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# Visualization of Three Dimensional Vortex Dominated Flows in a Towing Tank

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## Abstract

The present paper describes a series of flow visualization studies, which have been performed in a towing tank and utilize laser induced fluorescence as a means of observation. The setup, described herein, has been designed specifically for visualizing three dimensional vortex dominated flows. Two different projects are being performed currently in this facility. The first one focuses on the development of tip vortices on hydrofoils, and the second on the flow structures behind inclined bodies of revolution. The experimental setup required for both projects, particularly the optical system, is almost identical, and the details are provided in the following section. Brief summaries highlighting some of the results of observations, are provided in the chapters that follow. More detailed information is described by Ward and Katz (1987a,b), and by Francis and Katz (1986).

**Keywords:** hydrodynamics.

# Visualización de flujos dominados por vórtices tridimensionales en un tanque de remolque

## Resumen

El presente artículo describe una serie de estudios de visualización de flujo, que se han realizado en un tanque de remolque y utilizan fluorescencia inducida por láser como medio de observación. La configuración, descrita en este documento, ha sido diseñada específicamente para visualizar flujos dominados por vórtices tridimensionales. En la actualidad se están realizando dos proyectos diferentes en esta instalación. El primero se centra en el desarrollo de vórtices de borde en perfiles hidrodinámicos, y el segundo en las estructuras del vortice de flujo detrás de cuerpos de revolución inclinados. La configuración experimental requerida para ambos proyectos, en particular el sistema óptico, es casi idéntica y los detalles se proporcionan en la siguiente sección. En los capítulos siguientes se proporcionan breves resúmenes que destacan algunos de los resultados de las observaciones. Ward y Katz (1987a, b) y Francis y Katz (1986) describen información más detallada.

**Palabras clave**: hidrodinámica.

## Experimental Setup

A schematic description of the experimental setup is presented in Figures 1 thru 3. This system is mounted on the carriage of a 156 ft long towing tank which has an 11x5 ft cross section, and its maximum speed is 12.5 ft/sec, but because of Froude No. effects the maximum speed during the experiments has been kept below 5 ft/sec. In this setup an 8 watt argon ion laser beam is directed by several mirrors into the illuminating foil and then expanded to a sheet of light by a cylindrical lens. The thickness of this sheet is also reduced to less than 1mm by a long focal length spherical lens. The output beam is set to illuminate a vertical plane which is perpendicular to the direction of motion. Rhodamine dye can either be injected from surface ports, or distributed in the water shortly before each run. The latter technique has been adopted during the actual experiments. This dye responds with spontaneous fluorescence when it reaches the illuminated plane, and provides an image of the flow structure there without being obstructed by the rest of the flow field. The resulting image is then focused by a series of high resolution lenses and recorded by a TV, 35 mm or a high speed camera. The magnification and resolution of this image can be controlled by a proper choice of lenses, and by

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varying the concentration of the dye. In most cases the images have been recorded on a high resolution VCR for further analysis. A substantial effort has been invested in constructing a rugged and heavily supported mounting system for the various components. Repeated trial runs have also established the reliability and repeatability of the flow visualization data, as well as the layover period between runs, in order to eliminate the effects of secondary free stream flows. The camera strut has also been kept at least 10 ft behind the model in order to reduce its effect on the flow structure.

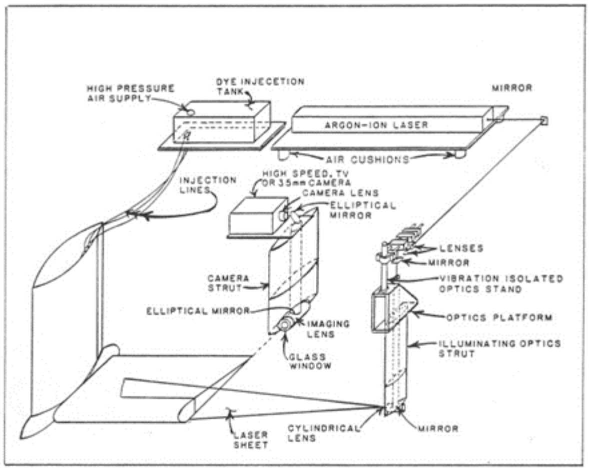

Figure 1 Flow Visualization System

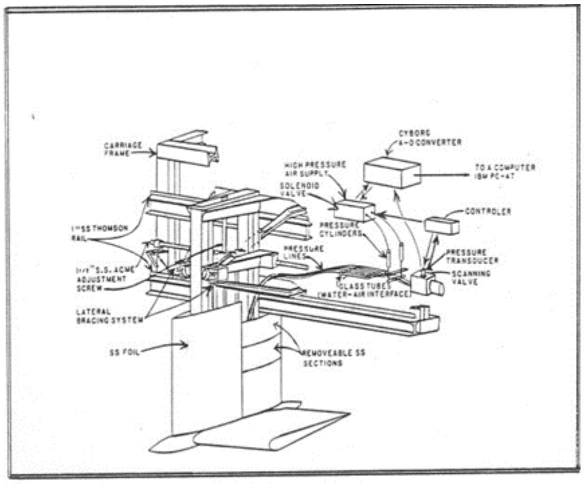

Figure 2 Main Support and pressure measurement system

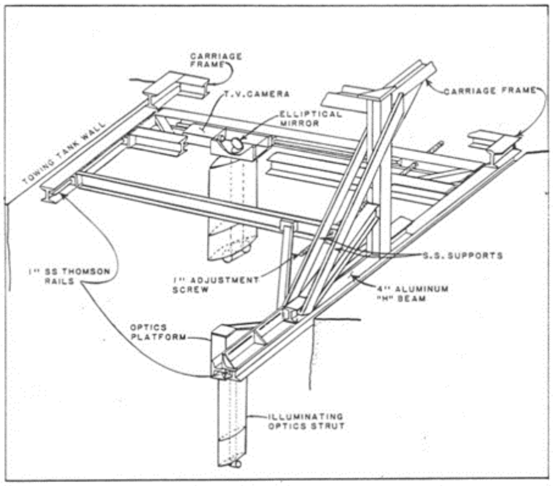

Figure 3 Illuminating and collecting optics support

## Sample of results

Several sample photographs demonstrating the flow structures around the tip of the hydrofoil and in the lee of the body of revolution are presented in Figures 4 and 5, respectively. In both cases the images provide clear evidence that the flow field is composed of several primary and secondary vortices. The characteristics of these structures are summarized in the following sections.

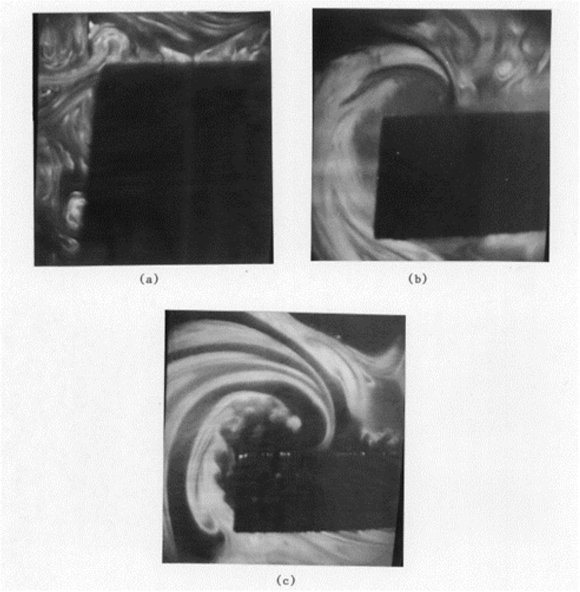

Figure 4 Photographs of Cross Sections Tip Vortex

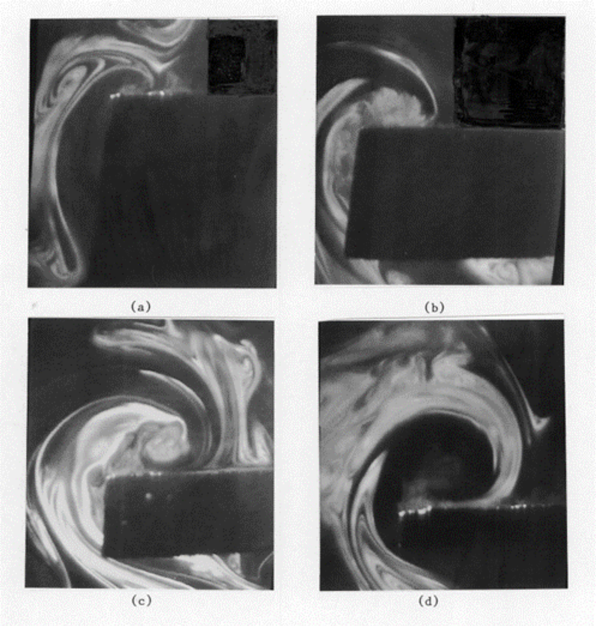

**Figure 5** Photographs of Cross Sections Tip Vortex

## Discussion

The present observations provide clear evidence that the flow around the tip of the rectangular hydrofoil is dominated by multiple vortex structures. The data demonstrate that the primary structure above the surface has a conical shape with its tip pointing towards the leading edge. This vortex also experiences the same reduction in size as the Reynolds number is increased and growth with increased incidence angle, which have been observed by Higuchi et al (1986). The existence of large vortex structures on the side of the foil, which have been observed by Francis and Kennedy (1969), has also been identified during the present study. The present images also confirm their claim that these vortices climb around the comer to the fall's suction side. However, their hot wire measurements cannot resolve the presently observed motion and deformation of the secondary vortex structure as they migrate around the upper copier of the tip. The present results also demonstrate that beyond the starting point, the entrainment of vortices continues throughout the entire chord. The only evidence for these phenomena in Francis and Kennedy' s measurements are the high level of velocity fluctuations within that region and the increase in the total circulation of the tip vortex. The outward motion of the primary structure close to the trailing edge agrees with the trends mentioned by Francis and Kennedy As far as the Reynolds number effects are concerned, the presently observed reduction in the vortex size as the velocity is increased agrees with the measurements of Higuchi et al. (1986), and supports the theories of McCormick (1962). Unfortunately, to the best of our knowledge, there is no other source that contains detailed information about the surface pressure distribution close to the hydrofoil' s tip. As a result, the present data cannot be compared to any other measurements. However, the reduction in the magnitude of CP near the tip as the roughness size is increased agrees with the reduction in the tangential velocities within the core when the boundary layer is tripped, and the effect of the roughness elements in suppressing cavitation. As noted before, the same trends with the incidence angle and the roughness size have been observed during the pressure measurement and the flow visualization studies

## Summary and conclusions

The development of the flow structures along the tip of a rectangular hydrofoil has been studied with a series of flow visualization experiments and surface pressure measurements. In the upstream sections, close to the leading edge, the primary vortex is located beyond the tip, to the side of the hydrofoil. Further downstream, part of this structure start climbing around the upper comer of the tip and an additional vortex, that eventually becomes the main structure starts developing over the model's suction side. In the mid sections the vorticity is fed into the upper surface as portions of side structures are "pinched" and entrained by the main upper vortex. Close to the trailing edge, as the foil becomes thinner, the tip vortex is fed by a series of shear layer eddies that form as the flow separates at the bottom comer of the tip. In general, the flow field around the tip contains multiple vortex structures whose size and significance depend on the incidence angle, chordwise location, the free stream velocity, and somewhat by the roughness of the hydrofoil' s surface. The primary structure above the surface moves inward (towards the root of the foil) an its size increases as the incidence angle is increased. Less drastic, but still clearly evident, is a reduction in the vortex size as the velocity is increased. This trend has persisted both on the smooth and rough models. The surface roughness has a limited effect on the vortex size and location. The largest, but not necessarily most inward, structures have been observed in the model with the intermediate, 250 microns particles. The smallest values of have been observed on the roughest foil. However, the starting point, at which the vortex climbs to the suction surface of the foil, moves upstream as the roughness size is increased. Finally, close to the trailing edge, at around X/C= 0.8, the tip vortex starts moving outward and away from the model's surface.

In general, the growth of the tip effect of the vortex along the chord, as well as its dependence on the incidence angle and the surface roughness have also been evident from the surface pressure measurement. The existence of a large vortex structure close to the surface creates a dip in the pressure that reaches a minimum close to X/C = 0.8 and it's spanwise location depends on the above mentioned flow conditions. The magnitude of this dip increases with the incidence angle, but decreases significantly as the characteristic roughness size is increased. The latter indicates that the addition of surface roughness causes a substantial reduction in the tip vortex strength.

## Acknowlegement

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