

Chapter 1 : Introduction

1.1 History

Since ancient times humankind has sought to learn more about how fluids flow around solid bodies. Interest in these flows has been piqued for a variety of reasons such as designing nautical vessels, designing plumbing to transport fluids over great distances, and designing flying machines. Famous names such as Aristotle, Da Vinci, and Newton, just to name a few, have considered the nature of fluid flows around solid bodies. Humankind's understanding of these flows has increased at a remarkable pace over the last 100 years through the development and implementation of such tools as the wind tunnel and computers. These tools have, in part, enabled human society to achieve feats that before the 20th century were the domain of science fiction writers and dreamers. Engineers and scientists have used these tools, in addition to a wide range of other tools, to design and improve upon airplanes, buildings, and nautical vessels as well as a wide variety of other engineered devices.¹

Over the last 200 years scientists and engineers have spent a great deal of time thinking about and performing experiments to better understand fluid flows around bluff and "aerodynamic" bodies. Intrusive measurement devices such as Pitot tubes and hot wires have been used to measure dynamic pressures, flow velocities, and other flow properties near these bodies. Non-intrusive devices such as pressure sensitive paint and Laser Doppler Velocimeters (LDV) have also been developed and used to measure various flow properties near these bodies.² While the development and use of LDV marks a significant improvement in our ability to measure flow properties in a way that will not directly influence these properties through the presence of a probe within the flow being measured, LDV is

not without its disadvantages. Perhaps one of the largest disadvantages to using LDV for large scale wind tunnel experiments is the time and effort required to map out a large portion of the flow field around and behind the body of interest.³ It would be desirable to have a non-intrusive device capable of measuring flow properties in large areas of the flow field quickly and with less effort than would be required using LDV.

1.2 Research Motivation

The purpose of this research is to develop a non-intrusive device which will measure a plane of instantaneous flow field velocities near the surface of a solid body. The primary motivation for this research is to use this device to measure flow velocities in the streamwise vortices shed in the wake of two different bodies of revolution, a 6:1 prolate spheroid model and a DARPA2 submarine model. Data gathered in the wake of the 6:1 prolate spheroid will be used to verify the performance of this new measurement system by comparing data obtained with this system to data obtained in previous tests performed with the same 6:1 prolate spheroid model. The data obtained in the wake of the DARPA2 submarine model will be used to improve performance of computational fluid dynamics flow simulations used to predict flow around full scale submarine hull shapes. This device measures a plane of flow field velocities in a single measurement realization. The device uses a measurement technique referred to as Doppler Global Velocimetry (DGV) or sometimes referred to as Planar Doppler Velocimetry (PDV).⁴

1.3 Basic Theory

The Doppler Global Velocimetry technique uses the Doppler effect to measure flow field velocities. The theory behind this technique can be described through the following equation:

$$\Delta \nu = \frac{\nu_o}{c} (\hat{a} - \hat{l}) \cdot \vec{V} \quad (1)$$

where $\Delta \nu = \nu_D - \nu_o$ which is the change in optical frequency of the light reflecting off of the seed particles passing through the laser sheet (ν_D is the optical frequency of the Doppler shifted light and ν_o is the optical frequency of the unshifted incident laser light), c is the speed of light, \hat{a} is the unit vector pointing toward the direction in which the data area is being viewed, \hat{l} is the unit vector pointing in the direction in which the laser light is propagating, and \vec{V} is the velocity vector.⁵ Figure 1.1 shows the basic setup for a single component DGV system. The vectors \hat{a} , \hat{l} , and $(\hat{a} - \hat{l})$ are shown in figure 1.1. Essentially, $\Delta \nu$, ν_o , \hat{a} , and \hat{l} are measured during the experiment and

equation (1) is rearranged so that it can be solved as a system of equations to determine the velocity components in the desired coordinate system.

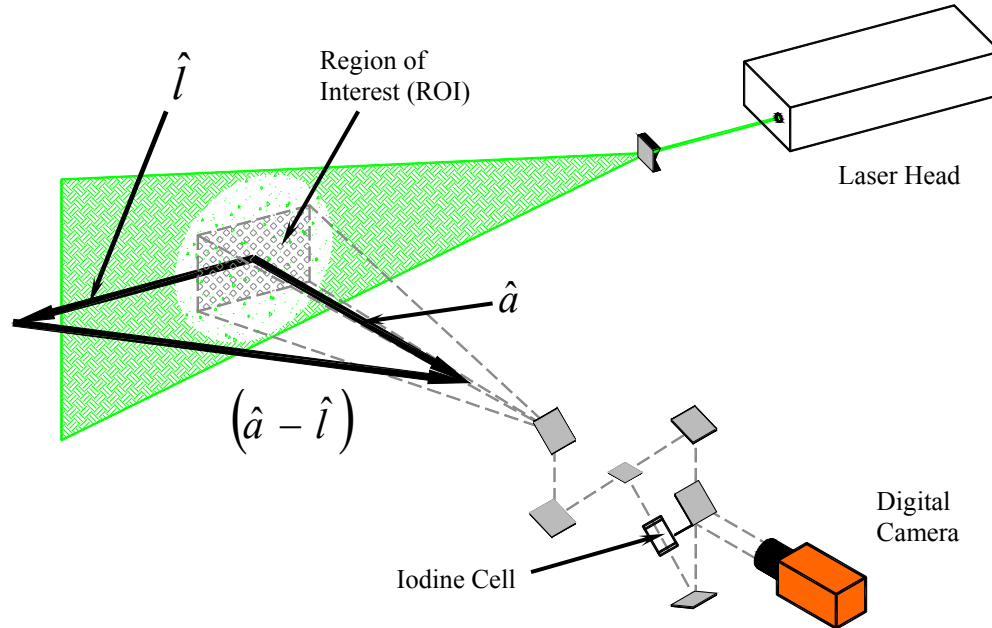


Figure 1.1 Doppler Global Velocimeter Setup

1.4 The Doppler Global Velocimetry Technique

In the Doppler Global Velocimetry technique, seed particles injected into the flow or particles naturally occurring in the flow are illuminated by a sheet of coherent, green, laser light. For a three component DGV system, a pair of images of the seed particles passing through the laser sheet are acquired from three different viewpoints using digital surveillance cameras or astronomy cameras.^{6,7} One of the images from each viewpoint is used as a reference and the other image passes through a hollow glass cylinder filled with iodine gas. The hollow glass cylinder filled with diatomic iodine gas (commonly referred to as an iodine cell) acts as an optical filter since gaseous diatomic iodine has several sharp transitions from total absorption to total transmission inside the green portion of the visible light spectrum. The light intensity of each pixel in the region of interest (ROI) of the filtered view is divided by the light intensity of the corresponding pixel in the ROI of the reference view.⁸

When a frequency doubled pulsed Nd:YAG laser is used in the Doppler Global Velocimetry technique additional steps are needed to account for variations in the optical frequency of the light pulses produced by the laser. For Doppler Global Velocimetry using a frequency doubled pulsed Nd:YAG laser, the ratios of pixel intensities for each pixel location in the ROI are compared to a ratio of pixel intensities for a portion of the laser beam that is projected onto a stationary target. The

difference between the pixel intensity ratio in the region of interest and the pixel intensity ratio from the stationary target is proportional to a shift in the optical frequency of the laser light due to the Doppler effect (i.e. $\Delta\nu$).⁹

1.5 Mie Scattering vs. Rayleigh Scattering

The Doppler Global Velocimetry technique makes use of a physical phenomenon known as Mie scattering. Mie scattering occurs when light is scattered by particles larger than the wavelength of the light being scattered. This scattering process is generally assumed to be elastic. In other words, none of the light colliding with each particle is absorbed by the particle. Seed particles with diameters roughly between 1 μm and 10 μm , such as smoke or dust particles, can cause Mie scattering when illuminated by light in the visible spectrum. This type of light scattering is also used in some Laser Doppler Velocimetry (LDV) systems and Particle Image Velocimetry (PIV) in addition to DGV.¹⁰ The white color of most clouds is attributed to Mie scattering since all visible wavelengths of sunlight are scattered equally by the water droplets contained in these clouds. Rain clouds appear various shades of gray because these clouds are thicker than clouds that do not produce rain and thus, less sunlight penetrates them.¹¹

Another type of light scattering, known as Rayleigh scattering, has been employed by some researchers using measurement techniques very similar to the DGV technique. Rayleigh scattering occurs when light is scattered by particles smaller than the wavelength of the light being scattered. As with Mie scattering this type of light scattering is assumed to be elastic. For light in the visible spectrum, this type of scattering normally occurs with particle sizes on the order of a molecule.¹² Rayleigh scattering is responsible for the sky being blue on a sunny day. The molecules in the air scatter shorter wavelengths of light (violet and blue) more effectively than longer wavelengths of light (Red and yellow). The sky appears red at dawn and dusk because the sunlight must travel farther through the atmosphere than during the rest of the daytime, so all of the violet and blue light has been previously scattered and only the longer wavelength (red and yellow) light remains.¹³

1.6 Previous Work

1.6.1 Origin of the Doppler Global Velocimetry Technique

The Doppler Global Velocimetry technique was first introduced by Komine *et al* in 1991. The technique was presented as a method to obtain quantitative velocity information through flow visualization. They chose to use Mie scattering to acquire DGV data, because this type of scattering did not appreciably broaden the laser spectrum, unlike molecular Rayleigh scattering. The original system used a continuous-wave argon-ion laser, molecular filters containing iodine gas, and three pairs of Charge-Couple Device (CCD) video cameras which captured filtered and reference images at a rate of 30 images/second. Komine *et al.* also performed tests with an Nd:YAG laser to obtain instantaneous velocity data. The system was calibrated using a disk rotating at a known constant speed. This first DGV system was used to measure velocities in a near sonic free expanding nozzle jet.¹⁴

1.6.2 Improvements to the DGV Technique

Dr. Hiroshi Komine worked with James F. Meyers of NASA's Langley Research Center to refine the technique. The first DGV system assembled by Komine and Meyers was a single component system used to acquire DGV data from a disk rotating at a known constant speed. Next the single component system was used to measure flow velocities in a subsonic jet and finally the system was used to measure a portion of the flow in the wake of a 75 degree delta wing.¹⁵

Through these tests, and tests of the technique that followed, Meyers and other researchers began to make improvements to the technique. One of the first improvements was acquiring images of a grid of dots or squares to align the filtered and reference views. These grid images were also used to "de-warp" the acquired images so each image appeared to be looking perpendicular to the data area. This allowed views from various viewing angles to be overlaid on top of each other. Another improvement made in the technique was accounting for variations in the pixel sensitivity in the CCD arrays of the cameras used to acquire DGV data. Images called pixel sensitivity images were acquired to account for these variations.¹⁶ The next improvement to be made to the technique was capturing "background" images to correct for ambient light, stray laser light from reflections, and dark current from the CCD array in the camera.¹⁷

Robert McKenzie, of NASA Ames Research Center, authored two important papers that influenced the design of the Virginia Tech DGV system. The first paper, published in 1995, discussed the measurement capabilities of a DGV system using a pulsed Nd:YAG laser. This paper documented several innovations. McKenzie's DGV system used a single 16-bit astronomy camera in place of two cameras to capture the filtered and reference images. McKenzie also monitored the mean variations in optical frequency of the laser from pulse to pulse using a pair of photodiodes and an iodine cell. In addition to these innovations McKenzie performed an extensive study on sources of uncertainties in the DGV technique. This analysis revealed that the velocity measurement uncertainty for a single realization using the DGV system described in the paper was 2 m/s (6.562 ft/s).¹⁸ This uncertainty calculation is relevant for the Virginia Tech DGV system because the equipment and techniques used in McKenzie's DGV system were very similar to those of the initial form of the Virginia Tech system. The second paper was published in 1997. This paper introduced the idea of using a small portion of the laser beam projected into the view of one of the camera systems, used to acquire DGV data, to monitor pulse to pulse variations in the mean optical frequency of the laser light before this light is Doppler shifted. This paper also suggested using pixel binning to reduce spatial noise. Pixel binning is a form of filtering. In this technique the pixels surrounding a given pixel are used to calculate an average value for the pixel in question. McKenzie stated that 3 x 3 binning minimized excessive spatial noise while having no significant effect on the spatial resolution of the image. Again this paper showed the single realization velocity measurement uncertainty of the DGV system described in the paper to be 2 m/s (6.562 ft/s).¹⁹

1.6.3 Development of the Virginia Tech DGV System

Development of the Virginia Tech DGV system began in 1996. The goal of this development was to use the Virginia Tech DGV system with the Dynamic Plunge Pitch and Roll (DyPPiR) apparatus to acquire instantaneous unsteady velocity data in the wake of a DARPA2 submarine model. During the initial development phase of this program basic hardware for the system was purchased or constructed, basic software to acquire data images was written, and initial tests of the camera module optical orientation were conducted. Next, a sophisticated Windows based control program was written to perform a variety of tasks needed to acquire DGV data. Some of these tasks included: controlling the Nd:YAG laser, monitoring the temperature of the cold finger on each of the three iodine cells, acquiring and storing various correction images needed, acquiring and storing iodine cell calibration and velocity images and processing and reducing these iodine cell calibration and velocity images into DGV data. The portion of the control program used to process DGV images

into DGV data involved writing software to perform various image processing tasks such as de-warping, mirroring, image addition and subtraction, as well as using correction images to improve data quality. Once the hardware and software for the Virginia Tech three component DGV system were ready, tests were conducted to demonstrate the capabilities of the system.

The first version of the Virginia Tech three component DGV system was tested in September - October 2000 with mixed results. The capability to capture and use various correction images and the capability to acquire iodine cell calibrations was demonstrated but attempts to acquire instantaneous velocity data were unsuccessful. Several significant problems were encountered during these tests. One of the three cameras began to malfunction and was only usable for 10 to 15 minutes at a time. The system was not able to detect a Doppler shift in the laser light reflecting off of a wheel rotating at a constant angular velocity. The laser began to have problems locking on to a particular optical frequency. Also, the smoke machine, used to produce seed particles in the flow, could not produce enough seed to acquire instantaneous velocity images. These problems eventually led to the end of the first set of tests of the Virginia Tech three component DGV system.²⁰

1.6.4: Recent improvements to the DGV Technique

A paper published in 2001, by Meyers *et al.* considered sources of measurement error and suggested several new improvements to reduce the single sample uncertainty of the DGV technique. The first suggestion made was to use vapor-limited iodine cells instead of cells with a cold finger. Small variations in the cold finger temperature translate to significant errors in the velocity measured by the system. In fact, the paper stated that an uncertainty of 0.1° C in the cold finger temperature resulted in an uncertainty of 3 m/s (9.843 ft/s) in velocity measurements. By using vapor limited iodine cells this uncertainty was eliminated because the number of gaseous iodine molecules remained constant as long as the body temperature of the cell was maintained above the temperature the cell was filled at.²¹

The next suggestion was to calibrate the iodine cells using a rotating disk. The previous generally accepted method used to calibrate the iodine cell determines the ratio of the filtered and unfiltered views of a white card illuminated by the diffused laser beam while varying the optical frequency produced by the Nd:YAG laser. The problem with this method was that the laser optical frequency drifts slightly from pulse to pulse. Meyers *et al* recommended using a disk rotating at a constant speed to calibrate the iodine cells. They stated that in experiments they conducted with the laser injection seeder at a constant setting, the standard deviation of the variation in laser optical

frequency was about 40 MHz. This means that using the average of a limited number of samples would not produce an acceptable uncertainty in the results. Their argument was that it is unnecessary to know the absolute optical frequency of the transition from full light transmission by the iodine cell to full light absorption if the absolute value of the optical frequency at the center of the absorption line is known. The rotating disk would produce a linear variation in the Doppler shifted optical frequencies along any vertical line on the wheel.²² In other words, the laser light frequency recorded by the ratio of the filtered and unfiltered images of any vertical line of pixels in a de-warped view of the rotating disk will vary linearly. By measuring the ratio of the filtered and unfiltered pixel values along the vertical diameter of the rotating disk and varying the laser optical frequency in small increments these successive measurements can be pieced together to create an absorption profile. Figure 1.2 shows how the iodine cell absorption profile is constructed.²³

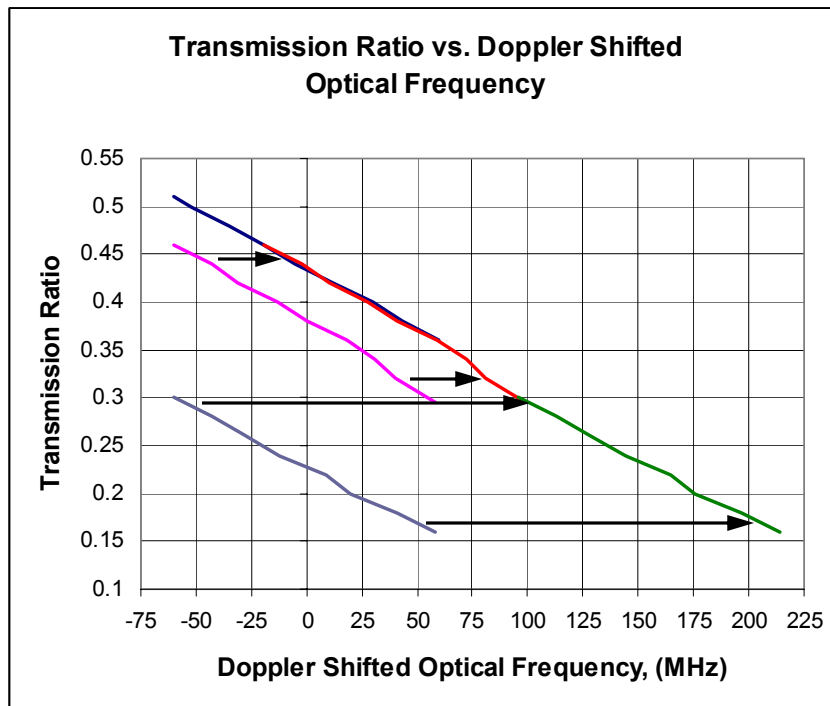


Figure 1.2: Construction of iodine cell absorption profile.²⁴

Another suggestion made in this paper was to use an extra camera to monitor the temporal and spatial variations in optical frequency each laser pulse produced by the Nd:YAG laser. The paper stated that the mean optical frequency of successive laser pulses can differ by as much as 80 MHz. For a pulse with a bandwidth of 120 MHz, this variation is significant. These variations are caused by the control system in the laser dithering the rear resonator mirror to produce single frequency output. In addition to variations in the mean optical frequency of each pulse there are spatial

variations within each pulse. These variations are caused by imperfections in the Nd:YAG rods. The extra camera, used to monitor these variations, would capture images of a stationary target illuminated by each pulse of laser light used to acquire data.²⁵

Other minor suggestions were also made in this paper. These suggestions ranged from the color the model should be painted to the minimum angle between the data plane and the detector to filtering data to reduce the effects of spatial and temporal measurement noise caused by laser speckle, variations in pixel sensitivity, and image to image intensity variations as well as other suggestions. They suggested painting the model and other items from which unwanted reflections might occur either flat black or flat red. They also recommended keeping the angle between the measurement plan and the detector greater than 30 degrees. The end result of all of these suggestions was to reduce velocity measurement uncertainties to 0.5 m/s for velocity measurements on a rotating wheel.²⁶

1.6.5 Filtered Rayleigh Scattering

A measurement technique similar to DGV that uses the Rayleigh scattering phenomenon is called Filtered Rayleigh Scattering (FRS).²⁷ This technique was introduced by a group of researchers led by Dr. Richard Miles of Princeton University. This technique was originally intended to be used to improve flow visualization in situations where the signal is obscured by background scattering but has also been used to measure temperature variations in fluid flows, and measure multiple properties in fluid flows. Like the DGV technique, a molecular filter such as a glass cylinder filled with gaseous diatomic iodine and digital surveillance cameras or astronomy cameras can be used in the FRS technique. The FRS technique also uses a laser to produce a sheet of laser light which illuminates the plane in which data is to be taken. As with DGV, a frequency doubled pulsed Nd:YAG laser is often used in conjunction with the diatomic iodine molecular filter.

In the Filtered Rayleigh Scattering (FRS) technique a portion of the flow field is illuminated by a sheet of narrow linewidth laser light and light scattered by molecules passing through the laser sheet passes through a molecular filter before being captured by a detector. As with the DGV technique, the laser is tuned to an optical frequency in the middle of an absorption transition for the iodine cell so that as the optical frequency of the light is changed by reflecting off of molecules in the flow field, the intensity of the light transmitted to the detector changes. Where DGV and FRS differ is in that Rayleigh scattered light intensity is directly proportional to the density of the scattering molecules. For this reason Rayleigh scattering can be used to measure density, temperature, and pressure variations in flow fields. Filtered Rayleigh Scattering does not use the Doppler shift which

occurs when light reflects off of molecules in the flow field, unless the flow velocity is being measured in addition to thermodynamic properties. The shape and position of the spectral profile, captured by the detector, is used to measure these thermodynamic properties.²⁸ For more information regarding the FRS technique please see the following references: 28, 29 30 31, and 32.