Levitated Golf Ball

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Figure 1: Golf Ball suspended in a high velocity jet of air and water vapor.

INTRODUCTION

The Flow Visualization course at the University of Colorado Boulder is designed to teach students the fundamentals of photography, videography, and fluid physics with the focus of creating aesthetically and scientifically valuable images of flow phenomena. This report outlines the techniques and tools used to create the image shown in Figure 1. The goal in creating this image was to provide a visualization of the flow of air around a sphere as it is suspended in a high speed jet. This experiment is commonly conducted using a ping pong ball in the stream produced by a hairdryer because of the ease with which this flow system may be setup. Suspending a much more dense sphere such as a golf ball requires a higher velocity stream of air which in turn can provide a more distinct flow pattern and boundary layer. Atmospheric air, which may be characterized as an ideal, inviscid, and compressible fluid, demonstrates an inversely proportional relationship between pressure and velocity along a streamline which can be shown using Bernoulli's equation for conservation of mechanical energy in a flowing fluid(3). Consequently the pressure within a high velocity free jet of air, and along the bent streamlines of air passing over a sphere, is lower than that of the still surrounding air resulting in a pressure gradient which can hold the sphere in line with the air stream (2). It was proposed that this phenomenon could be a viable basis for sustained observation of high velocity air-flow around a sphere.

APPARATUS

To generate a jet of air with sufficient velocity to suspend a golf ball an HVLP (high volume low pressure) paint sprayer was connected to a compressor and used as both a flowrate control, nozzle, and delivery system for the water vapor being used to create a visible flow pattern. The paint sprayer also provides control of spray pattern, and the liquid to air ratio making it a very convenient tool for creating the stream. Preliminary attempts to suspend the golf ball using compressed air were successful, given sufficient air pressure and a nozzle orientation directing the flow of air parallel to gravity. The paint sprayer was fixed to a platform in a heavy bench vice and then levelled such that the sprayer nozzle was pointed vertically. The paint reservoir was

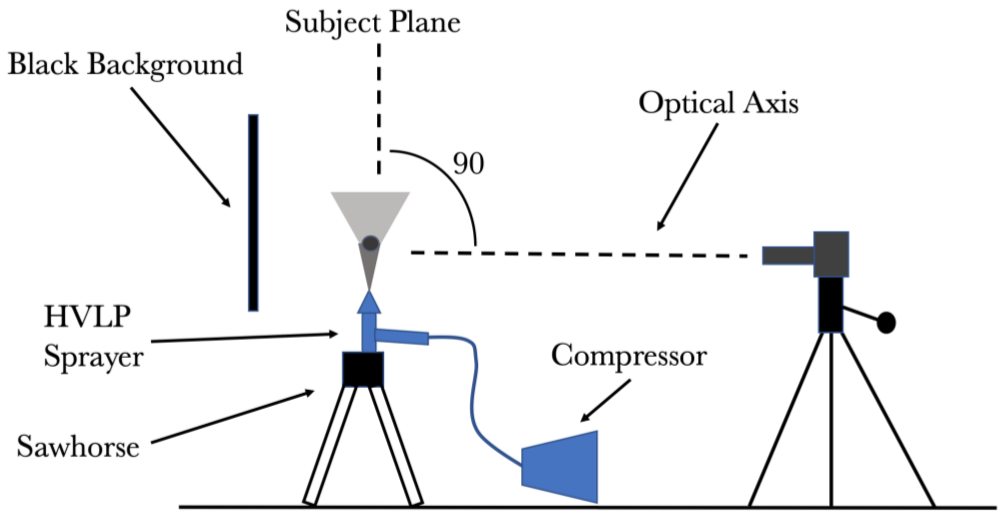

Figure 2: Diagram of Apparatus used to photograph the Suspended sphere.

removed so that it could be fixed out of shot and in an upright position. It was then reconnected to the sprayer using a rubber hose. An incandescent lamp was used to direct additional light into the stream path but away from the black paper background. Initial tests were conducted in the dark in order to localize light on the subject but since the motion of the hovering ball necessitated a short exposure time to avoid motion blur, the light sources being used could not supply adequate light. For this reason, the final shoot was carried out in daylight and with additional light sources to allow for higher shutter speeds. The camera was positioned on a tripod 3.5ft from the subject with its optical axis perpendicular to the stream. A sphere suspended in an air stream inherently provides a basis for estimating the velocity of the jet since the downward force of gravity must be equal to the upward force of drag from the air passing over the ball. Furthermore, the aerodynamics of golf balls, which differ to that of perfectly smooth spheres, have been well studied making it easy to find an approximate drag

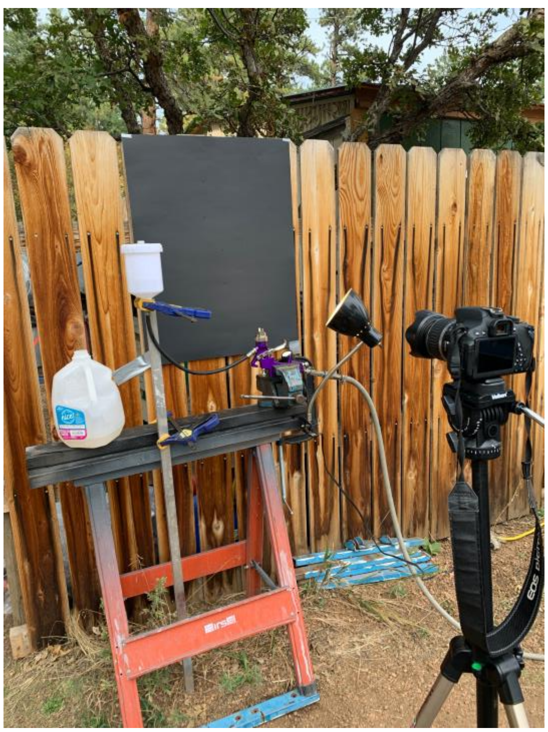

Figure 3: Image of Actual Apparatus used to photograph the levitated sphere.

coefficient for use in calculating the air stream velocity(6). The drag force and initial values in the scenario are(4):

$$F_{drag} = \frac{1}{2} C_d \rho V^2 A,\ m_{gb} = 0.0459kg, \rho_{air} = 1.225\frac{kg}{m^3},\ C_d = 0.35$$

Knowing that the force of drag must be equal to the weight of the golf ball allows for rearranging of the drag force equation to yield average velocity of the airstream:

$$F_{drag} = m_{gb} g, \qquad V = \sqrt{\frac{2\, m_{gb} g}{C_d \rho_{airA}}}, \qquad A = frontal\ area.$$

In this manner the approximate average air stream velocity was found to be 38m/s or 86mph. Once the velocity is known a Reynolds number may be calculated as(5):

$$Re = \frac{VL}{v}, \qquad L = characterisic\ length, \qquad v = Kinematic\ viscosity$$

Using an approximated hydraulic diameter as the characteristic length a Reynolds number of around 100,000 was calculated suggesting that the flow is solidly in the turbulent region. In the image in Figure 1 some vortex shedding is clearly present with the boundary layer separating into chaotic turbulent flow (1). This is also to be expected given the dimpled surface of golf balls, designed to prematurely induce turbulence near the surface with the goal of reducing the size of the wake behind the ball(6). It should be noted that the flow seen in the image is not entirely similar to that of a golf ball in flight primarily because of the small diameter of the jet hitting the ball's surface. It is plausible that this results in wider wake which breaks away from the boundary layer sooner than would be seen if the ball were in uniform flow of similar velocity. Additionally, the water vapor being used to visualize the airflow has its own motion characteristics depending on the droplet size discussed later.

WATER VAPOR AS SMOKE

As previously stated the flow of air around the golf ball was made visible by the addition of water vapor to the stream using the HVLP sprayer and normal tap water filling the paint reservoir (the gun had been thoroughly cleaned prior to testing). This item was purchased for less than $20 from Harbor Freight and Tool. The two-stage trigger on the gun allows for the desired amount of airflow to be initiated with the first stage trigger pull and for the vapor to be added to the stream when desired with the second stage. This was useful for stabilizing the golf ball first within a stream of air and later initiating the flow of water vapor close to the time the image was taken. The tiny droplets created by the 1.4mm tip on the sprayer are small enough to follow dominant patterns in the air flow and are naturally reflective when exposed to a light source. The use of water also addressed the obvious safety concerns with atomizing liquids into the atmosphere. It must be considered however, that the addition of water vapor to an air stream has the effect of increasing the drag force that stream exerts on an object. This is because some of the water vapor collides with the golf ball as the stream of air is forced to bend around the surface and in doing so transfers momentum to the ball. This can be observed by a jump in the hovering altitude of the ball above the nozzle when the flow of vapor is initiated. This suggests that water vapor may not always act as a perfect visual aid since, depending on their size, the tiny droplets in making up the vapor can deviate somewhat from the path of air flow as they have their own velocity and momentum. In this experiment however, the flow as visualized by the water vapor (Figure 1) is consistent with what was expected in the given scenario, showing all the major trends including the boundary layer, separation, and chaotic turbulence(3).

PHOTOGRAPHIC METHOD

The camera used to create the was a Canon Rebel T5i DSLR fitted with an 18-55mm lens with a focal length of 49mm. As mentioned previously, the photograph in Figure 1 was captured in indirect afternoon sunlight during partial cloud cover and with an incandescent lamp directed at the subject for supplementary light(Figure 3). These conditions allowed for adequate exposure while using a very high 1/2000s shutter speed to eliminate motion blur on the subject. The golf ball was painted black so that the brightest element in the image would be the flow itself. An ISO value of 800 was used, which was found to be the minimum allowable sensitivity while satisfying other constraints. This was done to eliminate noise in the final image,

Figure 4: .PNG version of the original unedited photograph used to create the final image.

a problem encountered during dark-room versions of this test that were explored initially. The image was acquired using shutter prioritization mode which automatically adjusted the aperture to f/5.6, a setting again optimized for light intake. The camera was set on a 10s shutter release timer which was coordinated with the insertion of the golf ball into the air stream. A four photo burst was used to increase the chances of obtaining a desirable image on each attempt. The camera was positioned out of range of the majority of spray with the lens 3.5ft from the subject, using optical zoom to fill the frame with the subject resulting in a FOV of 13 inches. The tip of the spray nozzle was intentionally included in the frame to add context for the flow and was also used to set the focus on the image. The Original image size of 5198 x 3162 was reduced to 1300 x1300 after some minor cropping on either side of the subject and a compression from a .CR2 to the PNG format in Figure 1. Edits made to the final image were made using Darktable, making use of the built in denoise and haze removal functions. Another manipulation made to the image was the removal of dark specs in the image caused by droplets of water landing on the black cardstock background during experiment. In hindsight this could have been avoided by using a fabric or felt background which would have absorbed the droplets and made them less visible. These spots were blended out from the final image using the spot removal tool in Darktable, but are clearly visible in the original image shown in Figure 4.

CONCLUSION

The final image obtained was a success in that the visualization technique and acquisition methods resulted in visible high velocity airflow around a sphere which clearly showed the key elements to be expected, such as a visible boundary layer, flow separation point, and chaotic wake turbulence. The image is also accessible to the viewer with the golf ball adding to the perception of scale and the nozzle tip hinting at the type of flow being shown. The process of creating the image also revealed the limitations and flaws of the apparatus, primarily being the use of a hard surface background and the difficulty in taking in enough light over a short exposure. Post processing methods were originally used to address the concern of not having used the full brightness spectrum, resulting in an image which is indeed much more striking and disctinct (Figure 5). This edit was not used in part because some of the less distinct boundary layer flow over the golf ball was lost in the RGB curve shift used to bring the grays of the background down to a black. Although it could be argued that this full spectrum edit is a clearer image than the one shown in Figure 1, it was decided that a sense of connection between the viewer and what is taking place in the image was lost by the obvious intervention of post processing and the introduction of more noise in the visible flow boundary. Perhaps further experimentation would reveal a compromise in this regard making for a better final result. This shows another area where improvement of both photographic method and editing technique are needed.

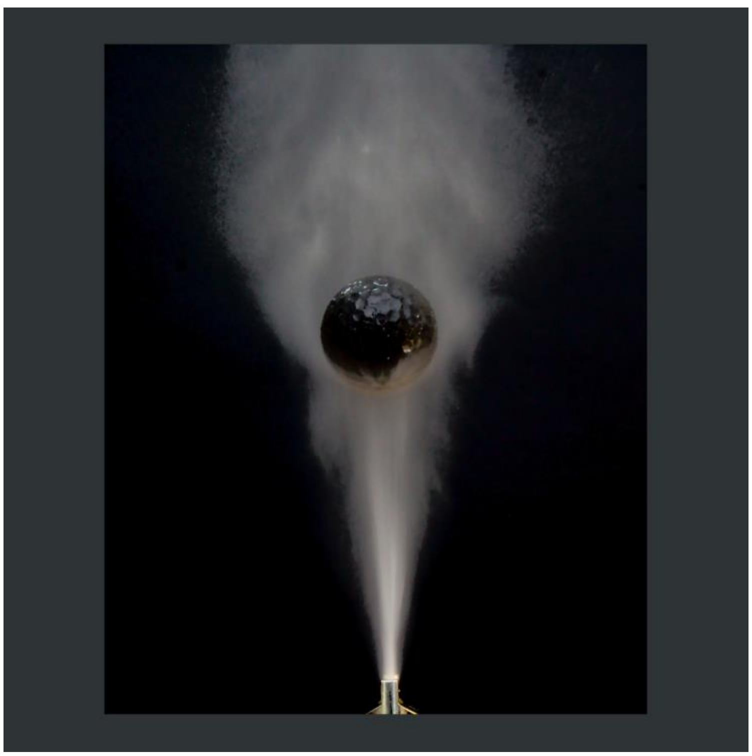

Figure 5: Experimental High Contrast edit of the original edit not used as the final photo due to subject boundary noise and some loss of less visible boundary layer flow.

SOURCES

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