Review and Comparison of Flow Measurement Techniques

Alexander Baron von Hohenhau

Abstract: *This article compares common methods of measuring pressure and velocity in liquid and gaseous flows. To this end, a graphical overview of the different types of pressures is presented. Furthermore, it is shown how multi-hole pressure probes can be used to not only measure pressure, but also to compute the component of velocity. This pressure-based measurement technique is compared to optical-based Laser Doppler Velocimetry and Particle Image Velocimetry. While the latter two methods are more recent developments and do not disturb the flow, it is shown that multi-hole probes are still a viable option for modern research facilities.*

Keywords: *flow measurement, pitot tubes, multi-hole probe, laser doppler velocimetry, particle image velocimetry.*

1 INTRODUCTION

Flow measurements are an integral part of evaluating the aerodynamic and hydrodynamic performance of engineering designs. In wind tunnels pressure measurements can be used to evaluate the power requirements of a particular wind tunnel section, while velocity measurements can be used to validate that the flow in the test section meets experimental requirements. Historically, velocity was measured using invasive techniques such as pitot-static tubes. While these devices allow for accurate measurements, they disturb the flow downstream and only measure a single velocity component. These devices were eventually developed into multi-hole probes which can measure various components of velocity. In the recent decades, non-invasive techniques have been developed, namely particle image velocimetry (PIV) and Laser Doppler Velocimetry (LDV), also known as Laser Doppler Anemometry (LDA). While these techniques are non-invasive, they tend to be more complex to setup and calibrate and are significantly more costly. Thus, the final choice of technique is dependent on experimental flow attributes and budgetary constraints of a project.

2 MEASURING PRESSURE AND VELOCITY

In any flow, the total pressure (p_t), also known as the stagnation pressure, is the sum of the static (p_s) and dynamic pressure (p_d), as shown in equation (1):

$$p_t = p_s + p_d \tag{1}$$

Dynamic pressure is dependent on fluid velocity (u) and density (ρ) as shown in equation (2):

$$p_d = \frac{1}{2}\rho u^2 \tag{2}$$

It is trivial to measure the pressure head (Δh) which can be used to calculate the pressure differential (Δp) using equation (3), where g is the acceleration due to gravity.

$$\Delta \mathrm{p} = \rho_m g \Delta h \tag{3}$$

It should be noted, that ρ_m is the density of the fluid in the measuring device, which may differ from the fluid in the main flow. In conjunction with the dynamic pressure, the pressure head can be used to calculate the flow velocity with equation (4):

$$u = \sqrt{\frac{2\Delta h \rho_m g}{\rho}} \tag{4}$$

These basic relationships can be used to estimate velocities from simple pressure devices such as pitot tubes and static pressure tubes (Katz, 2010).

2.1 Traditional Pressure Measurement Methods

Having established the mathematical foundation for the various types of pressure and how they can be used to calculate velocity, a visualisation of the various types of pressure tubes is shown in *Fig. 1*.

The piezometric tube (A) and the static pressure tube (B), both indicate the static pressure of the flow (White, 2011). However, the scale of a static tube tends to be much smaller than the channel walls. Therefore, the boundary layer surrounding piezometers is usually larger, making these devices more error-prone (McKeon and Engler, 2007). The Pitot tube (C) can be used to measure the total pressure of the flow.

The difference between the static and total pressure is known as the dynamic pressure, which can be thought of as the kinetic energy per unit volume of fluid. This can be directly measured using a pitot static tube (D) (Çengel, et al., 2014). The U-shaped portion of the pitot static tube is known as a manometer (Douglas et al., 2005). Note that all the flow measurement devices used to visualise pressure in gaseous flow rely on manometers filled with a fluid (Upp et al., 2002).

Nowadays, analogue tubes with varying levels of liquid have been replaced with digital pressure transducers. Internal strain gauges experience a change in electrical resistance as the pressure is changed. This change can be measured and converted into a pressure reading through appropriate calibration. Modern pressure transducers can measure with a precision of ±0.4 Pa, which is equivalent to approximately 0.04 mm of head in water.

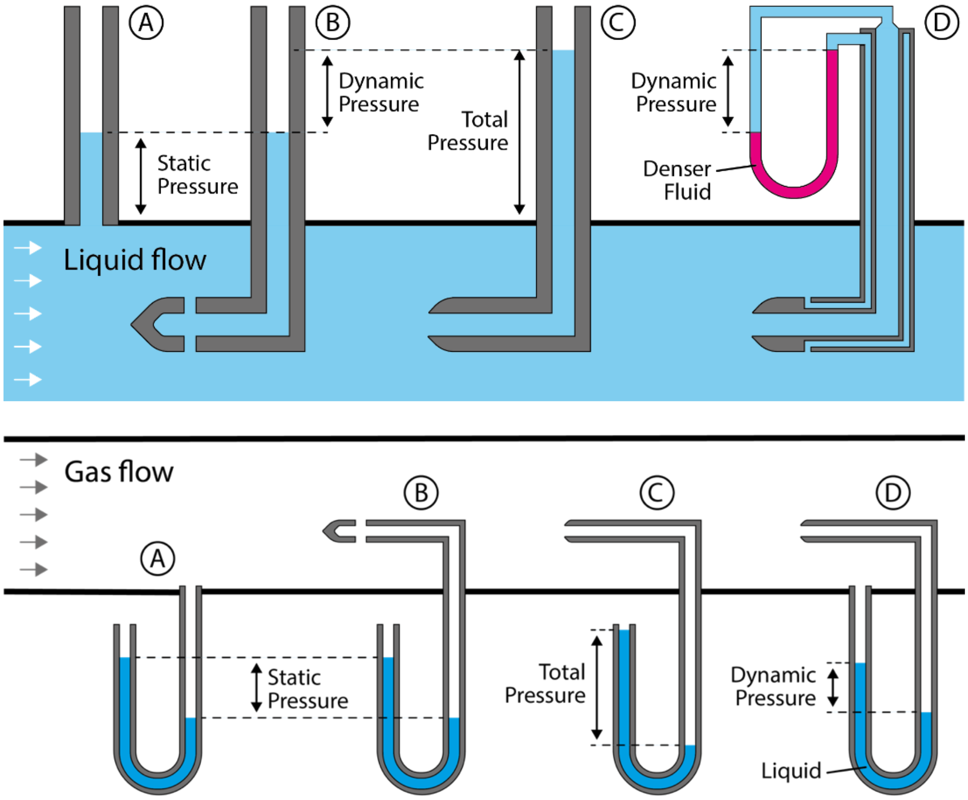

Fig. 1. Visualisation of pressure measurement devices, showing piezometric tubes (A) static pressure tubes (B), pitot tubes (C) and pitot static tubes (D)

2.2 Multi-Hole Probes

Standard pitot tubes are a useful tool to estimate flow velocity, but their accuracy decreases significantly if the flow is not aligned with the probe, as can be seen in Fig. 2:

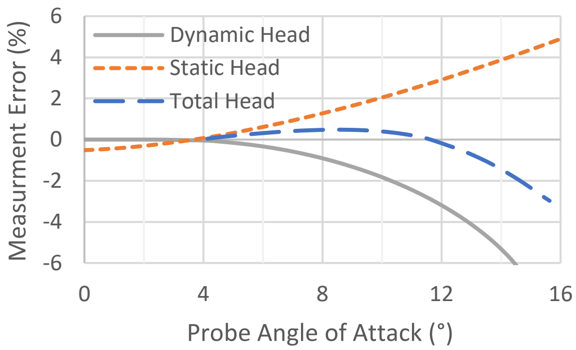

Fig. 2. Performance of a standard single Pitot-static tube in varying angles of yaw. Adapted from Thompson et al. (1958) and Russo (2011)

The error can be mitigated by using multiple pressure ports in close proximity to determine the angle of the incoming flow. Therefore, various configurations of multi-hole probes have been developed, some of which are shown in Fig. 3. While two-hole and three-hole probes can only be used to estimate yaw of the flow (Conrad, 1950), five-hole and seven-hole probes can estimate all velocity components (Bryer et al., 1958). As a rule of thumb, and increased number of holes leads to an increase in measurement accuracy and range of flow angles that can be measured. While a five-hole probe can only tolerate angles of attack up to 40°, seven-hole probes can measure accurately up to an angle of attack of 60° (Everett et al., 1983).

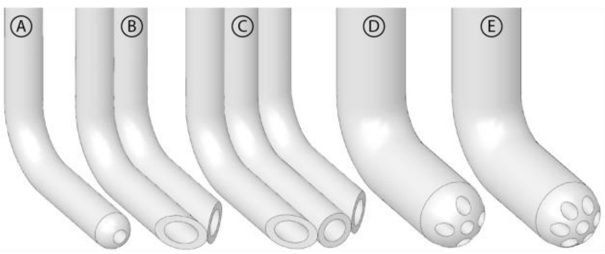

Fig. 3. Single-hole pitot tube (A), two-hole (Conrad) probe (B), three-hole (cobra) probe (C), five-hole probe (D) and seven-hole probe (E)

Recently, probes with up to 19 tubes have been developed (Shaw-War et al., 2015). An increased number of tubes also increases the complexity and thereby the cost of manufacture and calibration. Even the calibration of a seven-hole probe is complicated, as it requires a wind tunnel with accurately known performance and a mechanism that can shift the probe into a range of angles (±60°) for both yaw and pitch. Therefore, the cost of calibration can exceed that of procurement.

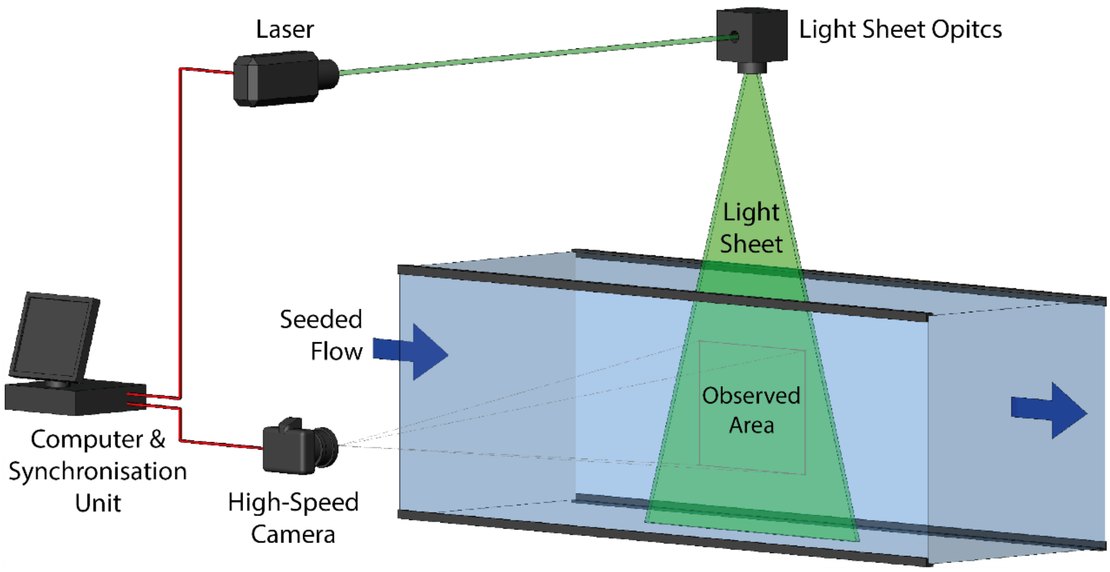

Fig. 4. Diagram of a generalised PIV setup, measuring a 2-D velocity field in the observed area.

3 UNOBTRUSIVE VELOCITY MEASUREMENTS

There is a multitude of ways to measure flow velocity in a wind tunnel; the Pitot-static tube mentioned in the previous section is one example. Inconveniently, many of these devices need to be inserted into the flow, changing the flow field during measurements and thereby falsifying observations. There are a select few measurement techniques which are non-intrusive, Particle Image Velocimetry and Laser Doppler Velocimetry being the most common among them.

3.1 Particle Image Velocimetry

A generalised PIV setup is shown in Fig. 4. A laser generates short successive pulses of light. Each pulse is shaped into a sheet of light using a mirror that facilitates 90° deflection. The light sheet illuminates seed particles (also known as markers or tracers) within the flow. A high-speed camera is used to capture the location of the particles during both illuminations. A synchronisation unit ensures that the laser pulses and high-speed camera are triggered simultaneously (Stanislas et al., 2000). Using specialised software, the successive images are compared to determine the change in position of particles in various subareas, known as *interrogation areas*, as shown in Fig. 5 (Raffel et al., 2018).

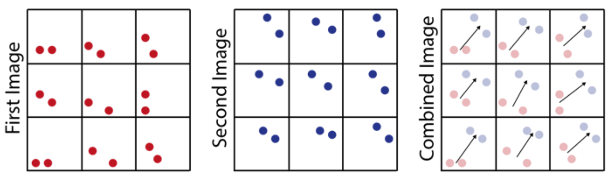

Fig. 5. Simplified processing of particle motion in two successive PIV measurements

Within the interrogation areas, dots represent the illuminated particles, while arrows indicate the velocity vectors. An overall velocity vector for each area is determined using the time between light pulses and statistical cross-correlation of particle position. This approach differs from particle tracking velocimetry (PTV), where particle density is lower, allowing for the tracking of individual particles rather than analysing grid areas. (Westerweel, 1997)

Fig. 6 shows what the processed PIV data can look like. The size and colour of the arrows indicates flow velocity. Short and blue arrows represent slow flow, while their red and long counterparts indicate fast flow. The original research on hummingbird flight was presented by Warrick, Tobalske and Powers in "Aerodynamics of the hovering hummingbird" (Warrick, et al., 2005).

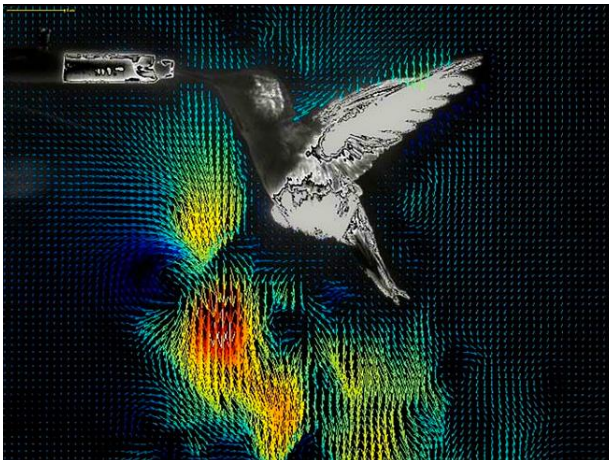

Fig. 6. Real world particle image velocimetry photograph of the flow field around a hummingbird in mid-flight (Çengel, et al., 2014)

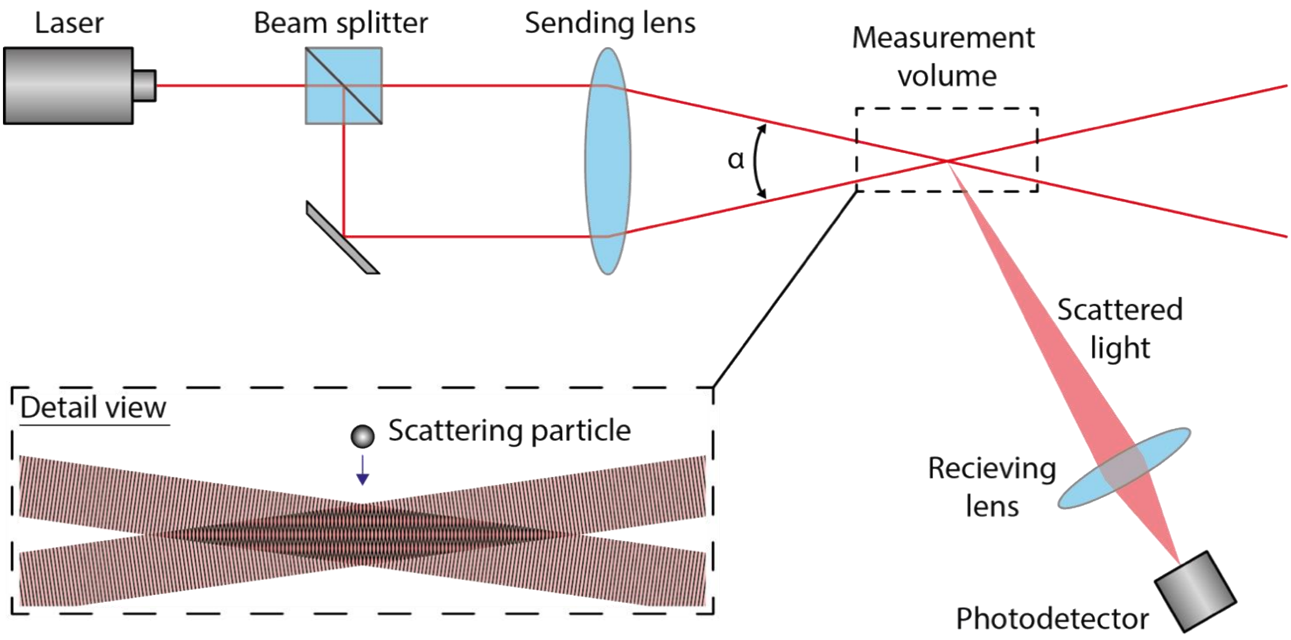

Fig. 7. A standard LDV setup, where a particle crosses an area of light interference. The resulting flicker is used to calculate flow velocity. Adapted from Mayinger et al. (2001)

3.2 Laser Doppler Velocimetry

LDV is another non-invasive measurement technique used to determine flow velocity. While PIV gives the measurement of turbulence and velocity across an entire flow field, LDV produces measurements with high precision and high sample rates (i.e., temporal resolution) at a single point, as shown in Fig. 7. Compared to PIV, this approach substantially simplifies post processing, as no image recognition is required. Furthermore, LDV requires less calibration and flow seeding to ensure accurate readings.

In LDV, a single laser beam is split in two using a beam splitter. With the aid of mirrors and a lens to guide the laser, the two beams are then focused on a single point in the measurement volume and intersect with a specific angle (α). Due to the monochromatic nature of the laser, the two beams form an interference pattern at their intersection. Bright fringes are created where the beams are in phase and dark fringes appear where they are out of phase. The alternating dark and bright fringes lead to the *horizontal* stripe pattern shown in the detail view above. As a marker particle passes through the intersection, the fringe patten causes light to be scattered in pulses. These pulses are caught by the receiving lens and photodetector and their frequency can be used to determine the velocity of the particle. Three pairs of beams can be used to measure all velocity components simultaneously.

The spacing between the fringe lines (s) can be determined from the wavelength of the light (λ) and the angle of intersection (α), as shown in equation (5):

$$s = \frac{\lambda}{2\sin(\alpha/2)} \qquad (5)$$

Using the frequency detected by the photodetector (f), the particle velocity (u_p) can be calculated using equation (6) (Çengel, et al., 2014).

$$u_p = f \times s = \frac{f\lambda}{2\sin(\alpha/2)} \qquad (6)$$

4 Comparison of Velocity Measurement Techniques

Despite the considerable advancements in optical flow measurement techniques, pressure probes are still a popular alternative. A comparison between PIV, LDV and multi-hole probes is made below:

Cost – A seven-hole probe with a digital pressure scanner is by far cheaper than commercial optical flow measurement techniques. In the experience of the author, a probe and a scanner can be purchased for approximately \$5,000. In contrast, commercial LDV and PIV systems can cost between \$50,000 and \$100,000. However, small scale prototypes have been made for as little as \$1,000 (Ring et al., 2013).

Velocity components – Seven-hole probes inherently measure all three velocity components. PIV usually is limited to two velocity components in the plane of the light sheet. However, it is possible to resolve a 3D volume using four cameras instead of one. (Raffel et al., 2018). LDV is limited to one velocity component per laser, so measuring all velocity components simultaneously requires three lasers.

Temporal resolution – Multi-hole probes have the lowest temporal resolution. Theoretically the pressure scanner connected to a pressure probe samples in the order of 100 Hz. However, if the silicone tubes that connect the probe to the scanner are long, they can have a dampening effect on the peaks and troughs within the measurement. LDV systems used to measure supersonic flows of 2,500 m/s, have burst (the scattered flicker of the particle) sample rates of 235 MHz, which equates to a velocity sample rate of several kHz. With advancements in camera technology, the sample rate in PIV systems is now restricted only by the pulse frequency of the laser. Faster successive pulses are dimmer, limiting the maximum size of the observed area. Nevertheless, modern systems can have a sample rate of several kHz.

Spatial Resolution – While the seven-hole probe and LDV only measure a single point, PIV measures along a plane, thereby providing a complete picture of the flow field.

Mobility – To move the measurement location of the seven-hole probe, it is only necessary to move the probe itself. For a three-component LDV system, the lasers and the photodetectors have to be moved. An LDV system requires shifting the high-speed camera, the laser and the optics. For both LDV and PIV the components have to be relocated carefully to maintain accurate measurements. Therefore, it is much easier to move a multi-hole probe.

Post processing – LDV requires the least post processing, as the signal from its photodetector can easily be converted into a velocity reading. The multi-hole probe requires more effort. The various pressure measurements have to be compared to the calibration data, akin to a large look up table. Only then can the velocity be computed. PIV requires the most post-processing. For each photo, each interrogation area must be analysed using image recognition software. Successive frames must then be compared to analyse the average movement in the areas to determine the velocity vectors.

Compatible fluids – Conventional multi-hole probes are mostly restricted to gas flows. With the right choice of tracer particle, PIV and LDV can be used in both liquid and gaseous flows.

Flow angle sensitivity – Unlike PIV or LDV the seven-hole probe is limited to a maximum angle of attack of 60°.

5 Conclusion

A brief overview of the relationship between pressure and velocity provides the basis for the understanding of measurement probes. Although newer, non-intrusive optical measurement techniques are now widely available, their high costs and complexity often makes their use unfeasible. In such cases, multi-hole probes offer a high-accuracy alternative. However, if high spatial resolution is a priority, no measurement technique can match the capabilities of modern PIV systems.

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Authors addresses

[1] Alexander Baron von Hohenhau, MEng, Edinburgh Designs, alex@edesign.co.uk