Vortex Cavitation

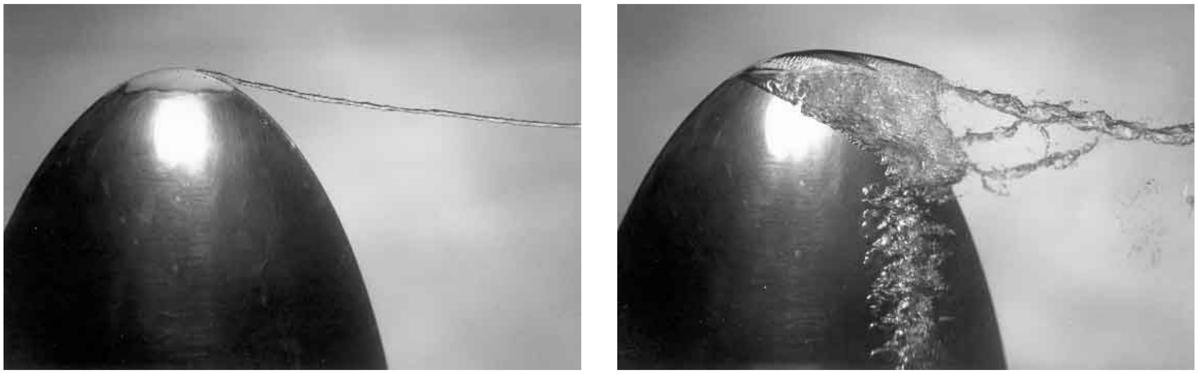

Figure 1: Cavitating tip vortices generated by a finite aspect ratio hydrofoil of ellipsoidal planform at an angle of attack. On the left is a continuous tip vortex cavity at a cavitation number, $\sigma = 1.15$, and an angle of attack of 7.5°. On the right, the tip vortex emerges from some surface cavitation at a lower value of $\sigma = 0.43$ (angle of attack = 9.5°). Reproduced from Higuchi, Rogers, and Arndt (1986) with the authors' permission.

Figure 2: Cavitating tip vortex on a scale model of the low-pressure LOX turbopump impeller in the Space Shuttle Main Engine. The fluid is water, the inlet flow coefficient is 0.07 and the cavitation number is 0.42. Reproduced from Braisted (1979).

Many high Reynolds number flows of practical importance contain a region of concentrated vorticity where the pressure in the vortex core is often significantly smaller than in the rest of the flow. Such is the case, for example, in the tip vortices of ship's propellers or pump impellers or in the swirling flow in the draft tube of a water turbine. It follows that cavitation inception often occurs in these vortices and that, with further reduction of the cavitation number, the entire core of the vortex may become filled with vapor. Naturally, the term “vortex cavitation” is used for these circumstances. In Figures 1 to 6 we present some examples of this particular kind of large-scale cavitation structure. Figure 1 consists of photographs of cavitating tip vortices on a finite aspect ratio hydrofoil at an angle of attack. In those experiments of Higuchi, Rogers, and Arndt (1986) cavitation inception occurred in the vortex some distance downstream of the tip at a cavitation number of about $\sigma = 1.4$. With further decrease in pressure the cavitation in the core becomes continuous, as illustrated by the picture on the left in Figure 1. This transition is probably triggered by an accumulation of individual bubbles in the core; they will tend to migrate to the center of the vortex due to the centrifugal pressure gradient. With further decrease in σ, bubble and/or sheet cavitation appear on the hydrofoil surface (Figure 1, photograph on right) and disturb the tip vortex which is nevertheless still apparent. Cavitating tip vortices are also quite apparent in unshrouded pump impellers as illustrated by Figure 2.

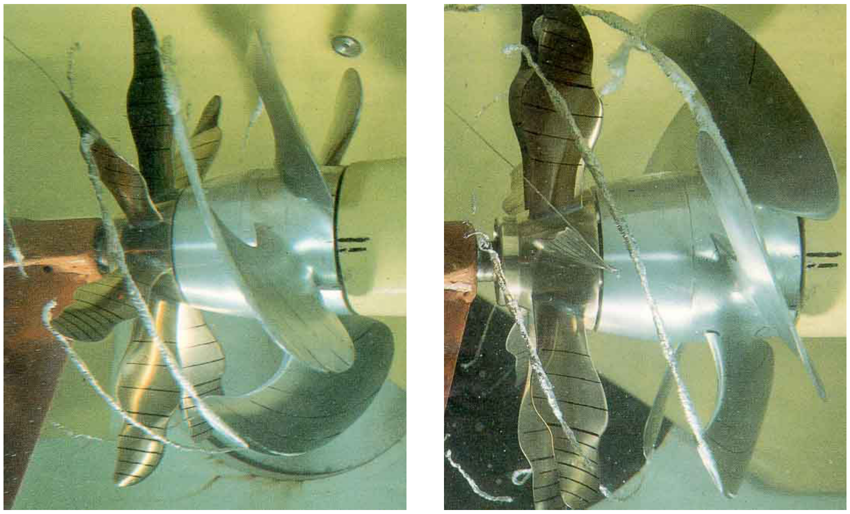

Figure 3: Tip vortex cavitation on a model propeller. Reproduced with permission of the Netherlands Maritime Research Institute and Lips B.V.

When continuous cavitating tip vortices occur at the tips of the blades of a propeller they create a surprisingly stable flow structure. As illustrated by Figure 3 the intertwined, helical cavitating vortices from the blade tips can persist for a long distance downstream of the propeller.

Clearly cavitation can occur in any vortex, and Figures 4 and 5 present two further examples. Figure 4 shows a typical picture of a cavitating vortex in the swirling flow in the draft tube of a Francis turbine. Often these draft tube vortices can exhibit quite complex patterns of unsteady flow. The vortices in a turbulent mixing layer or wake will also cavitate, as illustrated in Figure 5, a photograph of the separated wake behind a lifting flat plate with a flap. Looking closely at the structures in this turbulent flow, one can identify not only the large transverse vortices that contain many bubbles, but also the filament-like longitudinal vortices first identified in a single-phase mixing layer flow by Bernal and Roshko (1986). After that discovery by Bernal and Roshko one could recognize this secondary vortex structure in photographs of cavitating wakes and mixing layers taken many years previously, and yet its importance was not appreciated at the time. The streamwise vortices can play a particularly important role in cavitation inception. Katz and O’Hern (1986) have shown that, when streamwise vortices are present, inception occurs in these longitudinal structures before it occurs in the primary or transverse vortices.

The three-dimensional shedding of vortices from a finite aspect ratio foil or other device can often lead to the formation and propagation of a ring vortex with a vapor/gas core. Figure 6 shows such a cavitating vortex ring that has just emerged from the closure region of an attached cavity on an oscillating foil. Often

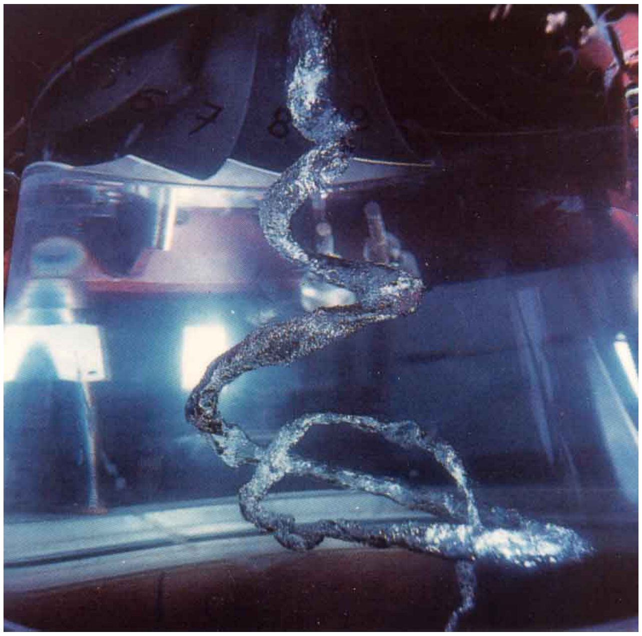

Figure 4: Cavitating vortex in the draft tube of a Francis turbine. Reproduced with the permission of P.Henry, Institut de Machines Hydrauliques et de Mecanique de Fluides, Ecole Polytechnique Federal de Lausanne, Switzerland.

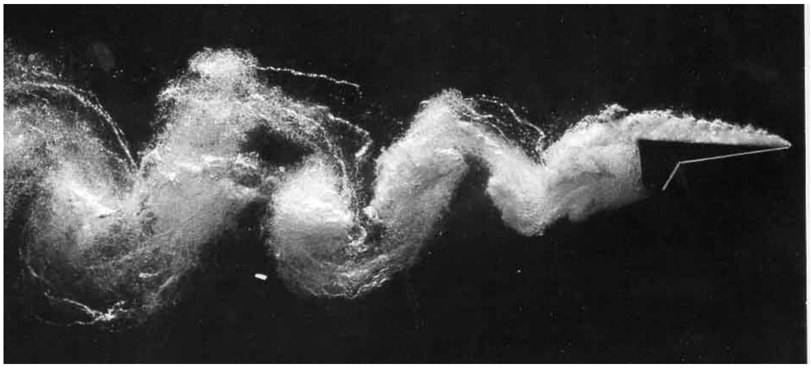

Figure 5: Cavitating vortices in the separated wake of a lifting flat plate with a flap; the flow is from the right to the left. Reproduced with the permission of A.J. Acosta.

these ring vortices can persist for quite a distance as they are convected downstream. Another example is shown in Figure 7; in this case the vortex shedding is caused by the natural oscillations of a partially cavitating foil (see section (Nti)). The cavitating ring vortex has its own velocity of propagation relative to the surrounding fluid and has therefore moved substantially above the rest of the wake at the moment when the photograph was taken.

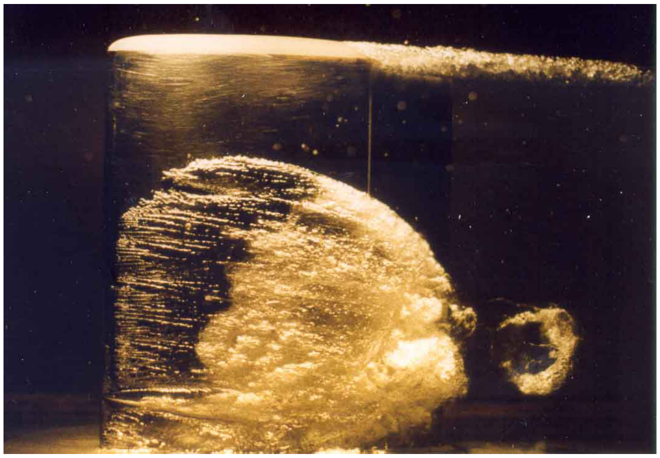

Figure 6: The formation of a ring vortex in the closure region of an attached cavity on an oscillating, finite-aspect-ratio hydrofoil with a chord of 0.152 m. The incidence angle is oscillating between 5° and 9° at a frequency of 10 Hz. The flow is from left to right at a velocity of 8.5 m/s and a mean cavitation number of 0.5. Note the cavitating tip vortex as well as the attached cavity. Photograph by D.P. Hart.

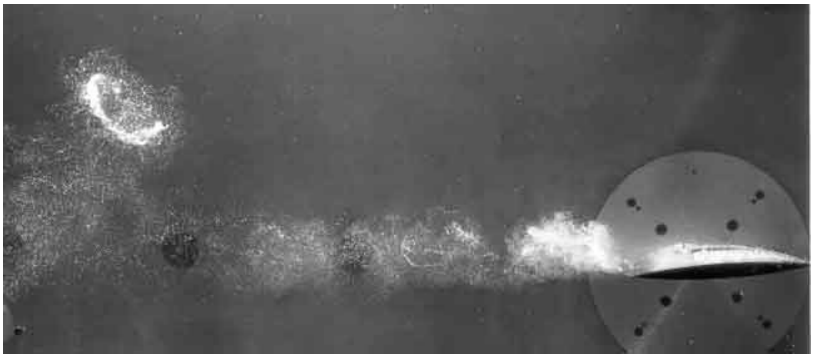

Figure 7: A vortex ring shed by the partial cavitation oscillations of a hydrofoil. The flow is from right to left. Reproduced with the permission of A.J. Acosta.