AN ANALYSIS OF A BALL SUSPENDED BY A JET OF AIR USING HIGH-SPEED SCHLIEREN

Matthew Cheifetz

***Supervised By*: Kevin Nolan**

Introduction

The objective of this experiment was to better understand why a ball levitates when exposed to a jet of air from below. More specifically, an investigation was conducted about the airflow properties and patterns that contribute to this levitation effect. The experiment used a dual-mirror Schlieren setup in conjunction with a high-speed camera. This Schlieren setup allows for fluid motion around an object to be accurately visualized [1]. This analysis of airflow reveals much about real-world fluid mechanics and could be used in a variety of applications where airflow analysis is useful.

Methodology

Schlieren Setup

A dual-mirror Schlieren setup combines two parabolic mirrors, a blue point LED light source, and a Phantom high-speed camera [2]. This setup allows the camera to record changes in density and light, which reveals airflow around the ball. A diagram of the setup with a Styrofoam ball is seen in Figure 1.

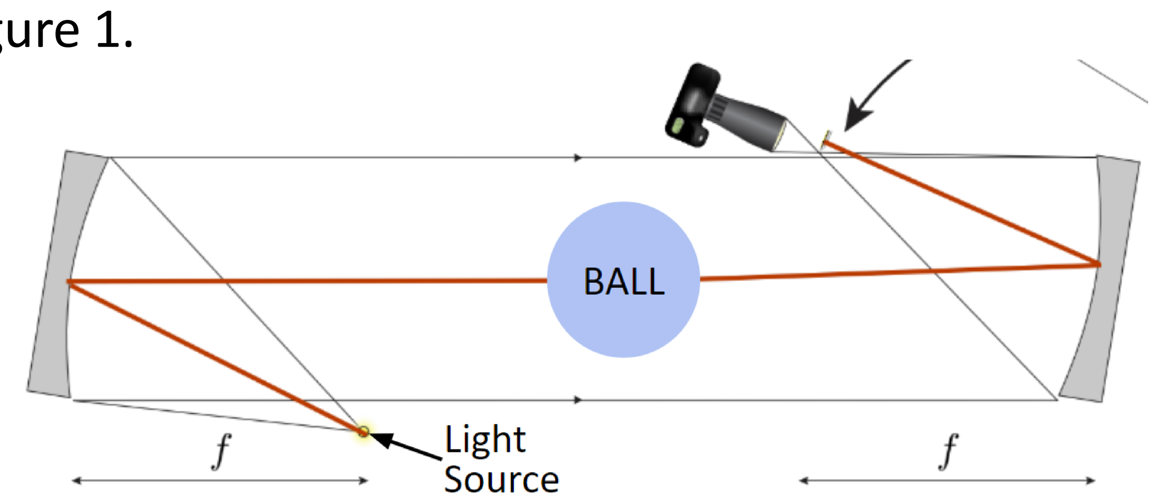


Figure 1: Schematic of Schlieren Setup with Styrofoam Ball

MATLAB Processing and Particle Image Velocimetry (PIV)

Image processing is utilized for meaningful analysis of the airflow. In MATLAB, raw images are processed to reveal the general shape of the jet over a set amount of time. The difference between raw and processed images can be seen in Figure 2.

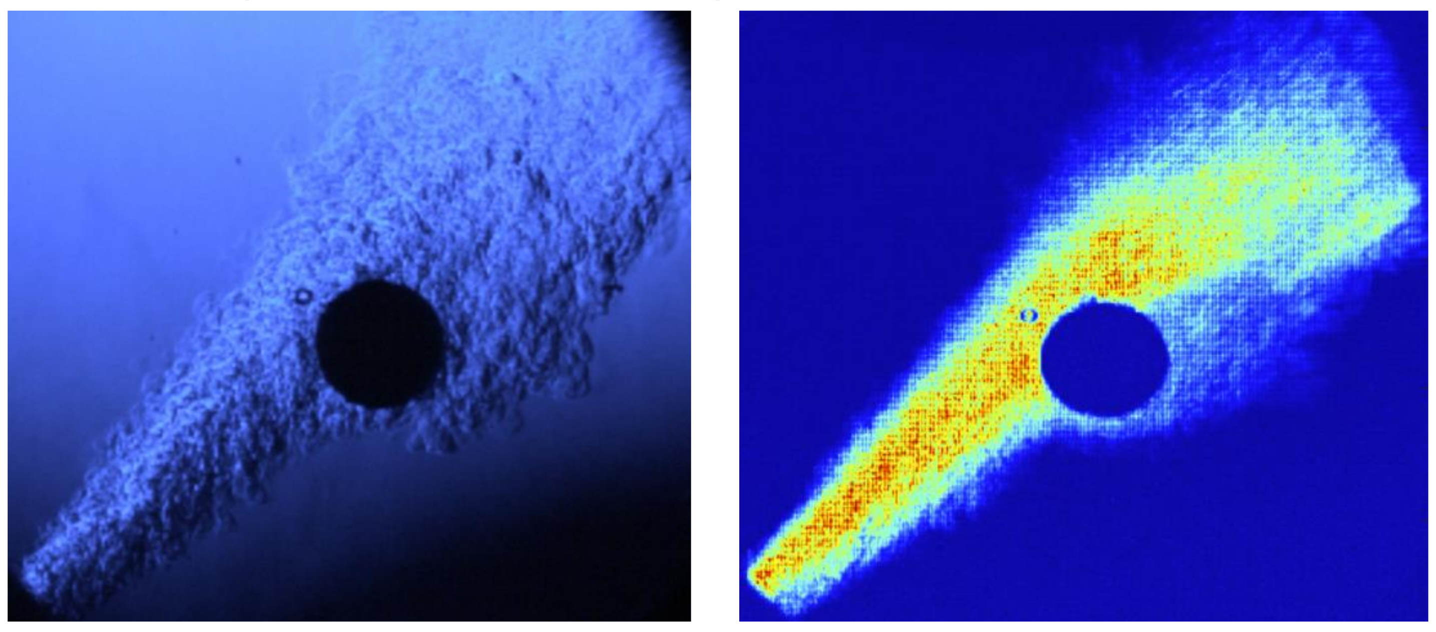


Figure 2: Raw Image (Left) and Processed Image of Jet Shape (Right)

PIV software is then used to analyze the airflow, revealing useful information such as air velocity vectors, velocity gradients, and streamlines, as seen in Figures 3 and 4. In the PIV software, a mask is applied to the ball that excludes it from flow analysis. Then, the software uses change in flow position over time to calculate these useful metrics.

Conclusion

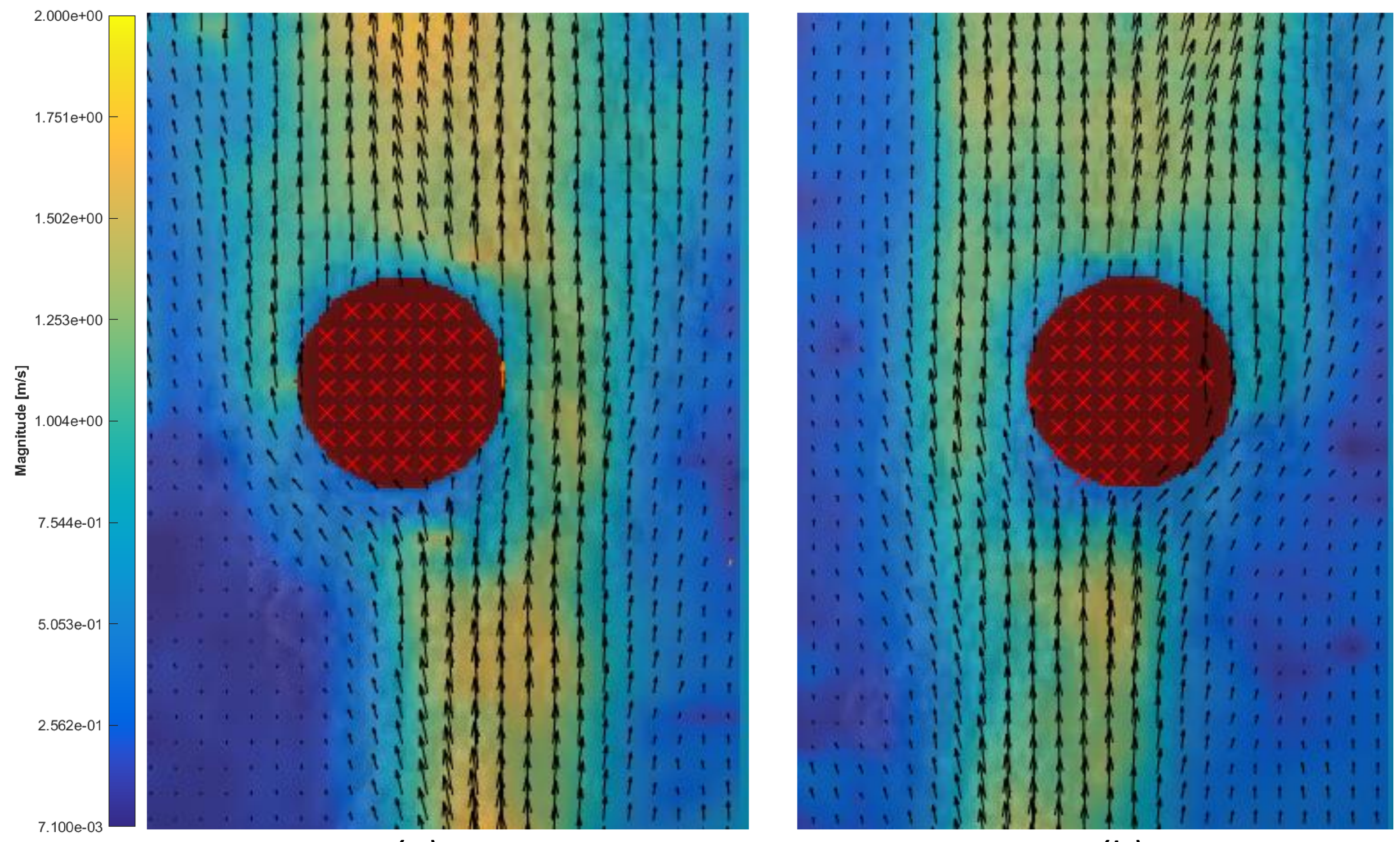
- *Goal*: Reveal airflow properties/patterns that cause a ball to 'float' in a jet of air.
- Slower flow on offset side → Pressure force re-centers ball.
  - Angled: Pressure force re-centers and balances weight of ball.
- Consider forces due to Coandă effect and flow separation.
  - Flow separates on slower side, reducing lift and centering forces.
- Pressure reduction from separation and pressure increase from slower air constantly alters net force on the ball.
  - Ball is suspended (but unsteady) due to competition of forces.
- All results apply for both vertical and angled setups.
  - Angled: Ball falls when angle is too great
  - Vertical: Ball falls when it moves too far in one direction.
- *Future Work*: Analyze moving objects (with spin), such as tennis ball

References

[1] Hall, Nancy. "Schlieren System." NASA, 13 May 2021, www.grc.nasa.gov/www/k-12/airplane/tunvschlrn.html.
[2] Nolan, Kevin. "Schlieren Setup Standard Operating Procedure." University College Dublin, 27 Feb. 2019.
[3] Savov, Vladimir. "On the Phenomenon of a Light Sphere in an Inclined Air Jet." Aeronautical Research and Development, vol. 1, 2022.
[4] Britannica, The Editors of Encyclopaedia. "fluidics". Encyclopedia Britannica, 6 Jan. 2012, https://www.britannica.com/technology/fluidics.

Results

The air is faster around the side of the ball closer to the center of the jet and slower around the side offset from center. When the ball is not directly centered, pressure drops on both sides. Per Bernoulli's principle, the faster flow in the center indicates a greater pressure drop. Because pressure on the off-centered side drops less, it is the 'higher' pressure of the two. This pressure force helps return the ball to its neutral position. For lift, the jet itself balances the weight of the ball. Figure 3 below shows this for setups where the ball floats both left and right of the jet.



(a) (b)

Figure 3: Flow Velocity Vectors and Gradient Around a Ball (a) Left and (b) Right of Jet

Bernoulli's principle assumes an ideal fluid with no viscosity, which is not fully applicable here, and thus this pressure force is not the sole reason for the ball floating [3]. The streamlines in Figure 4 below highlight that the layer of air below the ball thins and sticks to the ball's surface. This occurs due to the Coandă effect, or the tendency of a fluid to 'attach' itself to and flow along a surface [4]. The smaller radius of curvature on the streamlines with slower air indicates a higher acceleration normal to the streamline, which supports the conclusion of a larger pressure force in those areas. This applies to both vertical and angled jets. In the angled case, this force both balances ball's weight *and* keeps it centered.

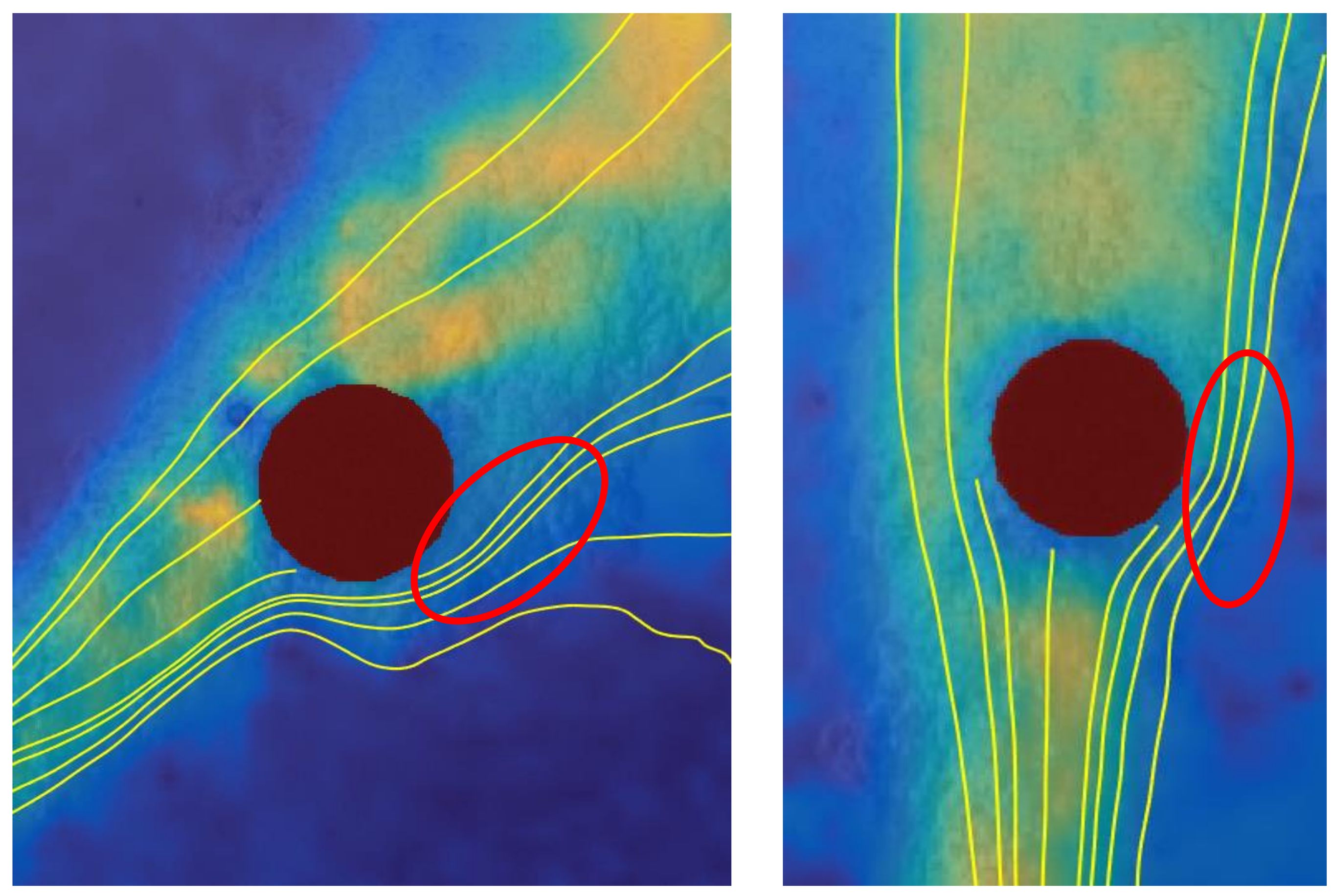


Figure 4: Streamlines and Velocity Gradient Around an Angled and Vertical jet

These streamline images display flow separation around the upper part of the ball. Instead of sticking completely around the ball, the air separates and trails off. This separation occurs mostly on the slower side, reducing lift. Conversely, the faster air does not adhere well to the ball. Thus, there is negligible lift reduction on that side. There is constant competition between this pressure reduction from separation and the aforementioned pressure increase from slower flow, highlighting why the ball is never perfectly balanced in the jet. If the ball moves too far to one side or if the jet's angle is too large, the magnitude of the separation force overtakes lift/centering forces and causes the ball to fall.