Direct density fluctuation measurements in supersonic flows

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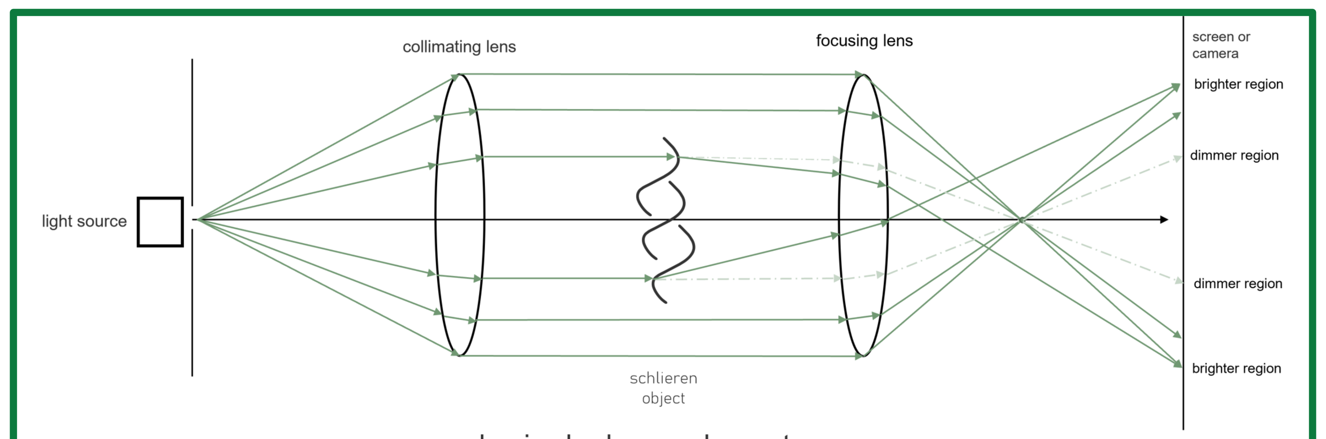
Background

- Turbulence occurs in compressible and incompressible flows, and is vital for many aerospace applications
- Compared to incompressible flows, compressible turbulence calculations are more challenging due to the presence of additional fluctuating quantities, such as density
  - Despite their difficulty, these calculations are very important because of their use in describing and modelling the behavior of compressible turbulence
- Shadowgraph and schlieren optical methods can be utilized to measure density data
  - First developed in the 19th century
  - These methods are based on changes in the refractive index due to density changes[1]
  - Only used *qualitatively* to observe density gradients
- *Quantitative* shadowgraph and schlieren techniques have recently been developed
  - More difficult than qualitative methods because multiple optical relationships that must be solved in order to get density data are added to the complexities of qualitative set up

Associated Disciplines

- Aerodynamics, optics, MATLAB programming, numerical analysis



basic shadowgraphy system

What is Shadowgraphy?

A shadowgraph is a shadow-image. You've likely seen natural shadowgraphs before in things like the shadows on pavement from heat waves on a hot summer day.

In the lab, shadowgraphs are captured from a beam of light that is passed through lenses or reflected between mirrors. The beam crosses a test space where the flow to be studied is located. (This flow can be as simple as the heat plume from a candle, but here we'll look at shock waves and high-speed flows).

The beam of light then projects an image of the flow onto a screen or into a camera. Rays are bent by the density gradients within the flow, resulting in brighter and dimmer regions on the screen.

Quantitatively

Relative light intensity on the screen corresponds to the angle of refraction (from refractive index) in the density gradient through which a ray of light is bent as it passes through the flow.

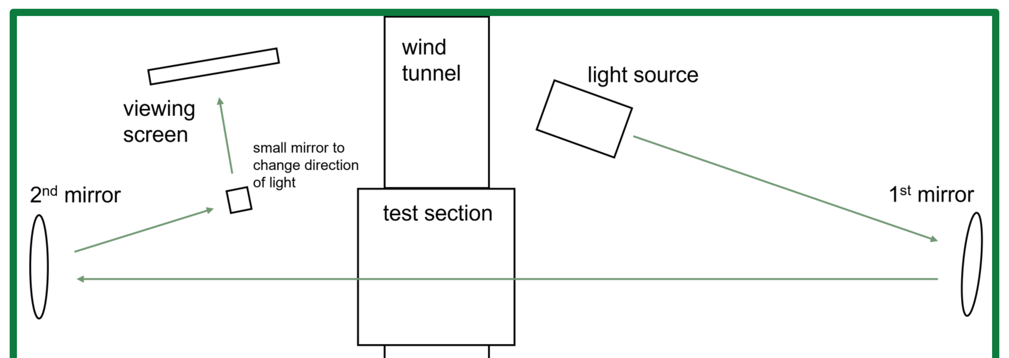
Refractive index data can be used with the Gladstone-Dale equation[2], $n - 1 = k\rho$, to determine the density of the gradient area.

Goals

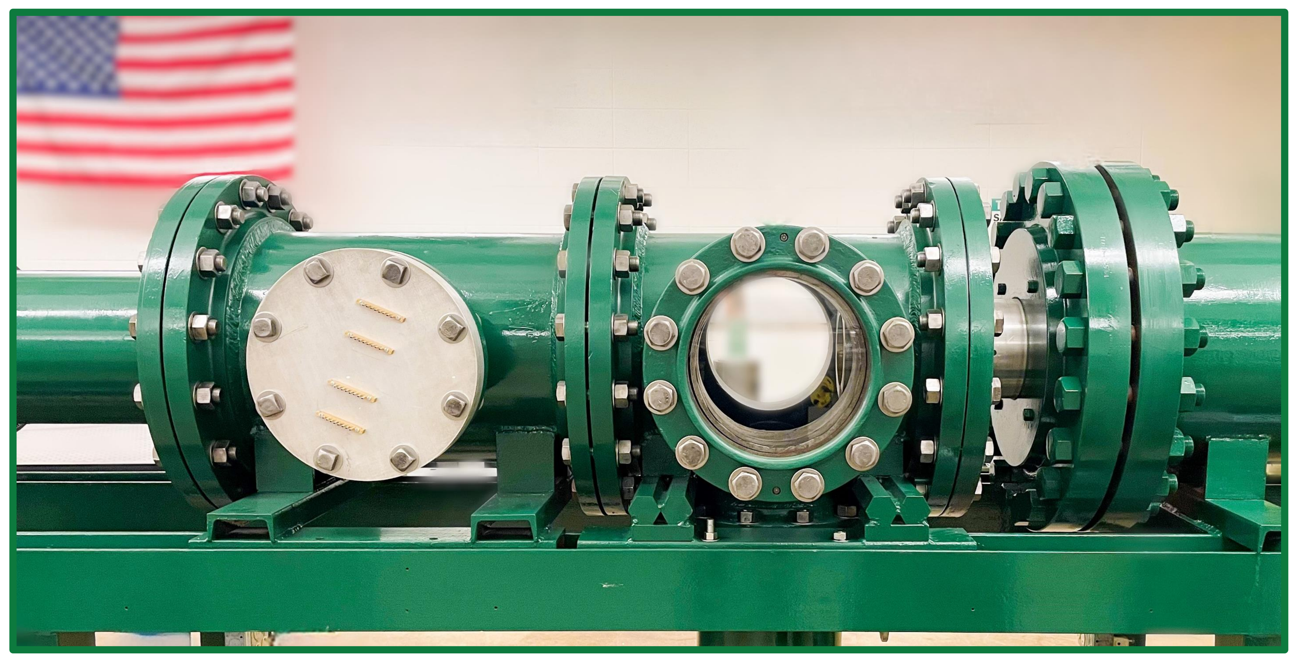
- Develop a *quantitative* shadowgraphy method to measure fluctuating (turbulent) density gradients in supersonic flows:
  - System geometry (determines sensitivity)
  - Calibrations to set accuracy for quantitative measurements
  - MATLAB code to convert instantaneous images into density gradients

Methodology

- Perform literature reviews of qualitative and quantitative shadowgraphy experiments
  - Determine parameters for system set-up:
    - Camera, camera lens
    - Mirror size, focal length, and angle
      - Position of the second mirror determines system sensitivity
    - Light source brightness, shape of opening
    - Distances between components
  - Determine calibration techniques for the system
  - Establish data processing procedure
- Develop MATLAB code to process data
  The code must:
  - Determine pixel gray levels of a shadowgraph photo or video
  - Solve a differential equation relating light intensity and the derivative of the refractive index
  - Use that refractive index and solve Gladstone-Dale equation[2] for density
- Test the system by performing a shadowgraphy experiment on a butane jet from a lighter
  - Calculate refractive index and density of butane jet and compare to known values
- Test supersonic flows in the wind tunnel using said methodology and calculate densities of the flow



our setup: z-type mirror system



Missouri S&T supersonic wind tunnel

Expected Outcomes

- Develop a shadowgraphy process to measure fluctuating density in supersonic flows
  - System set-up
  - Code for data processing
- Density measurements
  - These density measurements, along with velocity measurements, will enable the potential development of new turbulence correlations in compressible flows

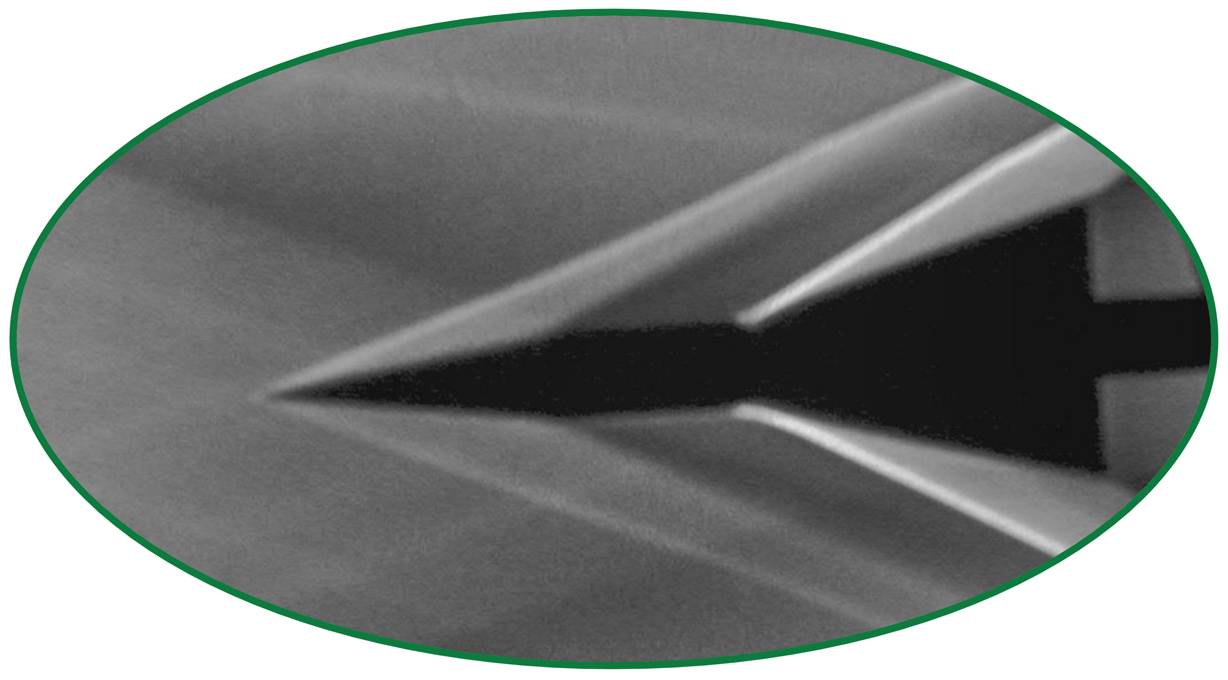
How do you get density from light?

[1] Shadowgraphy is based on the refractive index and the **Refractive Index Equation**, $n = \frac{c}{v}$, which says that the refractive index in a given medium is the speed of light in a vacuum over the speed of light in that medium. The denser the medium, the slower the speed of light is in that medium.

Snell's Law, $\sin\theta_i = n\sin\theta_r$, equates the angle at which a light ray enters a medium (θ_i) to the angle that the light ray is refracted (θ_r) times the refractive index (n). This allows the calculation of the angle at which light is bent upon switching mediums.

Snell's law is used to find the refractive index from the light and dark areas on the screen since these areas describe how much light was bent by the test flow.

[2] The **Gladstone-Dale Equation**, $n - 1 = k\rho$, relates refractive index (n) to some constant (k) times density (ρ). It is used to calculate density from the refractive index found using Snell's Law.



Shadowgraph taken at Missouri S&T supersonic wind tunnel

Acknowledgements/References

Acknowledgements

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References

Bowersox, R.D.W. & Schetz, J.A. (1995). Measurements of a compressible turbulent flow structure in a supersonic mixing layer. *AIAA Journal*.

de Izarra, G. & de Izarra, C. (2012). Quantitative shadowgraphy made easy. *European Journal of Physics*.

Garg, S. & Cattafesta, L.N. (2001). Quantitative schlieren measurements of coherent structures in a cavity shear layer. *Experiments in Fluids*.

Settles, G.S. & Hargather, M.J. (2017). A review of recent developments in schlieren and shadowgraph techniques. *Measurement Science and Technology*.

Settles, G. S. (2001). *Schlieren and Shadowgraph Techniques*. Springer.

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