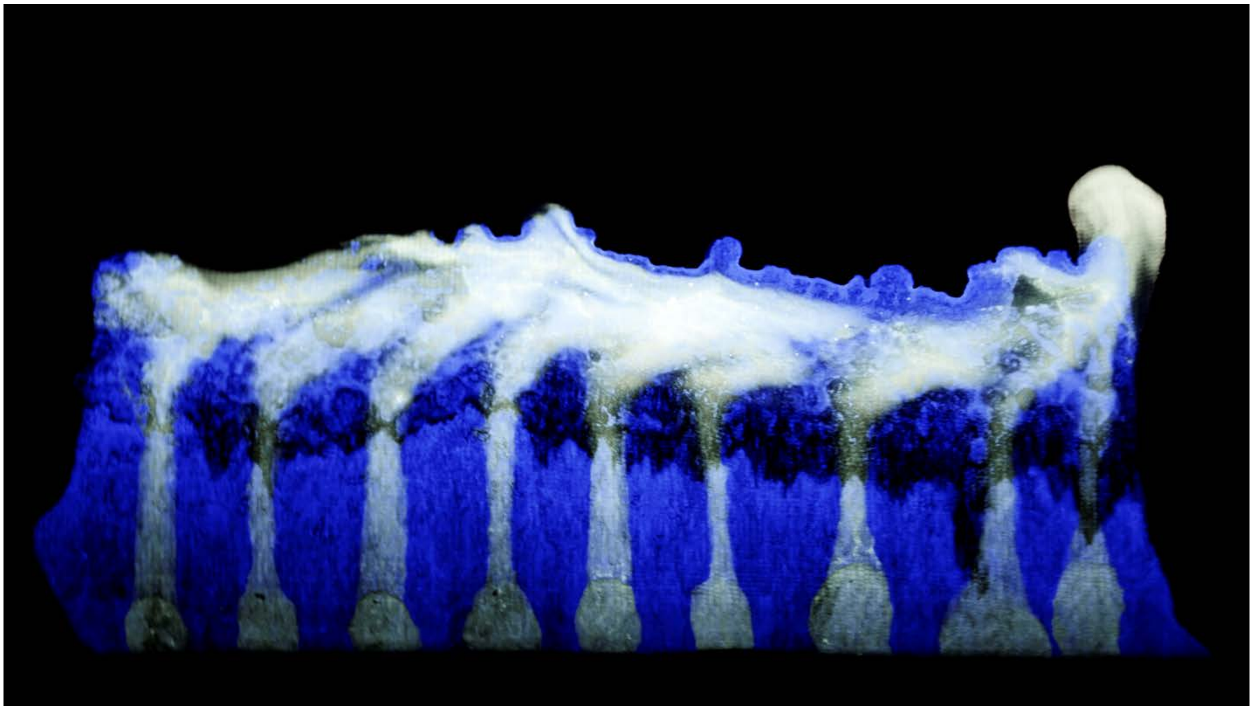
Liquid Laundry Detergent and Fluorescent Tracer on an Airfoil in a Wind Tunnel



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Introduction and Purpose

This photograph and paper are for the first team assignment in the Flow Visualization course taught at the University of Colorado at Boulder. This assignment allowed for graduate and undergraduate engineering and art/film students to work together to generate and capture complex flow phenomenon. The specific intent of this project was to visualize air streamlines within a wind tunnel over an airfoil. An airfoil is a shape that is designed to interact with a fluid flow field in some way (typically either generating or reducing drag or lift). Airfoils are used for wings and propellers in aircrafts and also for blades on turbines and pumps. Generating a flow field over an airfoil shows how an airfoil will act in application. This can lead to more efficient airfoil design as well as more efficient flying methods if the airfoil is used with an aircraft (in terms of roll, pitch, yaw, and angle of attack). This project could not have been completed without the help of teammates Gage Henrich, Hannah Schumaker, and Jacob Varhus as well as Professor Trudy Schwartz for instruction on operating the aerospace wind tunnel in the Integrated Teaching and Learning Laboratory.

Flow Generation

The generation of flow over the airfoil was performed using a wind tunnel. When turned on, the wind tunnel moves air in one direction perpendicular to the leading edge of the airfoil. For this experiment, an air speed of 21[m/s] was used. The particular airfoil used was an S4243 shaped aluminum airfoil that was 10[in] long and had a 2.5[in] chord. In Figure 1 below, the experimental setup can be seen. In this figure, the airfoil length goes into the page and the chord is the width of the airfoil. The airfoil was secured to a sting that existed in the wind tunnel with a set screw. The sting allowed for manual control of the angle of attack of the airfoil and this angle was set to 10°.

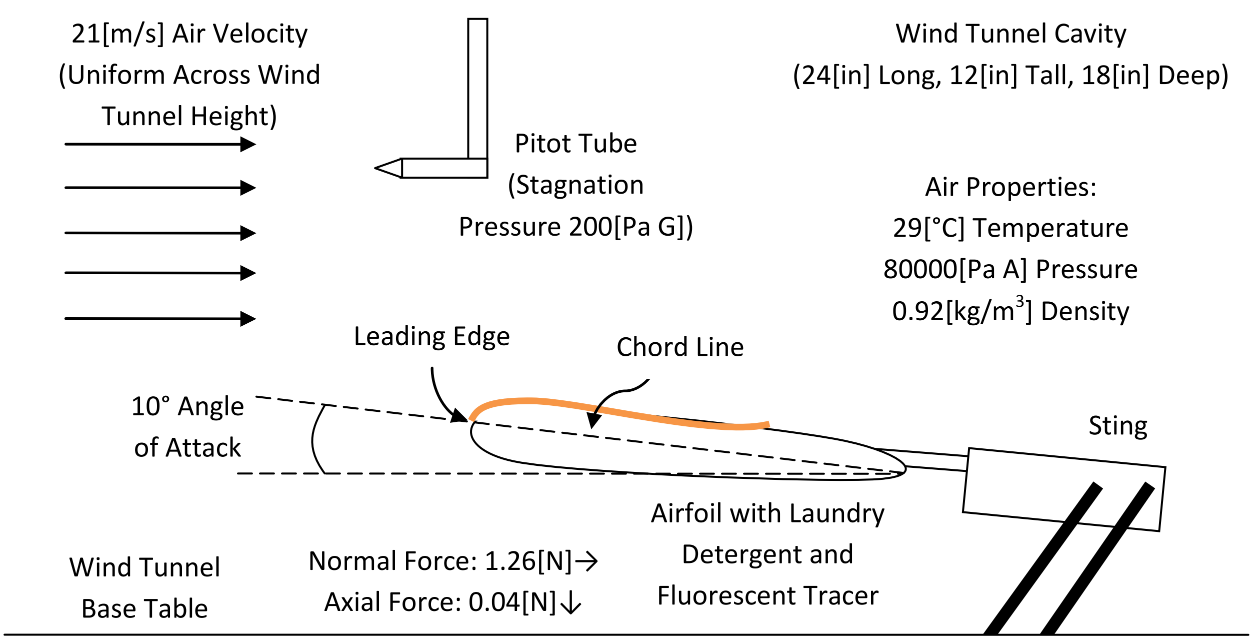

Figure 1: Experimental Setup

After the airfoil was in place, a layer of liquid laundry detergent was applied with a brush along the whole length of the leading edge. The wind tunnel was then turned and the detergent flowed down the airfoil until the air flow became detached and separated off of the airfoil. At this point, the laundry detergent stopped moving because no viscous interactions existed at the air-detergent boundary. After the detergent dried slightly, a mixture of mineral oil and orange fluorescent tracer was applied in nine droplets along the leading edge. The wind tunnel was turned on a second time and the fluorescent mixture flowed down the airfoil again until flow separation occurred. This time however, because the droplets were discrete points, streamlines were visualized along the airfoil. After the second wind tunnel run, the airfoil was detached from the sting and transported into a dark room for photography with a black light. During transportation however, the airfoil was turned slightly such that fluids began to run sideways down the airfoil length as seen in the photograph.

Fluid Physics

The particular wind tunnel used contained sensors that were attached to data acquisition instruments. A computer recorded the air free stream velocity, the stagnation pressure, the force applied on the airfoil (both normally and axially), the air density, the ambient temperature and pressure, and the angle of attack of the airfoil. These values are all shown above in Figure 1.

The stagnation pressure is the pressure detected inside of the pitot tube. A pitot tube allows for air to flow into the tube but there is no outlet leaving the air trapped inside. This leads to a stagnation region where the flow velocity is zero. At this point, the pressure can be measured and compared to the pressure outside of the tube (at the free stream velocity). With these two pressures known, the free stream fluid velocity can be calculated using the Bernoulli Equation [1]. This was all calculated by the wind tunnel though, and so the exact analysis will not be shown.

The angle of attack is the angular difference between the flow direction (in this case the horizontal) and the chord line of the airfoil. The chord line runs from the leading edge to the tailing edge of the airfoil. Changing the angle of attack effects the streamlines of air moving around the airfoil. Increasing the angle of attack moderately can lead to an increase in lift, but increasing the angle too much leads to flow separation and “stalling” in aircraft.

Lift occurs when the pressure below the airfoil is greater than the pressure above the airfoil. For an aircraft, when the lift force is greater than the weight of the aircraft, the aircraft will rise upwards. In order to achieve this differential pressure, the velocity of the air above the airfoil must be greater than the velocity below the airfoil [2]. This can be proven using Bernoulli’s equation. Bernoulli’s equation states that the energy along a streamline is constant as long as the fluid is assumed to be incompressible, inviscid, and at steady state. Inside of the free stream, the air streamlines will either move below the airfoil or above it. The state inside of the free stream must then be equal to both the state underneath the airfoil and the state above it, that is (from Bernoulli’s):

$$\mathrm{P_{freestream}} + \frac{1}{2}\rho_{\mathrm{freestream}}\mathrm{V_{freestream}} = \mathrm{P_{under}} + \frac{1}{2}\rho_{\mathrm{under}}\mathrm{V_{under}} = \mathrm{P_{above}} + \frac{1}{2}\rho_{\mathrm{above}}\mathrm{V_{above}}$$

In this form of Bernoulli's, the effects of potential energy were neglected due to minimal elevation changes between states. Because the fluid is assumed to be incompressible, all the densities are equal. Therefore, in order for the pressure underneath the airfoil to be greater than the pressure above the airfoil, the velocity above the airfoil must be greater than the velocity underneath.

Due to the geometry of the airfoil, a small vortex (moving counterclockwise for Figure 1) will start at the end of tailing edge of the airfoil. From conservation of linear momentum, an opposite spinning vortex (moving clockwise for Figure 1) is created around the airfoil. This vortex adds to the air velocity on top of the airfoil and detracts from the velocity at the bottom causing air to move faster above the airfoil [2]. This gives rise to the differential pressure and the lift. When slightly increasing the angle of attack, the vortices grow larger increasing the differential pressure and the lift.

When increasing the angle of attack too much, the flow at the top of the airfoil will become separated. This separation of air from the airfoil top causes the velocity to decrease at the top of the airfoil leading to a decrease in differential pressure. This can cause sudden stalling in aircrafts that try to increase elevation too quickly [3]. In the image captured here, it seems like separation occurs because the fluid does not reach the end of the airfoil width. This may not necessarily be true because the visualization fluids (detergent and tracer) are much more viscous than air and so the viscous resistance may have stopped the fluid as opposed to flow separation. However, flow separation can occur at angles of attack around ten degrees so flow separation is still a possibility [2].

The final fluid physics that will be discussed moves away from aeronautics and focuses just on the tracer in the image. The Reynolds number of the tracer is estimated from the size of the tracer streak and the properties of the liquid. The Reynolds number of the streak should indicate that the flow is laminar because there is no evidence of turbulent eddies and viscous forces at the surface dominate the flow [3]. From the data gathered from the wind tunnel, the test took 5 seconds to run. Using the image, the streak length is 50[mm] (this is a rough estimate though because the streak was distorted at the end). The average streak velocity is 50[mm]/5[s] or 10[mm/s]. The characteristic length is the width of the streaks and this is approximately 10[mm]. The kinematic viscosity is taken as the average of the viscosities of the tracer and the mineral oil because a 50-50 mixture was used (see References [4] and [5]). This leads to a Reynolds number of:

$$\mathrm{Re} = \frac{\mathrm{VL}}{\nu} = \frac{10\left[\frac{\mathrm{mm}}{\mathrm{s}}\right] * 10[\mathrm{mm}]}{\frac{1}{2}\left(8.5\left[\frac{\mathrm{mm}^2}{\mathrm{s}}\right] + 39.5\left[\frac{\mathrm{mm}^2}{\mathrm{s}}\right]\right)} = 4.2$$

This Reynolds number indicates that the flow is very laminar and this compares well to the observed characteristics. This also is strong evidence for flow separation not occurring as viscous forces dominate the tracer and oil (but not necessarily the air).

Visualization Method

There are two techniques used in order to visualize the air flow over the airfoil. The first was Tide liquid laundry detergent (the material safety data sheet (MSDS) of the detergent can be found in

Reference [6]). The second was a mixture of 50% mineral oil and 50% orange liquid oil tracer fluorescent ultraviolet dye (the MSDS of the mineral oil and the tracer can be found in Reference [5] and Reference [4] respectively). All of these fluids were purchased off the shelf. Both the detergent and the tracer glow when exposed to ultraviolet light and this technique was used to more easily visualize and enhance the flow field.

This flow was visualized inside with a single light source. An 8[W] ultraviolet fluorescent lamp was held roughly 12[in] horizontally away from the airfoil's leading edge. The room that the picture was taken in was completely dark room (no windows and all doors closed). The table that the airfoil was placed on was white, however because the table had no fluorescent fluid on it, only the airfoil was visible. The flash on the camera used was turned off. This particular picture was taken around 6:00PM on March 4^{th}, 2013. Figure 2 below shows the photographic setup.

Figure 2: Photographic Setup

Photographic Technique and Image Post Processing

A Nikon D5000 12.3 effective megapixel DX format DSLR F-mount camera was used to take raw images formatted in .nef (Nikon electronic format). The field of view is roughly 5[in] wide by 3.5[in] tall such that the airfoil takes up most of the space. This field of view is determined from the length of the airfoil (as about half the airfoil was captured and the airfoil is 10[in] wide). The camera lens was about 12[in] away from the airfoil. The focus was set to manual such that the clearest image could be achieved. The focal length was set to 52[mm] to both maintain focus with minimizing the field of view and to match closely with the perspective of the human eye (50[mm]). The camera was handheld to achieve shots at multiple angles and so the shutter speed was set to $1/20^{th}$ of a second even though the airfoil was stationary and the room was dark. The aperture was set automatically within the camera and was 9.3[mm] (from an f-stop of 5.6). The ISO (sensor sensitivity gain) was set to 100. Even though the room was dark, a low ISO was needed because the fluorescent fluid was very bright under the black light. The original image (seen in Figure 3 below) was 4288 by 2848 pixels.

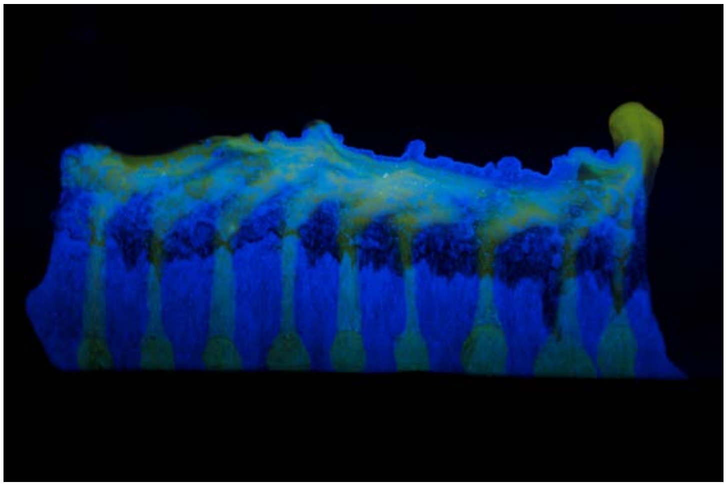

Figure 2: Original Image

Image post processing was completed entirely in Adobe Photoshop CS6 Extended. The image was rotated slightly such that the leading edge of the airfoil was parallel with the bottom of the image. The image was then cropped to remove evidence of rotation and to evenly frame the sides of the image with the black background. More black space was left at the top of the image to add an artistic touch. The image was also cropped to a standardized width-height ratio (16” x 9”) leaving the final image to be 4166 by 2343 pixels. The contrast was increased slightly to increase differentiation between the detergent and the fluorescent tracer. The saturation of the image was also turned down to increase the contrast between fluids. Decreasing the saturation also changed the colors of the fluids slightly and overall increased flow visibility. The dull dark blue detergent became more striking and clear while the yellow-green tracer became white. This color change adds differentiation between this image and the images produced by other members of the group.

Conclusion

This image captures both the air streamlines and the potential flow separation point very well. While it was slightly disappointing that the detergent and fluorescent tracer smeared at the back of the airfoil during transportation, it does add an interesting and visually appealing effect. Because this experiment was performed in a wind tunnel with data acquisition capabilities, it was easy to calculate relevant fluid dynamic values. The editing preformed on the image brought out the contrast between the fluids present and also increased clarity and sharpness. I think that the image looks like nine smoke stack towers or a melting glacier. Using the aerospace wind tunnel was a new experience for me and it was valuable to get insight from the aerospace engineer on the team as I had never dealt with aeronautic physics before. I hope to create an even more complex and dynamic flow in the next team assignment.

References

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