these two rings approach each other and crosslinking occurs around the touching point. General view of deformation with the coordinate system is shown in Fig. 1, in which the origin is set at the center of two orifices. The diameter of each orifice is 16mm and the distance between their centers is 32mm. Visualized pictures are taken at various instants from the driving pulse by Schlieren method for the two orthogonal directions using the time delayed strobolight. Time sequential velocity data phase-locked with the driving pulse were taken at each point spatially-discritized over the whole flow field using x-type hot-wire with micro-computerized A/D converter system. The measuring points were distributed three-dimensionally with 1.5mm mesh spacing. At every point, 256 data were taken sequentially at every 400μs time instant for 0 to 102ms. Also, 384 data at time interval of every 50μs were taken for 10 to 29ms to focus the fine structure of crosslinking. These time sequential velocity data were sorted into the space data at every time instant. In this measurements, it is important and necessary to reproduce the same phenomenon for every generation of vortex rings. So the reproducibility of the phenomenon was checked for various initial conditions by visualized photographs and the wave forms of hot-wire output, and initial condition with little scattering was selected. That is, the same photographs and the same wave forms were obtained with approval difference applying the same initial condition. Reynolds number based on the orifice diameter D and the initial traveling speed of the vortex ring V is about 4000.

3. Results and discussion

Figure 2 is a series of Schlieren photographs from two directions, in which upper one shows the X-plane and the lower one does the Y-plane at the same time instant, respectively. Two vortex rings are inclined to inside due to their mutual interaction, and they collide each other from the nearest parts, and then, small disturbances are observed at the touching part. Thus the closslinking starts to make a skewed elliptic vortex ring.

Typical equi-vorticity contours in the orthogonal planes corresponding to the visualized pictures are shown in Fig. 3, perspectively, in which the left and the right halves of the figure denote the contours of the X- and the Y-planes, respectively, at each time instant. At the early stage, it is seen that a pair of vorticity contours is observed in the X-plane where the two vortex rings are generated, while no vorticity is in the Y-plane. As the time passed, the inner side vorticity contour in the X-plane approaches toward the axis, and decreases its intensity while the new vorticity contour appears in the Y-plane. This vorticity in the y-plane continues to increase, and the inner vorticity in the X-plane finally disappears.

Figures 4 and 5 are the time dependent circulation over the whole field derived from the coarse and fine time interval measurements. After the generation period of vortex rings is over, $\Gamma\ y_{in}$ decreases rapidly causing appearance of $\Gamma\ x_{out}$ which inverse-proportional to $\Gamma\ y_{in}$ increase. It is said that $\Gamma\ y_{in}$ is transferred into $\Gamma\ x_{out}$ as a result of crosslinking. During this time period, $\Gamma\ y_{out}$ is kept almost constant, and a small amount of $\Gamma\ x_{in}$ is appeared as the sum of the disturbances over the whole flow field due to the mixing effect of crosslinking. Figure 6 shows the time variation of the maximum vorticity points in the two orthogonal planes for coarse measurement. After

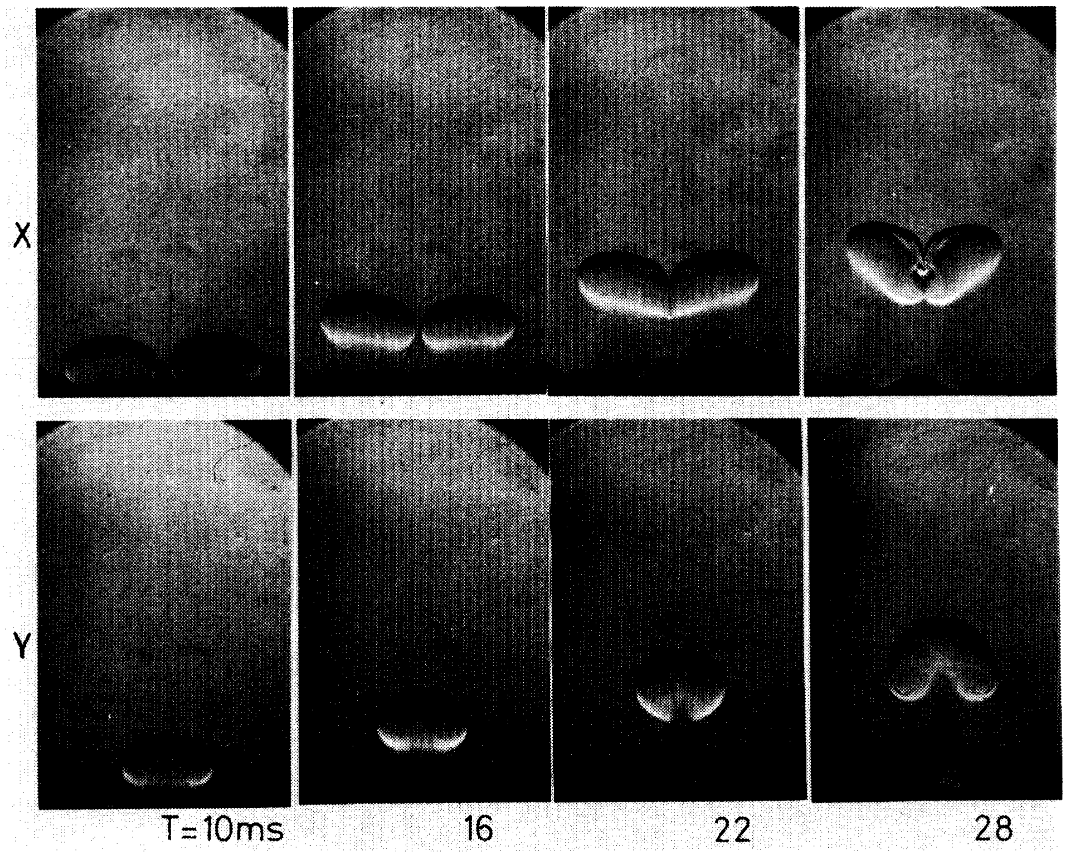

Fig. 2. A series of Photographs of crosslinking process. The upper and the lower photograph corresponds to the same time instant in the x- and the y-plane, respectively.

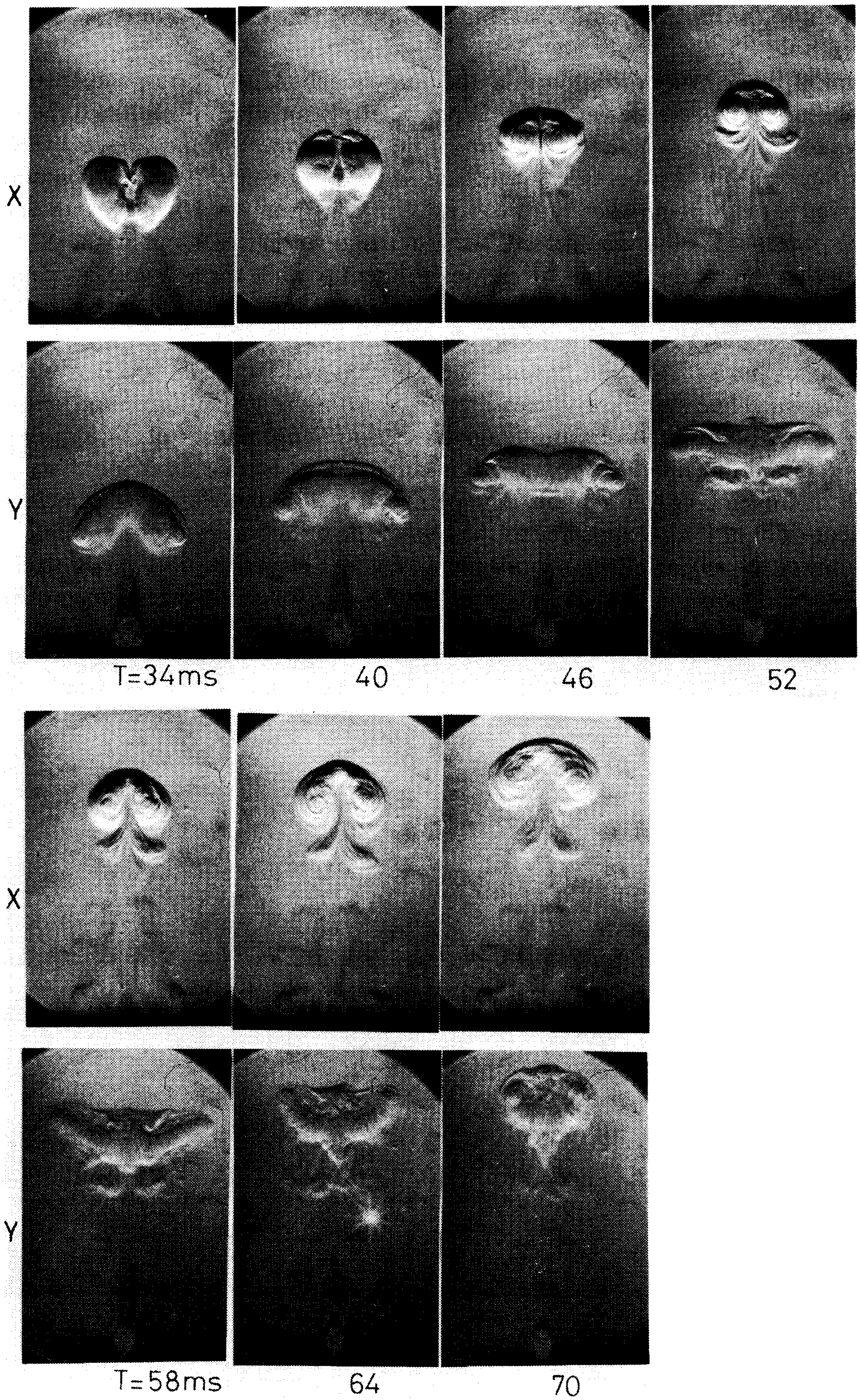

Fig. 2. (continued)

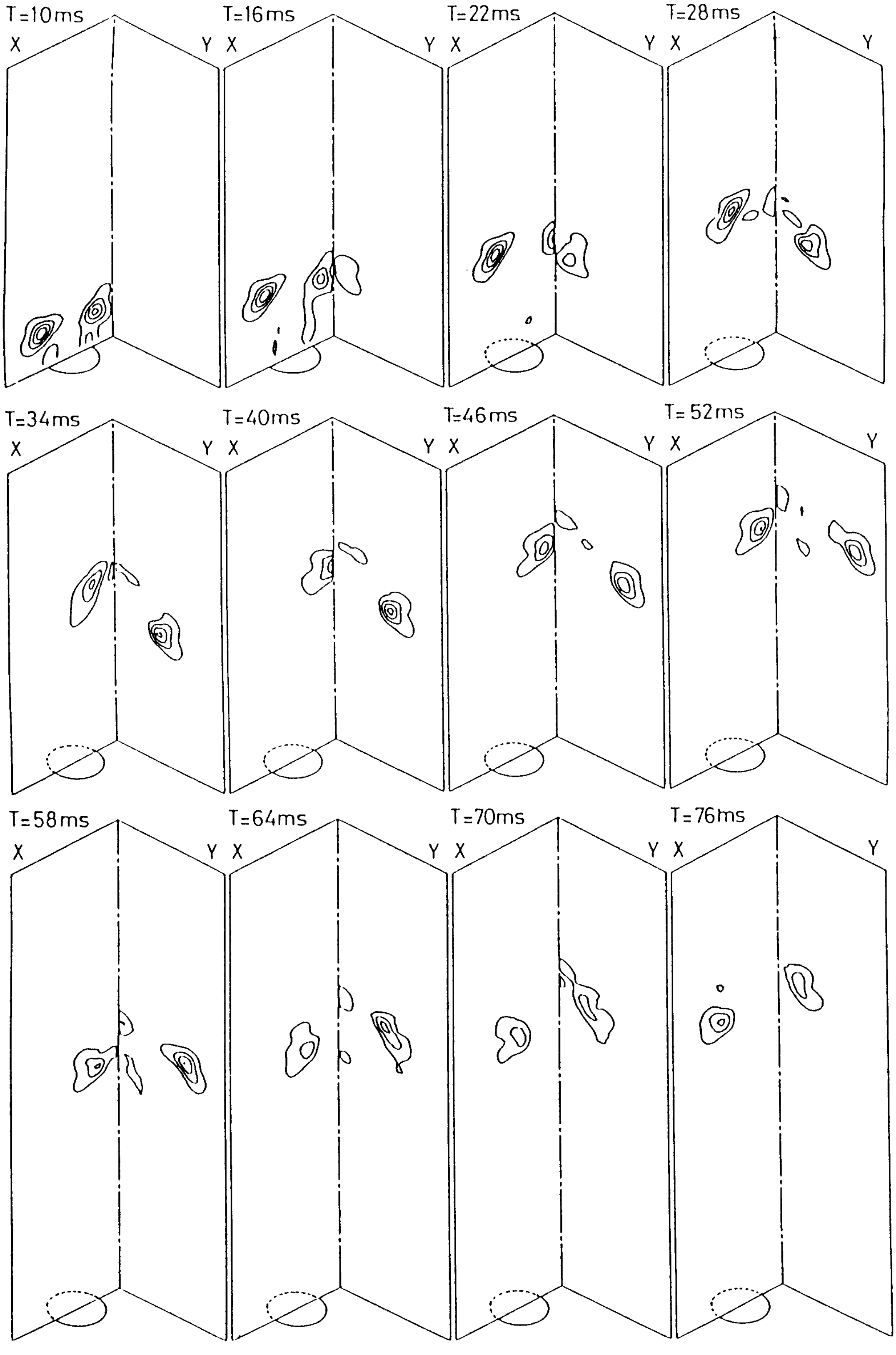

Fig. 3. Equi-vorticity contours of the two orthogonal planes. The right and the left halves correspond the x- and the y-plane, respectively.

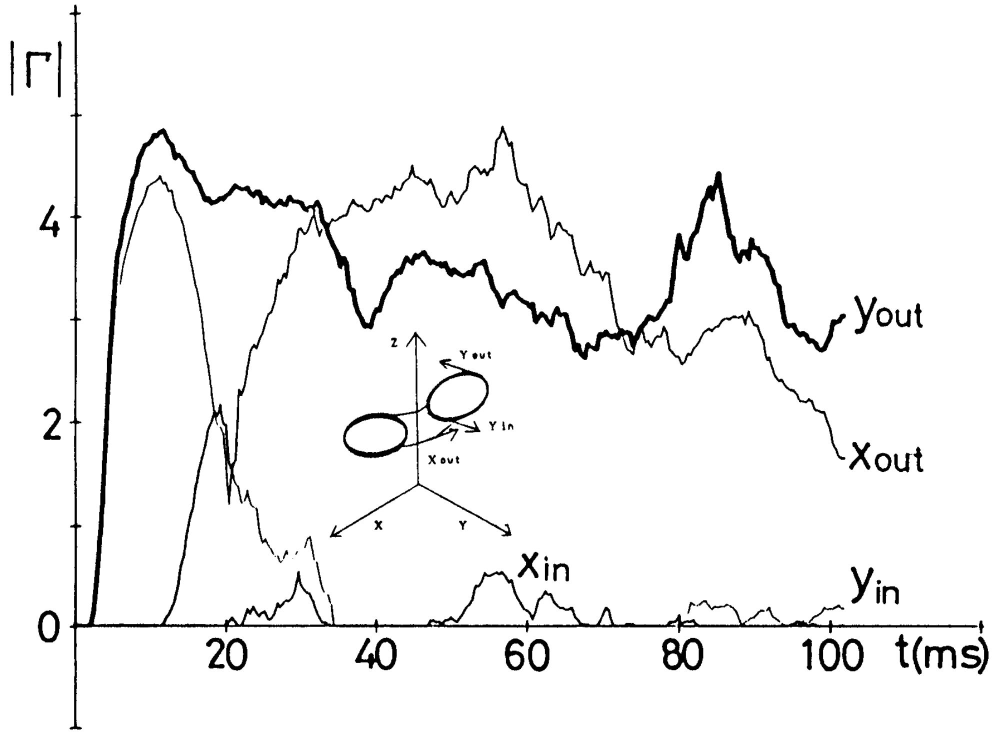

Fig. 4. Time variation of Γ with coarse time intervals.

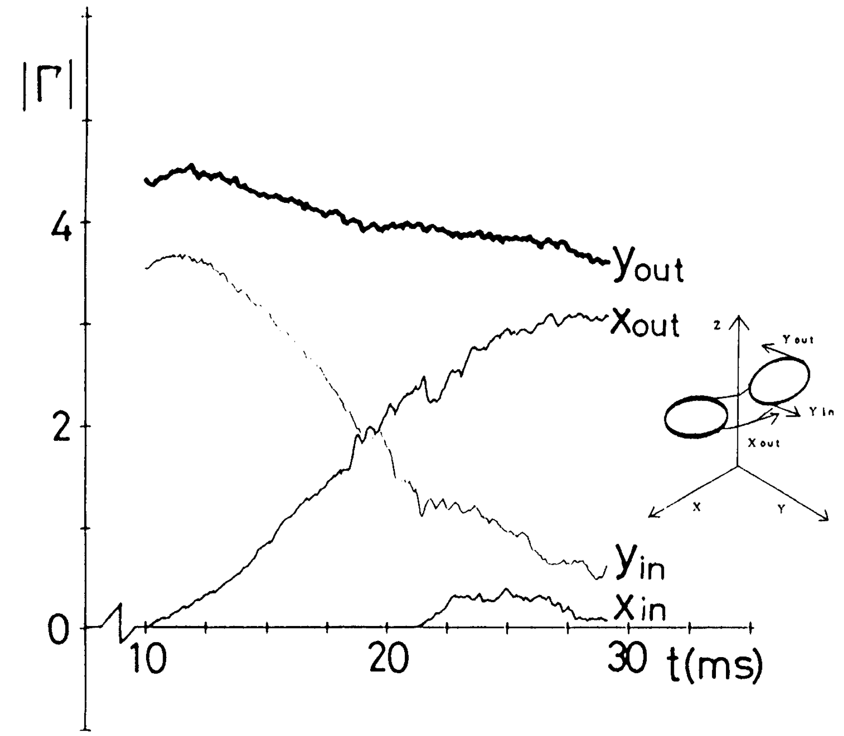

Fig. 5. Time variation of Γ with fine time intervals.

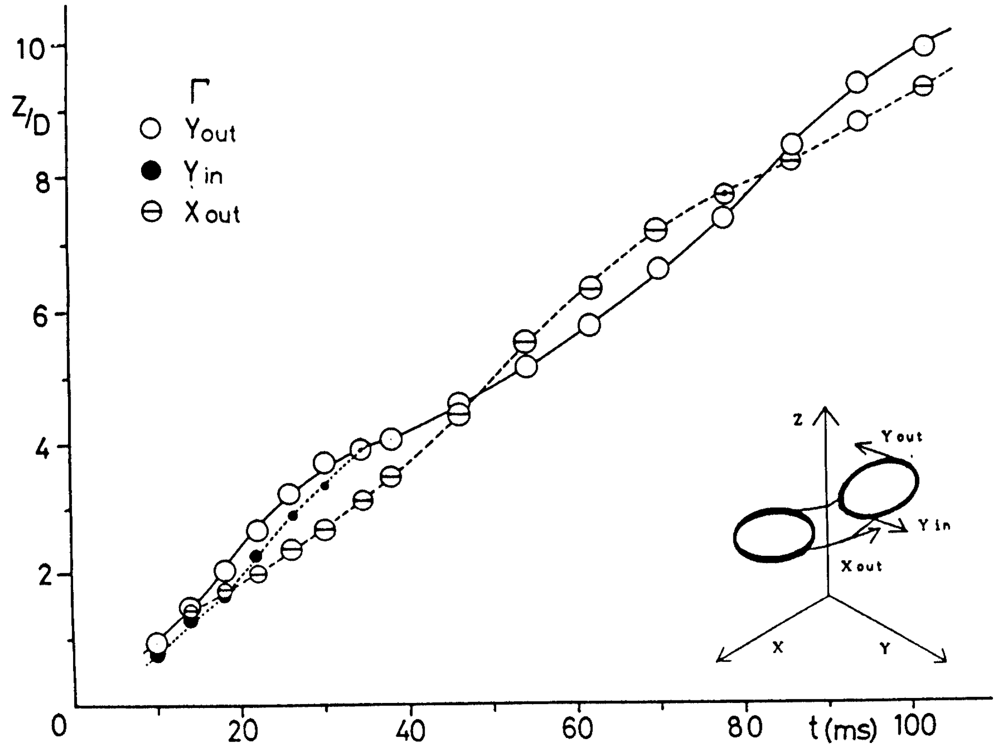

Fig. 6. Time variation of the positions of the maximum vorticity for the measurement with coarse time intervals.

the crosslinking is over, the maximum points of the circulations of outer parts of the rings alternate their positions oscillately, as seen in the deformation of an elliptic vortex ring. Also, the maximum vorticity points for fine measurement are shown in Fig. 7, in which the radii of the symbol circle show the reduced radius of the vorticity contour with the same level. The diameter of Γ x_{out} increases gradually while that of Γ y_{in} decreases and disappears when the radii of Γ y_{out} and Γ x_{out} become almost equal. Also Γ x_{out} is located behind Γ y_{out} and Γ y_{in}. Two curves of Γ y_{in} and Γ x_{out} have the same value at about 18ms, and this is agreed with the result of the orthogonal planes with the same value of circulations as shown in Fig. 5. From these figures, it is known that the vorticity Γ y_{in} of the initial two vortex rings is gradually transferred to forming a new pair of bridges of Γ x_{out} at the place apart from the initial vortex rings. So it is concluded that the whole vortex rings do not cut and reconnect at one point or at one moment, but the cutting parts dissolve gradually and the bridges appear at distant position. Another words, they behave as an assembly of a number of vortex filaments as used in discrete vortex method of numerical simulation[*6*, *7*]. Each filament individually crosslinks one by one and moves away quickly depending on the strong curvature in the direction normal to the plane of the filament. At the touching point of the initial two filaments, they form acute angles and then they flee away due to their large induced velocity. While the non-crosslinking parts of the vortex rings continue to proceed their way during this time, the new vorticity concentration transferred from the original one is formed.

In the case when the induced velocity of the original ring is in the same direction of

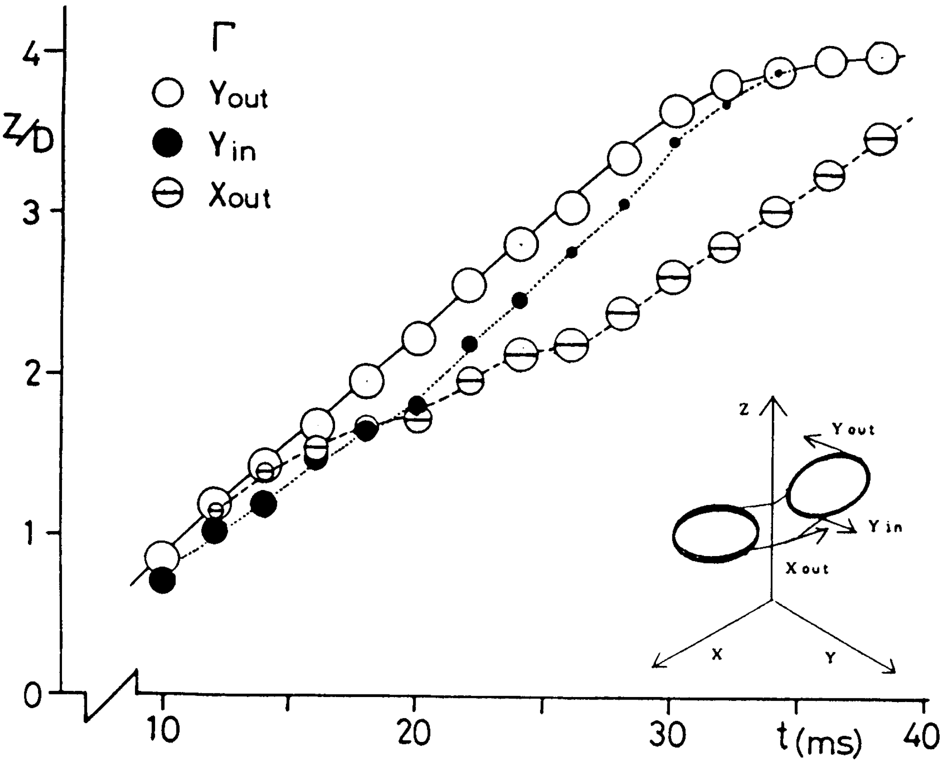

Fig. 7. Time variation of the positions of the maximum vorticity and the thickness of vortex tubes for the measurement with fine time intervals.

the cross-linked vortex tube, as in the case of an elliptic ring with high aspect ratio, the newly created vortex filament tends to overlap the original one and thus, it is hard to distinguish.

Considering the experiment visualized by smoke at low Reynolds number [*2*], it is observable two thin smoke lines like bridgings after the crosslinking. But it is difficult to say at this stage that the parts of smoke show the concentration of vorticity. Also it is not certain that the existence of vorticity coincide with smoke especially in the interaction process.

In the numerical calculation using a finite difference method of the incompressible Navier-Stokes equations by Chen [*8*], bridging of vortex tube was observed at both sides of the intersection of the two rings. Also the numerical simulation by Ashurst and Meiron [*9*] shows the crosslinking of vortex tubes although the fine time dependent structure was not reported.

On the other hand, in the numerical calculation for tangle of vortex tubes by Kida and Takaoka [*10*], new concentration of vorticity is observable as bridges, which increases with time. This vorticity is not transferred from the specific part of the vortex tube, but grows up with support from the whole vortical field. Although time evolution of each vortex filaments is difficult to identify experimentally, these observed phenomena will be said to correspond to the bridging numerically simulated.

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