Advanced Experimental Techniques in Fluid Mechanics

The Lab QR-Project

First of all…do you know what how wire anemometry is?

It might be the first time you hear such a name, or on the contrary, you might be familiar with it (if this is your case, keep your cell phone again in your pocket…or simply scan another QR… there are plenty of them in the lab!). Anyway, if you are willing to spend a few minutes reading this sheet, you will find herein interesting information about one of the most widely used velocimetry techniques. Well, hot-wire anemometry (HWA) is a versatile technique that can be used for the measurement of velocity and temperature fluctuations in the time domain. This method is used when one wishes to measure rapidly varying velocities with good spatial and time resolution, and it is based on the changes in heat transfer from a small heated sensor exposed to the fluid in motion. The sensor is made of a material whose electric resistivity varies with the temperature. It is approximately 1 mm long and has 5 μm diammeter (thinner than human hair! … so probably you won't be able to see it at first glance!). This wire is electrically heated, and when placed within the flow, it is cooled down through convection. Such effect provides with a measurement of the flow velocity.

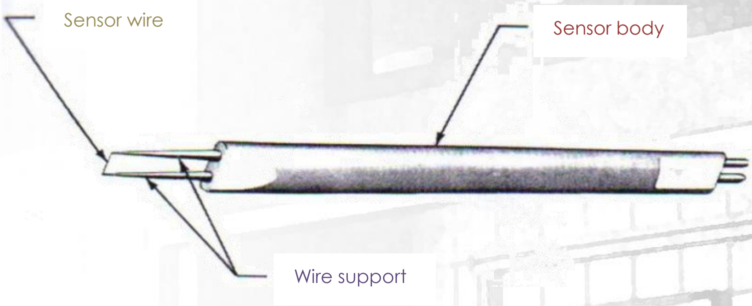

Figure1: Hot wire anemometry sensor [2]

How does it work?

The sensor is heated by Joule effect, being the heating power $R_w I_w^2$, where R_w is the heated wire resistance and I_w the current intensity. The cooling rate is proportional to the difference ($T_w - T_a$), being T_w is the temperature of the heated wire, and T_a the ambient temperature (or unheated wire). The proportional relationship is established through a function θ(w), that measures the convection effect and depends mostly on the velocity w normal to the sensor, which is to be deduced. If the flow is unsteady, an energy balance can be formulated to extract information about the cooling process, and ultimately, the flow velocity. Thus, we have:

$$m_w c_w \frac{dT_w}{dt} = R_w I_w^2 - (T_w - T_a)\theta(w) \qquad (1)$$

being m_w is the mass of the sensor and c_w its specific heat. The velocity w can be deduced from the electrical quantities R_w and I_w, that are adjusted to compensate the cooling process, being R_w related to T_w as follows,

$$R_w = R_o[1 + \chi(T_w - T_o)] \qquad (2)$$

where R_0 is the resistance of the sensor at the reference temperature T_0, and χ is the coefficient of resistivity (T_0 is usually chosen similar to the fluid temperature T_a). The sensor is an electrical element within a bigger electrical system, which takes advantage of the change in resistance to generate a measurable signal. In this sense, there are three operating modes for the sensor control, depending on which parameter is kept constant: constant voltage, constant intensity or constant resistance. The latter, also called constant temperature anemometer (CTA), due to equation (2), is the most used, and it works providing the sensor with a current I_w which varies when it cools down by convection, fulfilling consequently the imposed constant temperature.

A CTA example: the TSI®-IFA 300

To measure velocity and its variations (frequency), our laboratory counts with a TSI®-IFA 300 Constant Temperature Hot Wire Anemometer equipment, whose operation principle is briefly described next. The CTA includes a Wheatstone bridge and an amplifier controlling a 5 microns heated sensor of resistance R_w, that is located in series with a large bridge resistance (R_p = 10 Ohms) to increase the bridge voltage and its fluctuations, and therefore the resolution. Besides, the bridge has a passive arm made up by a large resistance R_2 and an adjusting resistance R_c, that set the wire overheat, according to a bridge ratio R_2/R_p = 25. Then, when the heated wire ($T_w \simeq 250C$) is cooled by exposure to the flow, the resistance changed (T_w and R_w are proportionally related as equation 2 indicates) and a voltage is measured in the middle of the bridge by the operational amplifier. Thus, an electrical current, I_w, is fed to the sensor by the operational amplifier, in such a way that the former wire resistance is restored, and therefore the temperature. Hence, if the velocity signal, w(t), changes, the upper bridge $E_p(t)$ voltage will change to supply the current needed in order to comply with the resistance requirement and, therefore, it can be used as the anemometer output.

Considering the heat transfer balance from the wire, expressed by (1), King's law for an incompressible flow around an infinite cylinder can be adapted to estimate the bridge voltage as

$$E_p^2 = C_1 + C_2 w^{1/2}, \quad (3)$$

where C_1 and C_2 are constants that include convection and conduction effects towards the wire supports (of small magnitude, not considered in equation 1). This fitting law is used by an additional equipment, namely the TSI ® 1129 Air Velocity Calibrator, existing also in the laboratory, to create a calibration velocity curve for the single probe that will be used to measure. In this sense, when the equipment acquires velocity signals, a thermocouple is connected to the IFA 300 CTA to precisely correct the bridge voltage values obtained at calibration, and, consequently, it gives the actual velocity values. Finally, the system allows to obtain the bridge voltage as an optimized output voltage signal, OE, to achieve maximum resolution provided from the A/D Board. Thus, OE is obtained after subtracting an offset to E_p and multiplying it by a gain, that are calculated for each sensor used with the equipment. Therefore, when we are interested on the velocity variations to evaluate, for instance, frequencies, the output voltage OE is a good parameter, since it uses the whole bandwidth provided by the A/D board, so that it has a good resolution, and it can be processed through spectral analysis (Fourier transform) to obtain frequency components (see next section to get a better insight about the physical phenomena studied with such process). When we are simply interested on velocity values, a good fitting law (eq.3) is required, and as occurs with the OE parameter, the resolution should be magnified within the range established by the A/D Board.

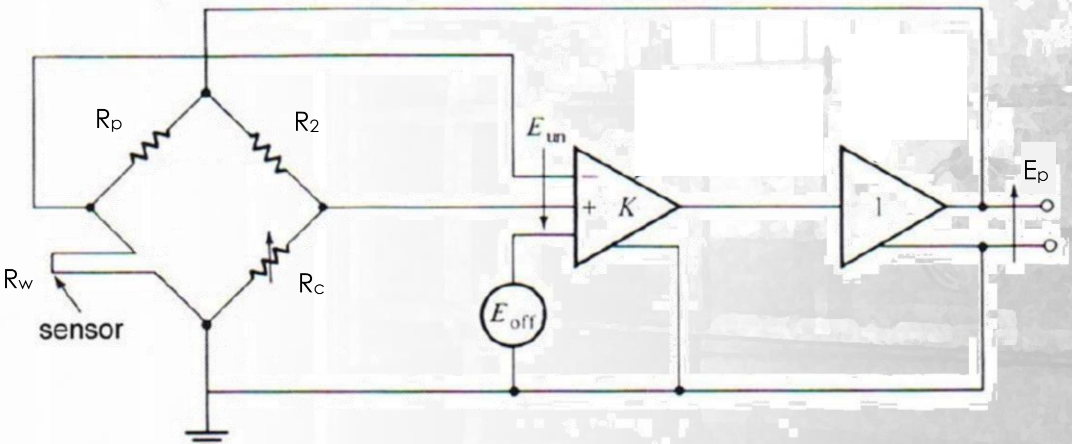

Figure2: Wheatstone bride circuit belonging to constant temperature anemometer [2]

What can we use such equipment for?

In general, Fluid Mechanics problems involve the determination of velocity, pressure and, sometimes, temperature fields, so that a technique such as hot wire anemometry can be used basically in plenty of application to obtain local measurements of velocity and temperature. However, aerodynamics, and more specifically wakes behind bluff bodies, constitutes a classical field in which hot wire anemometry is largely applied, mainly because of its high temporal resolution provided by large values of acquisition frequencies. This feature allows to perform accurate spectral analysis to characterize shedding frequencies in wakes, as explained next. Flow past bluff bodies is a widespread configuration in many engineering applications, taking place wherever there is fluid stream flowing around a body or a body in motion. Examples of such systems are found for instance, in aeronautic industry, cars industry, turbomachinery, physics of sports, civil engineering, architecture, etc. Bluff-bodies geometry provokes a massive separation of the boundary layer at a detachment point that depends on the shape and the dimensionless Reynolds number ($Re = \rho UD/\mu$, where ρ, D and μ stands for fluid density, body characteristic length and fluid viscosity respectively), giving rise to a wake that develops spatially behind the body. This flow separation creates a low pressure region at the near wake, that translates into a drag force, opposed to the body motion. On the other hand, it is well known that wakes behind bluff bodies undergo progressively, from a stable state (at low velocities), several bifurcations (drastic changes in wake stability nature, associated to changes in wake behavior and topology) with increasing Reynolds numbers, leading to different regimes that are associated with the existence of unstable modes at the wake, and the subsequent interactions among them. The onset of unsteadiness at the wakes occurs generally at low Reynolds numbers, and takes place in form of alternate vortex shedding with a constant frequency. An example of such problem is depicted in Figure 3, which shows an experimental laser visualization of the wake behind a cylinder at Re=140, where vortex shedding is clearly discernible. This vortex generation and shedding, enhances the drag, and creates a regular pressure change that leads to transversal forces distribution acting on the body, entailing consequently vibrations, noise generation and resonances. Therefore, an accurate characterization of this shedding phenomenon (velocity field and shedding frequencies) is crucial to apply control strategies (for instance, base bleed represents a widely passive control strategy, consisting in applying a secondary flow at the rear base or part of the body, as Figure 4a shows).

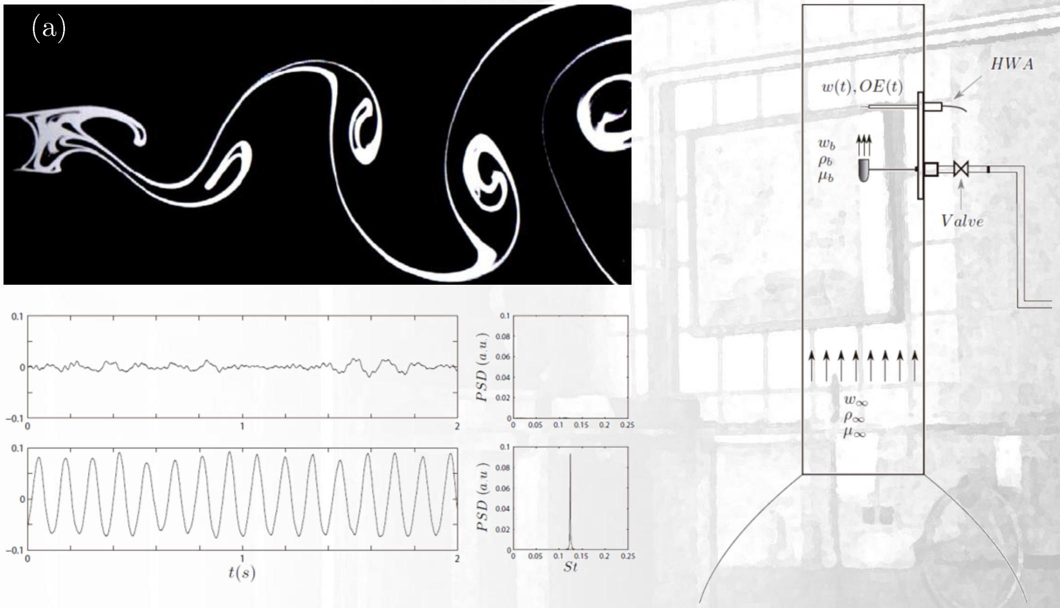

Figure3: (a) Vortex shedding from a cylinder (Re=140) [3], (b) sketch of a hot-wire experimental measurement behind a bluff body [4] and (c) typical HWA velocity signals and corresponding power spectra at the wake of a bluff body without (top) and with (bottom) vortex shedding [4].

To characterize properly vortex shedding at wakes using hot wire anemometry, we must place the probe behind the body (see Figure 4a), at a downstream position that will be selected after determining where the shedding amplitude is the largest (as it can be seen in Figure 3, vortex size develop downstream), what varies generally with Re. Once the probe is fixed, large temporal signals of velocity should be recorded (using large acquisition frequencies), to perform ultimately a spectral analysis (Fourier transform) that provides with the characteristic shedding frequencies.

Bibliography

[1] C. Tropea, A. L. Yarin, and J. F. Foss, editors. Springer Handbook of Experimental Fluid Mechanics. Springer-Verlag, Berlin, 2007.

[2] Charles G. Lomas. Fundamentals of Hot Wire Anemometry. Cambridge University Press. USA, 1986.

[3] An album of Fluid Motion, 10th edition. Van Dyke. The Parabolic Press. California, 2005.

[4] J.I. Jiménez-González. Study of the stability of jets and wakes. Application to the wake past slender bodies with blunt trailing edge, 2013, 197 p. [http://hdl.handle.net/10953/521]