University of Colorado at Boulder

# Group Project
# Flume Airfoil Flow


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# I. Background

This project was the first team assignment of our Flow Visualization course at the University of Colorado at Boulder. The purpose of the project was to capture the fluid flow behavior of a Clark Y airfoil in a water flume. We attempted to visualize the shift of the separation point on the back of the wing as the angle of attack was increased. The angle of attack is the elevation from horizontal that the wing is tilted, and the separation point moves up from the back of the wing towards the front as this angle is increased. At the critical angle of attack, the wing is stalled and lift is decreased significantly (Gal-Or 1990). We also sought to capture the eloquence of the wave and vortex patterns present in the airfoil flow. This footage was captured with the collaborative effort of Shweta Maurya, Jeffrey Pilkington, and Dillon Thorse at the University of Colorado at Boulder on March 4, 2013.

# II. Flow Analysis

The Clary Y airfoil was made from a source CAD file cut out of an acrylic sheet with a laser cutter (Nelson 2013). To capture the desired flow phenomena, the airfoil was placed in a water flume with a ventilated overshot weir downstream of the foil to create slow, more visible flow conditions. The airfoil was approximately five inches in chord length and one inch tall. Figure 1 shows the general flow pattern around the airfoil at a low angle of attack. The separation point is near the back tip of the wing when the angle of attack is approximately zero degrees, as seen in the first half of the video. In Figure 2, the angle of attack is increased to near the stalling point of the airfoil. The separation point shifts up the foil, inducing a turbulent boundary layer. When the critical angle of attack is achieved, the fluid flow no longer provides lift to the airfoil.

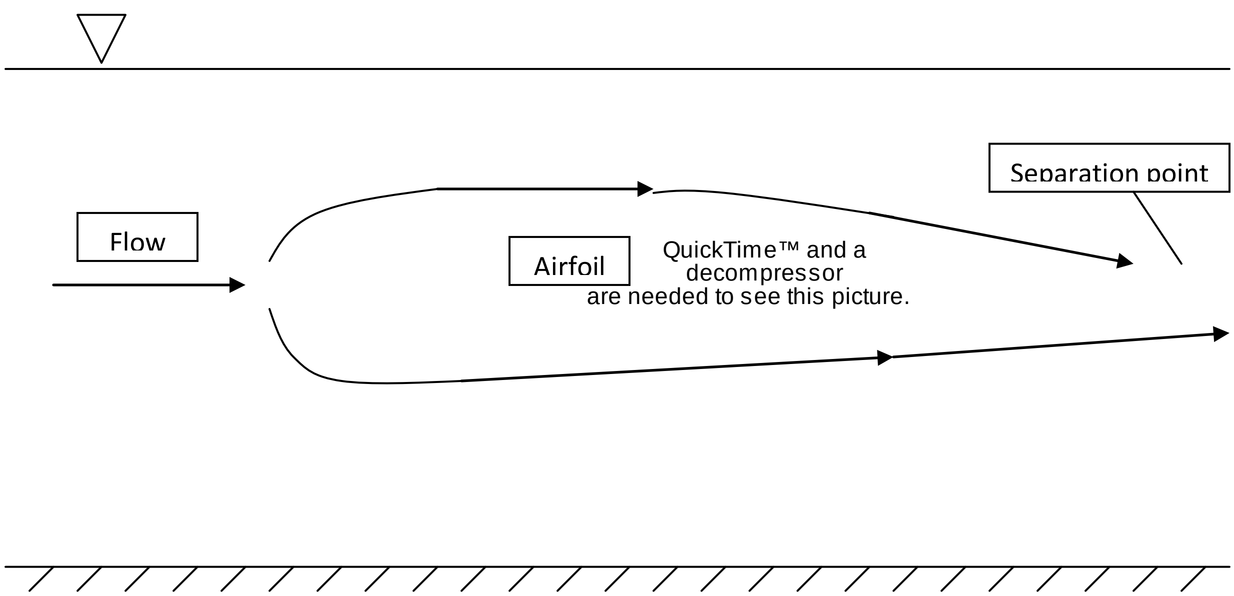


Figure 1: Schematic of fluid flow over airfoil in water flume at a low angle of attack. Water is contained on three sides by the flume, with the surface of the water open to atmospheric pressure.

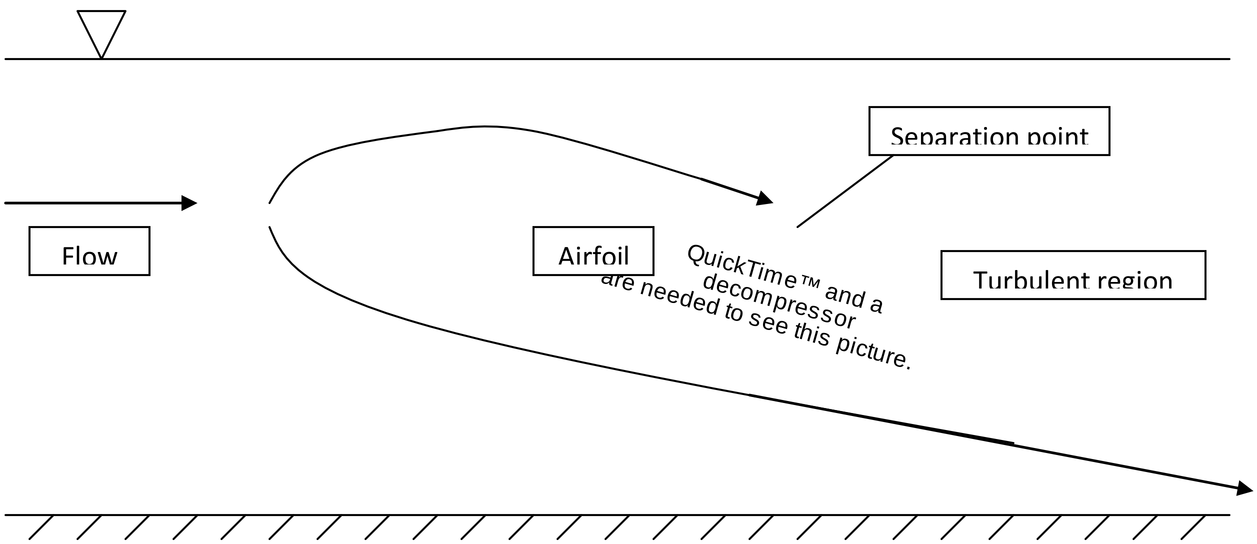


Figure 2: Schematic of fluid flow over airfoil in water flume at a high angle of attack. The separation point is high on the wing with a turbulent region formed near the back of the wing.

The flow conditions in the experiment were controlled by the flume and pump. The flume channel was 3.31 inches (8.41 cm) wide and filled with water to a height of 5.7 inches (14.48 cm), yielding a rectangular cross sectional area of 18.87 square inches (121.72 $cm^2$). The pump circulated water through the flume at a flow rate of 2.17 L/s. Under these conditions, the Reynolds number for flow through an open channel can approximate the behavior of the fluid flow (Inamdar 2012):

$$\mathrm{Re} = \frac{vL}{\upsilon} \tag{1}$$

In Equation 1, v is the velocity of the flow through the flume, which can be approximately by dividing the flow rate, 2.17 L/s or 2,170 $cm^3$/s, by the cross sectional area, 121.72 $cm^2$. This yields a fluid velocity of 17.8 cm/s or 0.178 m/s. The kinematic viscosity of the fluid is represented by $\upsilon$, which is approximately 1.004 E-6 $m^2$/s for water at 20 ˚C. The final quantity of the Reynolds number is the hydraulic radius of the channel, L, which is approximately by the following equation for open channel flow (Inamdar 2012):

$$L = \frac{A}{WP} = \frac{121.72cm^2}{2(8.41cm) + 2(14.48cm)} = 2.66cm \tag{2}$$

These values allow the Reynolds number to be calculated for the flow in front of the foil:

$$\mathrm{Re} = \frac{(0.178m/s)(0.0266m)}{(1.004 \times 10^{-6} m^2/s)} \approx 4{,}716$$

The Reynolds number is a ratio of the kinematic to viscous forces within the fluid. This result indicates turbulent flow for the open channel, as Reynolds numbers greater than 2,000 are considered turbulent. However, this flow is not extremely turbulent, which is clear in the video, and still shows the transition of flow over the foil quite clearly due to the drastic difference in turbulence before and after the separation point.

The fluid flow over the airfoil creates some very interesting fluid phenomena. In the first part of the video when the angle of attack is near zero, represented in Figure 1, a horseshoe vortex becomes apparent at the front of the wing as the dye travels over the foil. This phenomenon is the horseshoe-shaped dye shape visible at the front of the foil in the photo on the cover page of this report. The horseshoe vortex is formed by a constantly rotating bound vortex that travels with the foil, followed by two trailing vortices that form the sides of the "horseshoe". The trailing vortices induce drag on the airfoil and are a component of the downwash (McCormick 1979). This phenomenon can also been seen in the context of tall buildings standing in the wind (Penwarden et al 1975).

A second phenomenon is clearly visible in the second part of the video when the angle of attack is increased to near the stalling point, represented by Figure 2. The extreme turbulence created behind the separation point forms curling patterns known as Tollmien-Schlichting waves. These waves form as an instability at the boundary layer where the fluid transitions to turbulence (Baines et al 1996). Tollmien-Schlichting wave instabilities were illustrated very clearly in the second part of the video, where some of the waves became fully developed vortices downstream of the foil. With improved flow conditions and visualization techniques, both of these phenomena could be observed in even greater detail and clarity.

## III. Visualization Technique

The flow over the airfoil was primarily visualized with blue food dye. The dye was dropped into the flume in volumetric additions of approximately one cubic centimeter at a distance of approximately 0.5 m upstream from the foil. This allowed the dye to disperse vertically within the flume and flow over both the top and bottom of the foil. The water circulated through the flume was at approximately room temperature (20 ˚C), and was diffused through a bed of marbles at the top of the flume to reduce turbulence upstream of the airfoil.

To light the flow, two 500 W tungsten bulbs were used to backlight a piece of white fabric used as a backdrop, which was attached to the side of the flume. This combination of visualization techniques provided nice contrast between the dye and the rest of the fluid, allowing the desired fluid phenomena to be captured clearly.

# IV. Photographic Technique and Settings

The field of view used to capture the footage was approximately 6 x 10 inches across, with the foil at a distance of approximately one meter from the lens of the camera. The footage was captured on an EF-S 18-135 mm zoom lens at a focal length of 60 mm. A Canon EOS 60D DSLR camera was used to shoot the original footage that was 5184 x 3456 pixels in resolution. The video footage was captured at f/6.3 and 2500 ISO at 60 fps. Post processing was done in Adobe Aftereffects by providing fade in/out effects, cropping the frame, as well as making adjustments to the vibrance and contrast curves of the image. The final video is in 1080 x 720 resolution played back in a lossless video format.

# V. Conclusions

The footage of the flow over the airfoil reveals how the separation point shifts up the wing as the angle of attack increases. After the foil reaches the critical angle of attack, the separation point is at the very front of the wing, which results in a dramatic decrease in lift and an increase in the amount of turbulence behind the wing. The airfoils also show fluid phenomena such as horseshoe vortices and Tollmien-Schlichting waves quite clearly. The contrast between the dye and the rest of the fluid visualizes the flow very well, which can be mostly attributed to the lighting method in combination with the dark color of the dye. To improve this experiment, one could adjust the flow parameters until the fluids Reynolds number is well within the laminar region, which would allow the transition to turbulence to be seen more clearly. Also, the video could be played back at a slower frame rate to more easily visualize the flow over the foil if desired. There is a lot to be learned about fluid flow over airfoils, including how fluid behavior changes with the use of different airfoils and fluid properties. Overall this project provided great insight into how an airfoil works, as well as what visualization techniques are the most effective.

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