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Doppler Velocimetry

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Abstract

With the development and breakthrough of laser technology in finding a source for highly concentrated continuous electromagnetic radiation, the use of the well known Doppler effect could finally be implemented into accurate optical velocity measurements on small and even on large scale applications today. On the other hand, the Doppler effect can also be exploited acoustically in order to measure velocities in small sample sizes in various flow regimes. The goal of this lab exercise is to understand both measurement techniques separately and later on comparing them to each other. In addition, possible advantages and drawbacks are identified. Based on the present setup, improvements or alternatives were found which would lead to better results.

1. Introduction

In order to measure the speed distribution of a fluid flow one can use the Doppler effect. Knowing the speeds of a fluid at different points is of key importance for many different applications ranging from turbine designs, to drag measurements, to meteorology and ecology as well as biofluidics as the speed profile is one of the most significant characteristics of a flow.

The Doppler Effect is the change in frequency (and thus wavelength) of a wave compared to an observer if the observer or transmitter, or both are moving. This enables us to measure the frequency difference and from this in turn calculate the respective velocities.

$$f_R = f_0 \frac{1 - \frac{1}{c_0}\vec{u} \cdot \vec{e}_{TS}}{1 - \frac{1}{c_0}\vec{u} \cdot \vec{e}_{SR}} \approx f_0 \left[1 + \frac{1}{c_0}\vec{u}\left(\vec{e}_{SR} - \vec{e}_{TS}\right) \right] \tag{1}$$

There are two prominent methods that use this principle in Flow measurement, both were introduced in this lab demonstration. First "Laser Doppler Velocimetry" (LDV) that uses the doppler shift in a laser beam (electromagnetic wave), through a transparent medium. The second is "Acoustic Doppler Velocimetry" (ADV) which employs sound waves traveling through the fluid, in our case water excited at ultrasonic frequencies.

2. Experimental Setup and Conditions

For this experiment we used a water tunnel creating laminar flow at different flow rates.

For the LDV we use a Helium-Neon laser as our light source which emits a laser beam with wavelength $\lambda_0 = 633\ nm$. The light is split into two beams which cross in the focal volume where our measurement takes place. There, the light is scattered of the particles traveling in the flow. This scattering is then collected and amplified to receive the so called "Doppler bursts". For our experiment we measured the photons on the other side of the water tunnel rather than the laser and the optics, because even though measuring the backscattering is possible the intensity is much lower than with forward scattering. We used a fine tuned photo amplifier to create a measurable signal, which would have a significantly higher signal to noise ratio if mounted on the same side as the optics.

In our experiment the front lens of 250 mm resulted in a crossing angle $\frac{\theta}{2} = 5.52°$. The signal received is then Fourier transformed and corrected for the time and frequency correlation.

$$F(m\Delta f) = \sum_{n=0}^{N-1} f(n\Delta t)\, exp\left[-2\pi i \frac{mn}{N}\right] \quad (m = 0...N-1) \tag{2}$$

From the thus received value one can derive the actual velocity of the particle scattering the light which we assume to be the fluid velocity, as we only observe very small particles.

$$f_R = \frac{U_\perp}{\Delta} = \frac{2U_\perp sin(\theta/2)}{\lambda_0} \tag{3}$$

Thus we created 1000 independent burst samples with different instantaneous velocities. Nevertheless, assuming the flow to be stationary, we want to find the real velocity of our fluid. If we were to just average the frequencies we would be inaccurate, because we would count too many high-frequency short duration bursts and too few low frequency long duration bursts. This is due to the simple fact that short pulses occur more often because they are faster and thus overrepresented in our measurement. A better algorithm which we use, is correlating the bursts lengths inversely proportional to their frequencies

$$\tilde{f} = \frac{N}{\sum_{i=1}^{N} 1/f_i^*} \tag{4}$$

For the ADV we generate sound pulses of 10 MHz in water with the speed of sound at approximately 1500 m/s. This leads to a wavelength of 0.15 mm. From this we can derive a maximal detectable range ambiguity relationship of

$$r_{max} \cdot u_{max} \leq \frac{c_0}{2 \cdot f_{PRF}} \frac{c_0 f_{PRF}}{4 f_0} = 0.028126 \frac{m^2}{s} \tag{5}$$

Our probe is submerged in the flow and consists of one transmitter and three acoustic receivers. This allows us to recreate the three dimensional flow field because they are equidistant to the sample volume with different angles. To consistently obtain a good measurement one more adaptation has to be made. In the LDV case we were able to observe extremely small particles, this is not the case for the ADV anymore. As the water in the tunnel is clean, there are no natural scatterers of the required size magnitude present. Thus we mount a wire grid in front of the control volume. After applying a current to the wire grid, small hydrogen bubbles are created through electrolysis. These bubbles then travel with the flow through our measurement volume and act as the necessary scatterers. After sampling the flow field at 25 Hz we obtain the average Doppler shift of

$$\Delta f = \frac{1}{K} \sum_{k=1}^{K} \frac{\Delta\psi_k}{2\pi\tau} \approx f_0 \frac{u}{c_0} \tag{6}$$

Now to observe the potential of time resolution with ADV, we measure the wake flow behind a cylinder, which is also known as the “Karman vortex street”. This is a periodic phenomenon and thus we can use a trick to give us a temporal resolution as well. We measure the force acting on the cylinder with strain gauges mounted in a “half bridge” configuration. The force measurement has the same periodicity as the flow vortices and after accounting for the phase changes and correlating with the ADV measurements, we obtain a flow field that is differentiated in all spatial dimensions as well as time. These measurements have to be carried through at every point we want a resolution of, while simultaneously measuring the force on the cylinder. Another speciality of the Karman vortex street is that the relation of the Strouhal number stays approximately constant at around 0.2 while the Reynolds number can cross multiple orders of magnitude from slow laminar flow to fast turbulent flow.

3. Measurements

We now measure the water flow at different velocities with the LDV method. Starting from 5 RPM pumping frequency up to 25 RPM. Using the LDV method the individual doppler bursts can be seen in Fig. 1.

There we observe how a particle enters the observation volume and scatters the laser wave. We see a strong trend towards compressed waves, if we increase flow speeds the Gaussian wave packet is denser. After Fourier transforming the wave packets and binning around 1000 signals we obtain Fig. 2. There we observe a small spread of the different

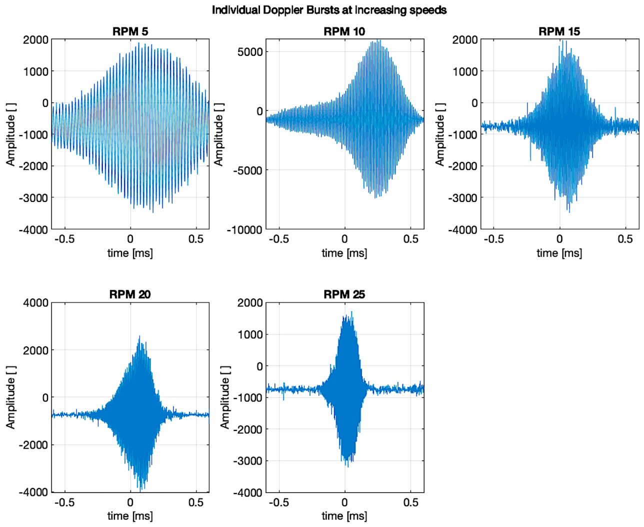

Figure 1

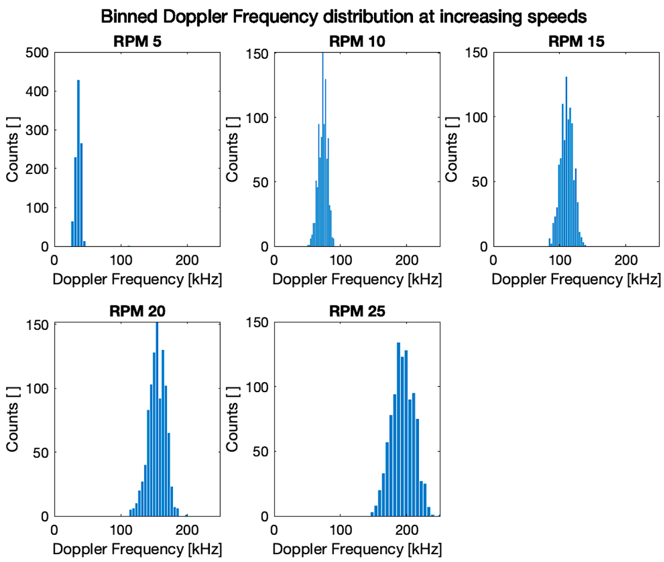

Figure 2

particle speeds around a central point that increases if we increase flow speed. With higher flow speeds the deviation starts to grow as well.

For the ADV Measurement we now implement a cylinder with diameter of 6cm in front of the measurement volume and create hydrogen bubbles which act as our scatterer. With the known kinematic viscosity of water at $8.19 \cdot 10^{-7}\ \frac{m^2}{s}$ we can calculate the Reynolds number with the mean velocity the ADV measurement provided. We can also calculate the Strouhal Number using the shedding frequency we measured at the cylinder. Plotting the Reynolds number against the Strouhal number in Fig. 3.

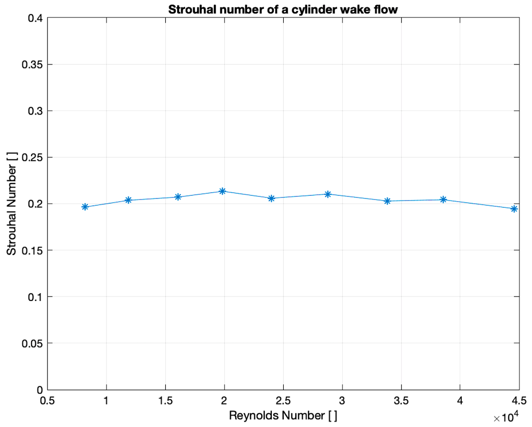

Figure 3

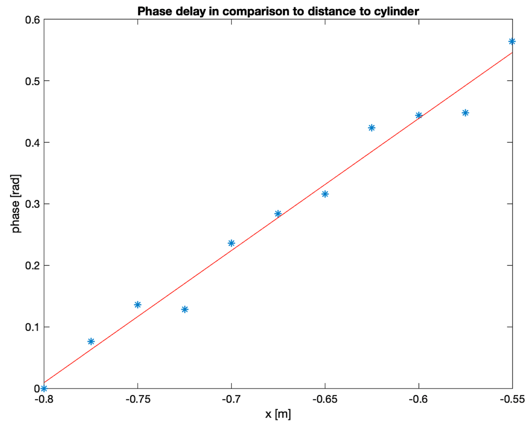

Figure 4

We can easily see that the Strouhal number remains nearly constant, except for small measurement noise, no matter at which Reynolds number we measure. This is in sync with the known behavior of the Karman vortex street. Using the fact that the periodicity of the flow measurement is the same as the periodicity of the measured force on the cylinder, we can calculate the phase difference of the measurement volume compared to the distance of where the measurement was carried out. This is plotted in Fig. 4.

There we can see that the measurement data follows a clear linear trend for the phase difference against the distance from the cylinder, which agrees with the theoretical intuition. Very small outliers stem from measurement uncertainty as both the measurement of the force and the speed have to be considered and this leads to a small propagated error. If one now plots the signal correlation for both of the crosscorrelations as well as the autocorrelation one

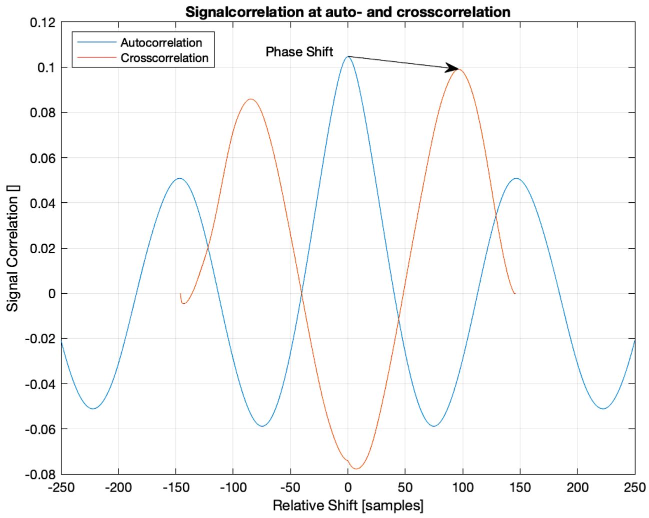

Figure 5

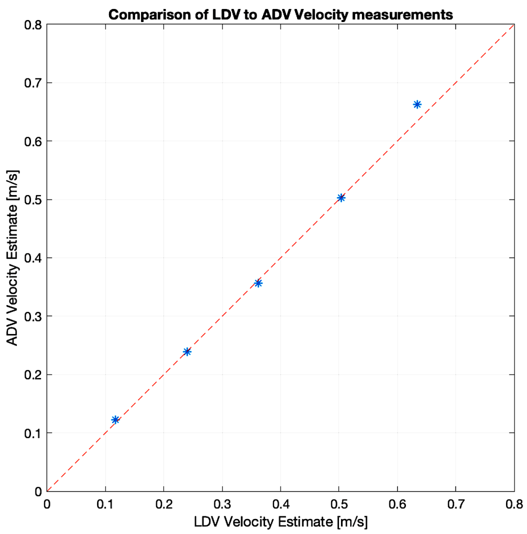

Figure 6

receives Fig. 5. There it is apparent that the same periodicity is truly observed. The plot looks very accurate except for one very small dent in the cross correlation close to the zero-crossing on the y-axis.

If one now compares the velocity measurements made for the LDV with the measurements made for the ADV, we receive Fig. 6. There we observe that both velocities agree very well with each other. There is a very small difference at the highest measured velocity where the ADV is slightly larger.

Conclusions

We saw two different velocity measurement methods that are both based on the Doppler Effect but employ different kinds of waves which leads to strong differences. Both are capable to produce accurate velocity measurements.

Advantages of the LDV method are for example the fact that it works without any calibration and is not dependent on the properties of the fluid or for example the temperature, which makes it very robust and is the reason it sometimes is used as a reference measurement to validate that another system is calibrated correctly. Another strong advantage is that the measurement is completely non intrusive and only requires small optical access to the flow.

Disadvantages are that the required optics are quite delicate as you have to focus multiple beams on a volume of a few mm^3, this is especially so if you want to measure all three dimensions of the velocity field, which makes multiple laser sources necessary and focusing them even harder. This means moving such an LDV system is a very hard task as they lasers and optics have to be precisely set up. Another drawback is that the LDV method requires the medium to be transparent to the laser beam, so not every fluid is usable, but with air and water very important ones are usable. In addition, the fact that measurements occur at random times means that one has to account for a certain bias in particle distribution, which is another source of complexity and can introduce errors if not handled correctly.

Advantages of the ADV method are that it is easy to resolve the flow in all spatial dimensions. If a reference measurement is periodic this makes it possible to resolve for the temporal component as well as we did with the force measurement on the cylinder in our measurement.

Disadvantages are that the measurement devices usually are somewhat intrusive as the wave needs to be propagated through the medium. Another disadvantage is that it requires scatterers which in the case of clean flows as we observed it have to be created artificially. This introduces some problems as they have to be small enough to not disturb the flow around them but also large enough to scatter the sound waves. They also have to be created in regular intervals. Another disadvantage is that the speed measurement strongly depends on the speed the wave propagates through the medium which usually is dependent on multiple external factors that have to be calibrated for e.g. the temperature and salt content in water. Also calibrating of forces can be a challenge to synchronize with the velocity measurements as we had to perform for the cylinder strain gauges, this is especially hard for analog systems.

Advantages of both system is the high frequency at which measurements can be carried through to allow for a very accurate tracking of the flow. So both methods of measuring velocities have their respective strengths and weaknesses, so one should consider the objectives of measurement before deciding on a method.