# On the interaction of vortex rings and pairs with a free surface for varying amounts of surface active agent

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Observations are reported of the interaction with a free surface of vortex rings and vortex pairs moving normal to the surface when different amounts of surface active agents are present on the surface. At a vortex ring Reynolds number $\Gamma/\nu \approx 3800$, the interaction with a contaminated free surface results in the generation of secondary and tertiary vortex rings that limited the outward motion of the vortex ring core. When the experiment was repeated with a cleaner surface the formation of the secondary vortex ring was delayed so that the outward motion and stretching of the vortex ring core was much more than for the contaminated surface. At a Reynolds number $\Gamma/\nu \approx 18\,000$, the vortex pair was observed to rebound from the free surface contrary to what one would expect for an inviscid flat boundary. When the surface was cleaned by draining away a portion of the contaminated surface water the amount of rebound was reduced. These changes in interaction are believed to be caused by the reduction in concentration of the surface active agent which, in turn, results in a reduced generation of secondary vorticity ahead of the vortex ring or pair before and during the interaction with the surface.

## I. INTRODUCTION

Recent experimental evidence on the interaction of vortex rings and pairs with the free surface suggests that contamination of the surface by surface active agents might play an important role in the dynamics of underwater vortical flows.[1,2] It has long been recognized that capillary stresses are generated at a water–air interface by flow induced concentration gradients of surface active agents. A manifestation of these flow processes is the modification of the propagation characteristics and damping of surface waves by surface active agents.[3] In the case of the interaction of underwater vortical flows with the free surface, it is apparent that advection of surface active agents by the underwater vorticity can generate capillary stresses at the surface that must be balanced by viscous stresses in a boundary layer at the free surface. These flow processes can also influence the dynamics of turbulent eddies at a contaminated water surface, as discussed by Davies[4] and by Davies and Driscoll.[5]

In the present experiments we study the role of these capillary forces and associated viscous effects on the evolution of two relatively simple vorticity distributions: a vortex ring and a vortex pair. Each vorticity distribution is investigated for two surface conditions: a highly contaminated surface and a cleaner free surface. The study focuses on the changes of the global evolution of the flow caused by the surface active agents at moderate (vortex ring) and high (vortex pair) Reynolds numbers. In all cases the vortices approach the surface in the direction perpendicular to the surface, thus avoiding more complex vortex reconnection processes of the type discussed in Ref. 2.

## II. VORTEX RING RESULTS

The vortex ring experiments were conducted in the free surface water tank facility described in Ref. 6 using a newly designed vortex ring generator. A pressurized water tank connected to the generator through a solenoid valve was used to drive the flow. The vortex rings were produced by opening the solenoid valve for a short time ($\approx 0.6$ sec). The vortices formed at the exit of a contoured nozzle having circular cross section with a diameter of 2.54 cm at the exit. The nozzle exit was positioned parallel to the water surface at a distance of 9 cm from it. Thus the vortex rings propagated normal to and toward the free surface. The circulation of the vortex rings was determined from hot-film velocity measurements along the centerline of the generator. These measurements showed that the vortex ring formation process is completed at a distance of approximately three nozzle exit diameters downstream of the generator. The vortices were visualized by adding a fluorescent dye (Rhodamine 6G) at a concentration of 3 ppm to the fluid in the generator. The flow was illuminated with a thin sheet of laser light from an argon–ion laser positioned along the centerline of the generator, perpendicular to the free surface. It follows that only fluid that started its motion in the generator is visible on the photographs of the flow cross section. Photographs of the flow were obtained with a 35 mm Nikon camera synchronized to the solenoid valve driving circuit. Measurements of the flow evolution were made on video recordings of the vortex core location using the same visualization technique.

Typical evolutions of vortex rings at a Reynolds number $\Gamma/\nu \approx 3800$, when the surface was contaminated with surface active agents and with a cleaner surface, are shown in Figs. 1(a) and 1(b), respectively. The Froude number, based on the vortex ring diameter before the interaction, was $\Gamma/(ga^3)^{1/2} \approx 0.1$. Each photograph in the sequences was obtained on a different realization of the flow. The location of the free surface is indicated in each photograph. The mirror image appearing above the surface is an optical effect resulting from total reflection of the underwater image on the water surface. For the experiments with a contaminated

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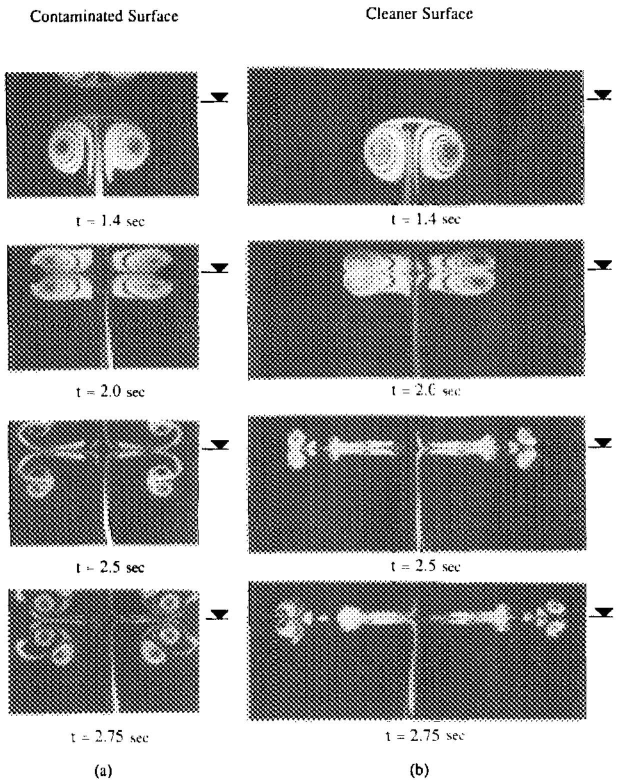


FIG. 1. Interaction of a vortex ring with a free surface. (a) Contaminated surface; (b) cleaner surface; ▼, surface location.

surface shown in Fig. 1(a), the water was left in the tank overnight without a surface cover. The water was originally drawn from the Ann Arbor city supply through a 5 $\mu$m filter. The photographs in Fig. 1(a) clearly show the formation of a secondary vortex ring with vorticity of opposite sign compared to that of the original vortex. A third vortex ring with the same sign vorticity as the secondary vortex was also formed and can be seen at an early stage of development in the last photograph of the sequence in Fig. 1(a). This evolution of the vortex ring is very similar to the evolution at a solid surface.[7,8] This observation suggests that the water on the surface may not move during the interaction. Observations of small particles on the surface confirmed this conjecture, indicating that capillary forces prevented fluid motion tangential to the surface for these vortex ring experiments.

Figure 1(b) presents a sequence of photographs of the vortex ring interaction with a cleaner free surface. The vortex ring Reynolds and Froude numbers were the same as in Fig. 1(a). The cleaner surface was obtained by allowing a small continuous flow of filtered tap water in the free surface tank for several days. During this time a stand-up pipe connected to the drain was used to produce a surface current that continuously removed surface contaminants. Prior to the experiments, the flow was turned off and the water in the tank was allowed to come to rest before generation of the vortex ring. The evolution of the vortex ring in this case is closer to what would be expected in the absence of capillary effects at the surface. The self-induced outward motion of the vortex core persists for a longer time. Also, the vortex core size is significantly reduced as a result of stretching. Although there is some dyed fluid left behind the vortex ring during the stretching process, the amount of vorticity in these pockets of fluid must be small since it does not alter the trajectory of the main vortex core. Only in the last photograph of the sequence is there evidence of the formation of a secondary vortex ring.

The trajectory of the vortex ring core for the contaminated and cleaner surface case, measured on video recordings of the evolution, are plotted in Fig. 2. The Reynolds number for the cleaner surface case plotted on the right was $\Gamma/\nu \approx 3800$ and for the contaminated surface case plotted on the left was $\Gamma/\nu \approx 2500$. In the case of a contaminated surface, the formation of the secondary and tertiary vortex ring limits the outward motion of the original vortex to $2\frac{1}{2} \times$ the initial radius. In contrast, in the case of a cleaner surface, the outward motion continues to a radius of $3\frac{1}{2} \times$ the initial radius. There is, however, a secondary vortex formed, which, as in the case of a contaminated surface, causes the trajectory of the initial vortex to rebound from the surface.

## III. VORTEX PAIR RESULTS

The vortex pair was generated by the motion of a pair of flaps as described by Willmarth *et al.*,[1] which were actuated with a new stepping motor system. The vortices were generated at the tip of the flaps, which were 12.7 cm beneath the free surface. Flow visualization of the vortices was accomplished with fluorescein dye injected into the otherwise dye-free fluid between the flaps, and illuminated by a sheet of light from an argon–ion laser. The light sheet and point of dye injection were located at the center plane of the generator. The position of the vortex pair was photographed with a 35 mm motor driven Nikon camera at a rate of three photographs per second using Kodak T Max film and a Nikon 50 mm, $f = 1.4$ lens. Good control of the strength of the vortices was possible with the stepping motor actuating system. For six realizations, in which the tips of the flaps were initially 2.8 cm apart and closed to a distance of 0.2 cm at an average rotation rate of 0.23 rad/sec, the average distance between the vortices was 2.5 cm and the average propagation speed was 11.5 cm/sec, giving a Reynolds number $\Gamma/\nu \approx 18\,000$. The corresponding Froude number, based on the distance between the vortices was $\Gamma/(gb^3)^{1/2} = 1.45$.

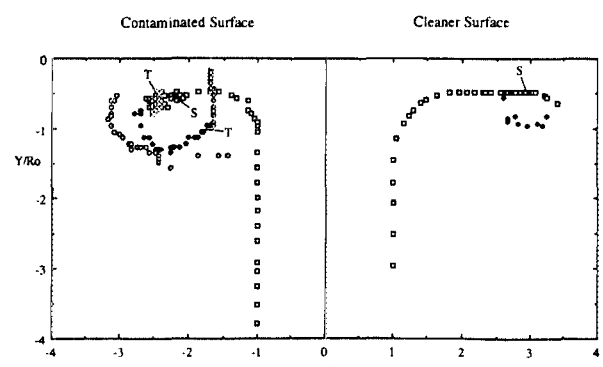


FIG. 2. Vortex ring trajectories with contaminated surface (left side) and cleaner surface (right side). □, Primary vortex core; ◇, secondary vortex core; O, tertiary vortex core; *S*, location of primary vortex when secondary vortex is first observed; *T*, location of primary and secondary vortex when tertiary vortex is first observed.

The vortex pairs were not perfectly two dimensional as a result of end wall effects and small-scale three-dimensional motions. However, the vortices showed good spanwise coherence over the center region (10 cm) of the flow.

A comparison of the vortex pair evolution with a contaminated surface and with a cleaner free surface is presented in Fig. 3. These pictures are representative of those obtained in the center region of the generator, where the flow is by and large two dimensional. Figure 3(a) is a sequence of photographs showing the evolution of the vortex pair with a contaminated surface. The Ann Arbor tap water in the tank had been standing without surface cover for two weeks. It can be seen that the trajectory shows a definite rebound after the pair has made its closest approach to the free surface. We have observed that vorticity of opposite sign to the incident vorticity is generated along the surface ahead of the incident vortices (see the photograph at $t = 1.8$ sec). The interaction between this secondary vorticity along the surface causes the incident vortices to be turned back away from the free surface. It should be noted that Barker and Crow[9] also observed this type of rebound in their studies of a vortex pair interacting with a free surface. Also Peace and Riley[10] have observed vortex pair rebound at a solid surface and at a shear-free rigid boundary in numerical simulations at a lower Reynolds number. However, these authors did not discuss the possibility of the generation of secondary vorticity, owing to the presence of surface contamination as a cause for vortex pair rebound.

When the surface contamination was reduced by draining away water from a thin layer near the surface, the trajectory of the vortices showed less rebound than with the more contaminated surface. Figure 3(b) is a series of five photographs of the vortices with a less contaminated surface. The amount of secondary vorticity that was generated also appeared to be reduced for this case.

The trajectories for the above two cases are shown in Fig. 4. The time given on the figure is the elapsed time since the beginning of the flap motion. The rebound for the contaminated surface can be clearly observed after $t = 1.5$ sec. The amount of rebound for the less contaminated surface (the dashed line) is clearly reduced. We also observed that the transition to turbulence for these relatively high Reynolds number vortex pairs seemed to occur sooner than in the case of the more contaminated surface.

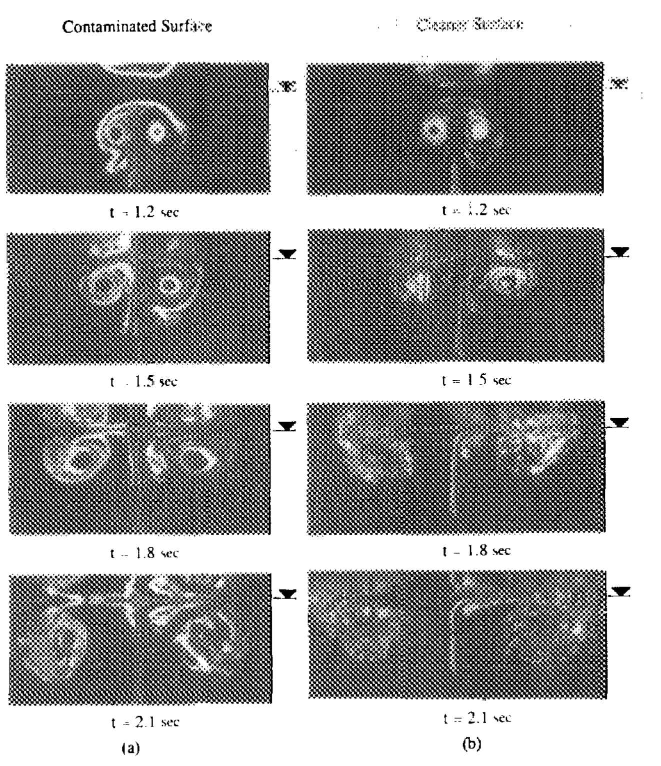


FIG. 3. Interaction of a vortex pair with a free surface. (a) Contaminated surface; (b) cleaner surface; ▼, surface location.

## IV. DISCUSSION

It is apparent from these observations that, when present, surface active agents play an important role in the dynamics of the interaction of vortical flows with a free surface. Both the vortex ring and vortex pair experiments show generation of increased amounts of secondary vorticity at the free surface when additional surface active agents are present on the surface. This vorticity diffuses away from the surface and rolls up into secondary vortices that alter the global evolution of the flow.

In the vortex ring experiments at moderate Reynolds number, $\mathrm{Re} \approx 3800$, and relatively low Froude number, $F \approx 0.1$, there was negligible vertical motion and no motion tangential to the surface during the interaction of the ring with the contaminated surface. The contamination formed a stagnant film. With a cleaner surface, motion tangential to the surface was observed during the interaction of the ring with the surface. It is emphasized that at the low Froude numbers of the vortex ring experiments the surface remained essentially flat during the interaction.

In the vortex pair experiments, both the Reynolds number and the Froude number were higher, $\mathrm{Re} \approx 18\,000$ and $F \approx 1.45$, with the result that motion tangential to the surface was observed during the interaction of the vortex pair with the contaminated surface and with the cleaner surface. At this larger Froude number, a slight motion of the surface in the vertical direction was also observed. With a cleaner surface less secondary vorticity was generated on the free surface ahead of the vortices than was observed with the contaminated surface. The reduction in the rebound of the vortices with a cleaner surface is attributed to the reduction in the generation of this surface vorticity.

It should be noted that with the contaminated and cleaner surface, the free surface directly above the vortex

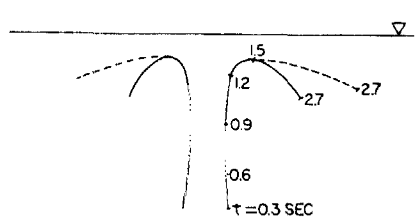


FIG. 4. Observed trajectories of vortex pairs with contaminated surface (solid line) and less contaminated surface (dashed line); ▽, surface location.

pair during the interaction was slightly elevated by the upwelling fluid carried with the vortex pair. The resulting distortion of the free surface has the result that vortices will rise to a maximum height and then sink somewhat as they move apart after the more intense surface interaction phase is complete. This phenomena has been discussed by Yu and Tryggvason,[11] who have performed numerical calculations of the interaction of a vortex pair with a free surface for an inviscid fluid. Their calculations show that a vortex pair exhibits an inviscid rebounding effect, which is a function of the Froude number. This inviscid rebound, at higher Froude numbers, will be in addition to the rebound caused by the generation of secondary vorticity when a surface active agent is present on the surface.

The phenomena of generation of secondary vorticity when the surface is contaminated is closely related to the observations of Scott,[12] who reported experiments on the flow beneath a stagnant film on a water surface. Scott[12] describes the observation of a ridge (termed the Reynolds ridge), which marks the origin of a boundary layer beneath the stagnant film on the water surface. In our observations of the rise of a vortex pair generated by a delta wing traveling beneath the surface in the manner first described by Sarpkaya and Henderson,[13] we have observed what appears to be a Reynolds ridge on either side of the center of the wake disturbances (striations) produced by the rising vortex pair when the surface is contaminated. We have not observed the Reynolds ridge with the vortex pair generator. We believe that owing to the relatively large vortex pair Reynolds number and/or Froude number, the ridge does not form before the surface is violently disturbed by the vortex pair interaction with the surface.

In concluding, we note the significance of surface active agents in the fluid dynamics of free surfaces. Very small concentrations of surface active material in the bulk water can result in significant changes in surface tension when and if the material reaches the surface. Even the dyes used in these experiments, Rhodamine 6G and Fluorescein, are known surface active agents.[14] It is apparent that the experiments with a *cleaner* surface reported here were not conducted with a *clean* free surface, i.e., free from surface active agents. Scott[15] discusses techniques to obtain clean free surfaces for fluid dynamics research. At high Reynolds number the need for large quantities of water and large surfaces makes the problem even more difficult. Further, it seems that in most practical cases the water surface would be contaminated with surface active agents to some degree, unless special precautions are taken. These results indicate that capillary effects can be important, even in high Reynolds number flows. More quantitative studies of these flow processes are currently being conducted in our laboratory.

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