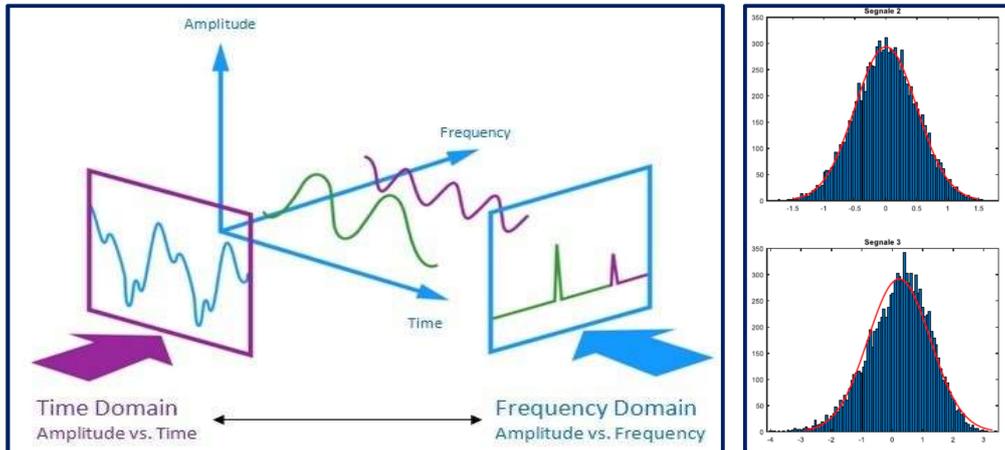


EXPERIMENTAL FLUID-MECHANICS

Numerical Practice: Signal & data analysis



Objectives:

Mandatory

- Compute statistical moments, probability density functions, auto-correlation coefficients and power spectral densities for each data set.
- Compute errors on statistical moments.
- Identify the different signals.
- Compute cross-correlation functions among some of the data sets.

Additional

- Use advanced processing to investigate the effects of filters, by changing the filter bandwidth and plotting original and filtered signals.
- Investigate the effect of the number of samples on statistical moments.
- Compare different algorithms for computation of power spectral densities.
- Compare probability density functions with Gaussian behavior.
- Implement the use of windowing functions.

References:

- G.P. Romano, Experimental Fluid Mechanics - Lecture notes
- J.S. Bendat, A.G. Piersol, Random data: analysis and measurement procedures, Wiley, 1971
- A.V. Oppenheim, R.W. Schaffer, Elaborazione numerica dei segnali, Franco Angeli, 1990

Practical notes:

The practice consists of the analysis of eight data sets, each one of 10^4 data, u_i , equispaced in time, for a total acquisition time of 10s. They are a sinusoidal signal, a velocity signal from a turbulent boundary layer, a pure noise and the combinations sinusoidal+noise and turbulent+noise with different noise levels. Probability density functions can be evaluated and compared with the Gaussian curve, allowing a first identification of the signals. Then, the following statistical moments have to be computed (sum over i):

mean value (average)	$\bar{U} = \frac{1}{N} \sum_1^N u_i$
standard deviation	$\sigma = \left(\frac{1}{N} \sum_1^N (u_i - \bar{U})^2 \right)^{1/2}$
skewness factor	$s = \frac{1}{N\sigma^3} \sum_1^N (u_i - \bar{U})^3$
flatness factor	$k = \frac{1}{N\sigma^4} \sum_1^N (u_i - \bar{U})^4$
auto-correlation coefficient	$\rho_j = \frac{1}{\sigma^2(N-j)} \sum_1^{N-j} (u_i - \bar{U})(u_{i+j} - \bar{U})$
spectral density function (absolute and phase)	$S_k = \sum_0^{N-1} \rho_j e^{-i2\pi kj/N}$
cross-correlation coefficient	$\rho^{AB}_j = \frac{1}{\sigma_A \sigma_B (N-j)} \sum_1^{N-j} (u^A_i - \bar{U}^A)(u^B_{i+j} - \bar{U}^B)$

A e B are referred to two different data sets and N being the total number of data. The analysis of the previous moments allows identifying definitely the five different data sets (this is specifically true for correlation coefficient and spectral density functions). Note that the spectral density function can be evaluated from the correlation coefficient or directly from data and these two methods can be compared.

For advanced processing, it is required to set-up a simple filter for the data set with noise contribution. The simplest filter to be designed is a band-pass one, in which two frequencies have to be selected in the frequency spectrum, which is forced to vanish outside this interval. After that, an inverse Fourier transform of the filtered spectrum has to be performed, in order to determine the filtered signal in time. Filtering has to be performed on the sinusoidal and turbulent flow signals in which noise is added.

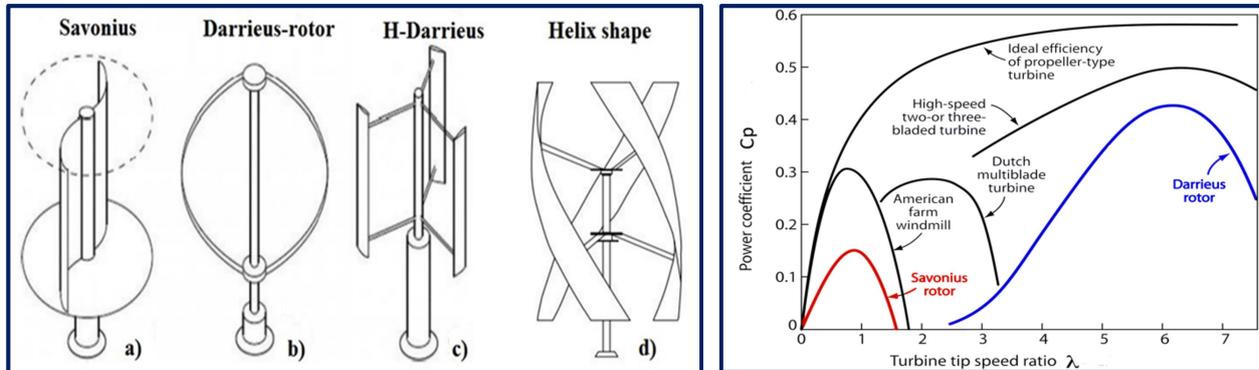
The effect of the number of samples can be also investigated by evaluating the average and other statistical moments over different partitions of the entire data sets, so far plotting each statistical moments as a function of the number of the total number of samples used.

Window functions, as for example rectangular, triangular or higher-order functions, can be used to improve the spectral determination, by multiplying each signal for the window in time and then using Fourier transform algorithms. Comparisons with the original signal can be performed in order to investigate the effect of the specific window.

EXPERIMENTAL FLUID-MECHANICS

Laboratory Practice N°1:

Performance of a VAWT in Wind Tunnel



Objectives:

Mandatory

- Measure rotational velocity of turbine at different flow velocities.
- Derive tip-speed ratio in each condition.
- Measure torque under different velocities from direct torquemeter data.
- Derive torque and mechanical power coefficients.
- Measure electrical quantities and power from the connected motor.
- Derive electrical power coefficients.
- Evaluate errors (readings, oscillations and statistical).

Additional

- Plot power coefficients as a function of tip-speed ratio at different flow velocities.
- Compare quantitatively present results with those in References, obtained by other authors on similar turbine models.
- Evaluate effect of vertical axis inclination on performances.
- Compare quantitatively ratio of electrical to mechanical power (*i.e.* conversion efficiency) at different flow velocities.

References:

- Bhutta, M.M.A.; Hayat, N.; Farooq, A.U.; Ali, Z.; Jamil, S.R.; Hussain, Z., Vertical axis wind turbine – A review of various configurations and design techniques. *Energy*, 2012, 16, 1926-1939.
- Chauvin, A.; Benghrib, D. Drag and lift coefficients evolution of a Savonius rotor. *Experiments in Fluids*, 1989, 8(1-2):118–120.
- Aliferis D., Stette Jessen M., Bracchi T., Hearst R.J. Performance and wake of a Savonius VAWT. *Wind Energy*. 2019; **22**:1260–1273.

Practical notes:

This practice consists of measuring performances of a Savonius type Vertical Axis Wind Turbine (VAWT) in wind tunnel. The turbine is rotating under the air stream and it is connected to a torsionmeter, to measure torque moment and frequency of rotation, to get mechanical power, and to a 200 W motor, through a resistor in parallel and a wattmeter, to derive electrical power.

The parameters to be changed during the practice are the free-stream velocity, U_0 , (from 7 m/s to 13 m/s) and the electrical resistance, R (three values 10 Ω , 20 Ω and 32 Ω , to be selected directly during the measurements). The quantities to be measured are the same velocity, the frequency of rotation of the turbine, f , the electrical voltage, V , and the torque intensity, T .

The velocity is measured by using a Pitot tube placed enough far from the turbine, the error on this quantity being related to readings and oscillations. The signal from the torsionmeter, can be acquired on a PC, usually the data rate being equal to 100 Hz and the acquisition time around 10 s. Being the signal similar to a sinusoidal one, during each turbine revolution, using procedures, as those performed in the numerical practice on signal and data analysis, it is possible to compute the Power Spectral Density (the spectrum) of the signal and then the frequency of rotation. The error on this quantity is related to the resolution in frequency, *i.e.* to the inverse of the acquisition interval, 1/10 Hz. By computing the offset to zero and the average amplitude of this signal it is also possible to evaluate the mean torque. The error on this quantity is statistical and depends inversely on the square root of the number of samples (consider the practice on signal and data analysis).

The measurement procedure must be repeated for different wind tunnel velocity and electrical resistance. The mechanical power is then evaluated as the product $P=T\omega$ (ω being the angular frequency) and the tip-speed ratio as $\lambda=\omega D/2U_0$, where D is the diameter of the turbine (to be measured). So far, it is possible to plot the power coefficient

$$C_p=2P/\rho U_0^3 S$$

(where ρ is the air density and S the turbine cross-section) as a function of the tip-speed ratio and compare results with those in references.

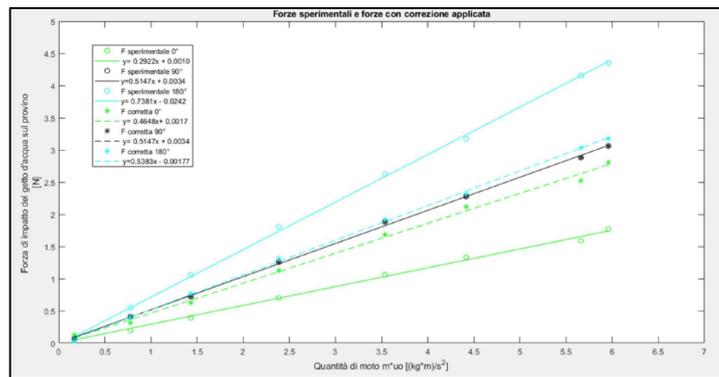
Simultaneously, the wattmeter measurements of voltage intensity and the value of the electrical resistance in each condition, allow the derivation of the electrical power, P_e , and electrical power coefficient which can be also plotted as a function of the tip-speed ratio. It is also possible to evaluate the efficiency of mechanical to electrical conversion, η_e , by computing the ratio $\eta_e=P_e/P$, again to be plotted as a function of tip-speed ratio. Error propagation must be applied on all derived quantities, starting from measurements of primary ones.

In order to test the performances of the Savonius turbine under different air stream inclinations, as those present at the top of buildings or hills, it is possible to change the angle of inclination of the turbine to the free stream, α , in a range between 10° and 30°. All previous measurements at different air velocity can be repeated (maybe using only one electrical resistance, rather than three for this test). The results in terms of plots as functions of tip-speed ratio can be compared to previous ones and to those reported in references.

EXPERIMENTAL FLUID-MECHANICS

Laboratory Practice N°2:

Measurements of the thrust due to the impact of a jet on plates



Objectives:

Mandatory

- Measure forces acting on plates with different geometry.
- Repeat the measurements for different Reynolds numbers of the jet.
- Measure flow rates by direct volumetric method.
- Compare force increments with the simple model proposed.
- Evaluate errors (reading and dimensions).

Additional

- Measure forces for different orientation of the inclined flat plate.
- Compare results without and with the proposed correction.
- Compare all data with references and with other data.

References:

- Handbook of TecQuipment apparatus.
- B.R. Munson, D.F. Young, T.H. Okiishi Fundamentals of Fluid Mechanics, Wiley, 1994
- X. Ortiz *et al.*, Forces and Moments on Flat Plates of Small Aspect Ratio with Application to Wind Loads and Small Wind Turbine Blades, *Energies*, 8 2015.

Practical notes:

The practice consists of measuring the thrust of an impact jet on plates with different shape, by means of a force balance, for different jet velocities. The impact region and the plates are inserted into a large transparent cylinder.

The thrust force (F) is derived by using a balance equipped with a mass ($m_p = 0.6$ kg), which is moved along a horizontal scale (y is the distance of this mass from the initial position). The angular momentum equilibrium allows obtaining

$$F y_p = m_p g y \qquad F = m_p g y / y_p \qquad (1)$$

where $y_p = 15$ cm is the known distance among the reference position and the balance pivot and g is the gravity acceleration.

Measurements are performed for variable jet Reynolds number ($Re = U_0 d / \nu$, being U_0 the outlet jet velocity, $d = 1$ cm the jet diameter and ν the water kinematic viscosity). To get the velocity U_0 , it is required to determine the jet flow rate (Q) by using a known volume of fluid and measuring the time interval required to fill it. This measurement should be repeated some times to obtain an accurate value, as also to repeat the measurement of the equilibrium position of the test mass, for each Reynolds number. There are four different pates, *i.e.* flat plate, inclined flat plate (60°), conical plate and hemispherical plate and for each one it is required to plot the experimental results in the form F vs $U_0 Q$.

The experimental data can be compared with the theoretical formula derived from the balance among the thrust force on the plates (F) and the change in jet momentum before and after the impact on the surfaces (projected in the vertical direction)

$$F = Q (U_0 - U_1 \cos \beta)$$

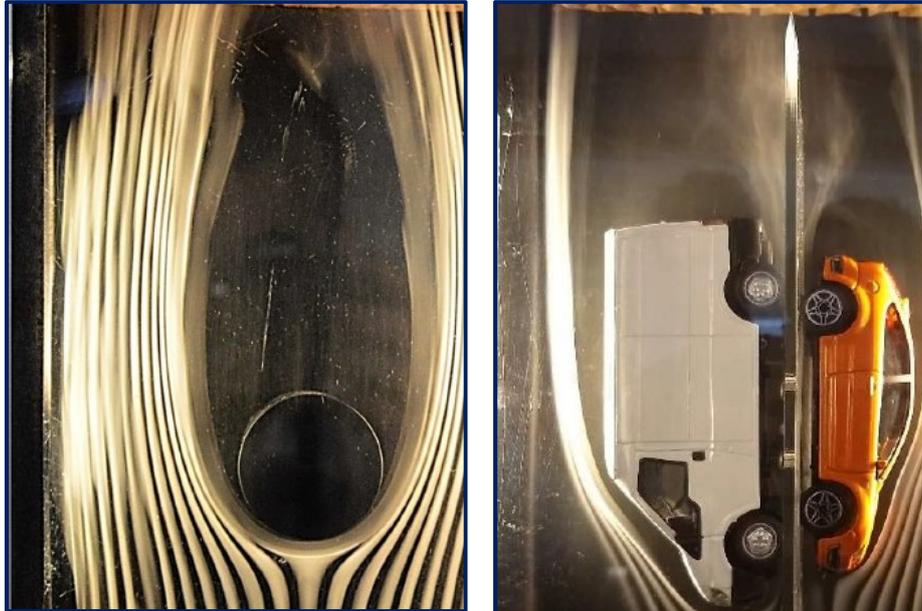
being U_1 the fluid velocity after the impact and β the inclination angle to the vertical direction. For the flat plate ($\beta = \pi/2$), the previous relation is linear and is a function of the initial momentum (QU_0) with a slope equal to 1. For the other plates, by assuming $U_1 \approx U_0$, a slope equal to 0.5 is obtained for the inclined flat plate ($\beta = 60^\circ$), namely dependent on the orientation, a slope equal to 1.5 for the conical plate ($\beta = 120^\circ$) and a slope equal to 2 for the hemispherical plate ($\beta = 180^\circ$). The comparison between experimental and theoretical results can be made also by considering the arguments 3, 4 and 5 at page 4-3 of the equipment handbook (for example, it is possible to consider the vertical deceleration of the jet by using the formula $U_1 = (U_0^2 - 2gs)^{1/2}$, where s is the distance from the jet outlet to the impact point).

It is also possible to change the orientation of the non axi-symmetric inclined flat plate (angle θ) and to verify the dependence of the slope on this angle. In this condition, the previous formula (1) must be replaced by the following $F = m_p g y / [y_p - x_p \text{ctg}\beta \cos\theta]$, where x_p is the vertical distance from the impact point to the balance horizontal bar and $\theta=0$ or $\theta=\pi$ are referred to orientations in which the plate is inclined along the bar (towards the pivot or opposite respectively), whereas $\theta=\pm\pi/2$ refer to orientations orthogonal to the bar.

EXPERIMENTAL FLUID-MECHANICS

Laboratory Practice N°3:

Flow Visualizations in Wind Tunnel



Objectives:

Mandatory

- Acquire good images of streamlines around different models in a wind-tunnel.
- Derive pressure coefficients from streamline distances around cylinder, sphere and blade section at different angles of attack.
- Derive velocity variations from streamline distances for different orifices.
- Evaluate errors (line thickness).
- Compare results with those from potential flow theory and turbulent flows.

Additional

- Evaluate stagnation point variation with angle of attack for the blade section.
- Acquire flow visualization images and videos for different models.

References:

- Handbook of TecQuipment apparatus.
- B.R. Munson, D.F. Young, T.H. Okiishi, Fundamentals of Fluid Mechanics, Wiley, 1994
- Blade sections, airfoil and wing software: XFLR5, JAVAFOIL, NVFOIL
- H. Kang, A. Altman, Generalized Empirical Airfoil Stagnation Point Location Prediction, *Journal of Aircraft*, Vol. 44, 2007.

Practical notes:

This practice is a flow visualization of streamlines around almost two-dimensional and three-dimensional models in a wind tunnel, by using smoke streamlines made visible through a rake in front of the test section. The velocity of the wind tunnel can be changed externally and must be verified using a Pitot tube positioned at the discharge section. The Reynolds number must be derived from the size of the available models to be placed in the wind tunnel, *i.e.* a cylinder, a NACA 2412 blade section, a circular orifice, a slotted orifice, a flat disc, two hemispheres, one wing-tip vortex generator and two car-model van-model vehicle geometries. For each one of those, image acquisition must be performed with high resolution using mobile phones, photo cameras or video cameras, in order to fix the instantaneous streamlines configuration.

Once downloaded on a PC, by using image analysis software (for example AutoCad, Matlab), it is possible to measure the distance among the streamlines around the models (d), to derive the tangential velocity from volumetric flow rate conservation:

$$U S = U h d = U_{\infty} h d_{\infty} \quad U = U_{\infty} (d_{\infty} / d)$$

S being the fluid surface between two streamlines, h the transverse distance and d_{∞} the upstream distance among streamlines. Therefore, the ratio d_{∞}/d is equivalent to the ratio U/U_{∞} for each position around the model contour. For the cylinder and hemispheres, the evaluation of such ratios can be performed around the model at different angular positions, whereas for the blade section it must be evaluated along the streamwise direction. Distances are made non-dimensional by the longitudinal size of the model. By using Bernoulli equation, it is possible to derive the pressure coefficient

$$c_p = 1 - \left(\frac{U}{U_{\infty}} \right)^2 = 1 - \left(\frac{d_{\infty}}{d} \right)^2.$$

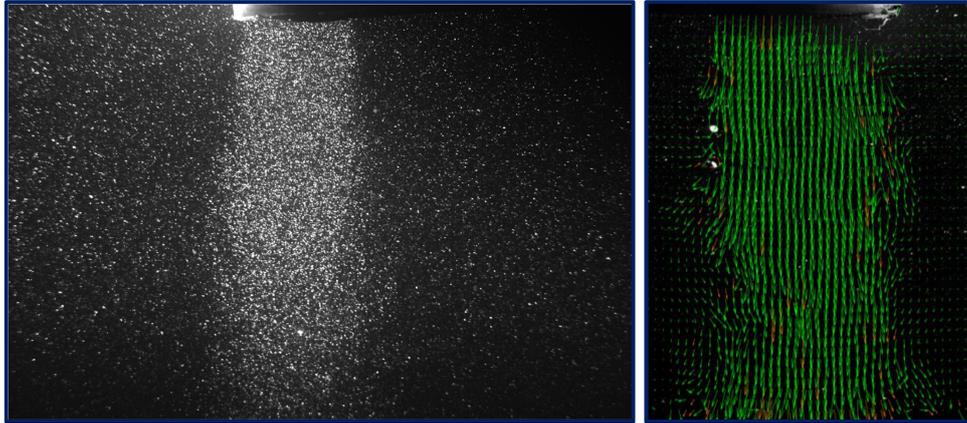
The quality of the results and related errors on this pressure coefficient estimate are dependent on the thickness of the streamlines close to the model surface, so that is extremely important to have well defined lines as thinner as possible. In order to acquire reliable images of the streamlines configuration, for each model in the wind tunnel it is convenient to get several pictures in the same conditions, by changing the streamline generation conditions (opening valve and pressure level) and the image acquisition parameters (shutter time, objective aperture, distance of acquisition, illumination).

The derived pressure coefficients can be compared with analytical and empirical solutions, the former for example in the case of potential flows around a cylinder ($c_p = 1 - 4 \sin^2 \theta$), a sphere, or for the blade section by using the free software given in the references, and the latter for the modifications due to turbulence. For the blade section, it is also possible to detect the stagnation point position as a function of the angle of attack and to compare results with those reported in the references. For the orifice models, the previous flow rate conservation can be used to evaluate the local flow rate, once the geometry of the slot is known, and to compare it with that derived from the change in geometry.

EXPERIMENTAL AERODYNAMICS

Laboratory Practice N°4:

High-Speed Particle Image Velocimetry (HS-PIV)



Objectives:

Mandatory

- Acquire image of the flow field with different parameters as light intensity, camera aperture and shutter, tracer concentration and laser pulse separation.
- Process acquired images with PIV software and identify the best settings.
- Compare the processed instantaneous and average velocity fields in order to determine the optimal values for acquisition parameters.
- Use optimal parameters for image acquisition in a turbulent jet.
- Compute statistical moments of the two measured velocity components and compare quantitatively results obtained at different Reynolds numbers.
- Evaluate errors (displacement, statistical, tracers) and effect of image number.

Additional

- Compare quantitatively non-dimensional transverse and axial profiles of statistical moments with references.
- Use vortex identification to highlight vortex generation and interactions.

References:

- PIVLAB Software.
- G.P. Romano, Experimental Fluid Mechanics - Lecture notes
- P.R. Suresh *et al.*, Reynolds number dependence of plane jet development in the transitional regime, *Physics of Fluids*, vol. 20, 2008.
- A.P. Vouros, Th. Panidis, Turbulent properties of a low Reynolds number, axisymmetric, pipe jet, *Experimental Thermal and Fluid Science*, Vol. 44, 2013.

Practical notes:

The High-Speed Particle Image Velocimetry (HS-PIV) is a non-intrusive optical measurement technique able to determine velocity fields in fluids with high temporal resolution. In this practice, the image acquisition and processing phases will be considered in detail, in order to determine the best parameters for optimal set-up. They are attained with a continuous illumination, framing being given by a high-speed camera, rather than in the arrangement of a pulsed laser synchronized to a camera as in the PIV practice. To this end, images of a turbulent jet are preliminary acquired by changing the light intensity of the light source (laser light), the interval between images acquired by the camera, the objective aperture and camera shutter and the concentration of tracers injected in the fluid. The number of acquired images is around 100 in order to derive instantaneous and average fields and compare the different choices of parameters. Image pairs are processed with a free software based in the Matlab environment (PIVLAB) and best settings of processing must be also determined, as filter and mask selections, interrogation window size, window overlapping, number of passes and post-processing parameters.

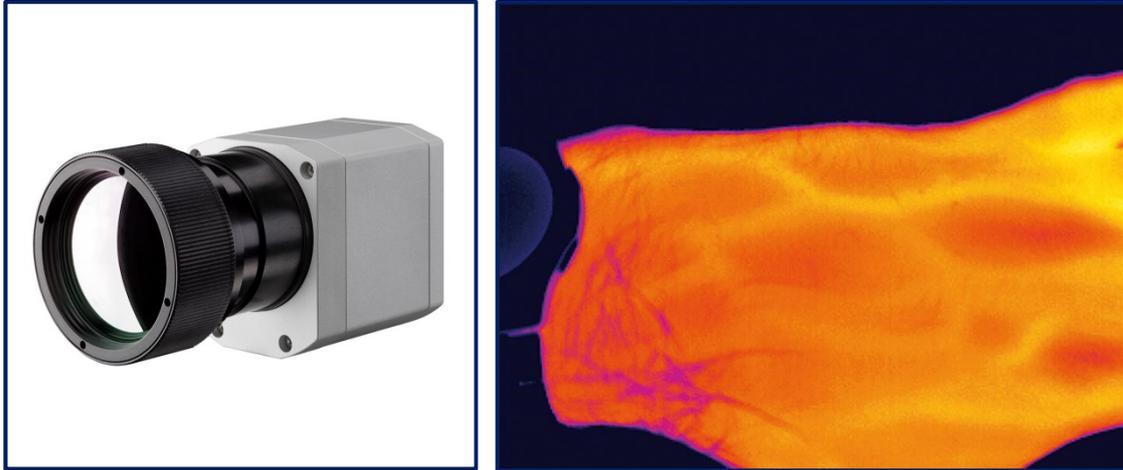
Once optimal parameters for image acquisition and processing have been established, the attention is focused onto the investigation of a the turbulent jet. The region after the exit of the jet in water, is considered in details for different Reynolds numbers ($Re=Ud/\nu$, where U is the average jet exit velocity, derived from the imposed flow rate, and d is the jet diameter). Thousands of images are acquired in each condition in order to get reliable statistical accuracy (subsets of each data set can be used to investigate the effect of the number of samples on statistics). The following quantities can be derived from measuring two velocity components: instantaneous and average vector fields, color plots of average axial and transverse velocity components, velocity magnitude, vorticity, *rms* values of both components and Reynolds stress.

For comparing the results among them and with reference results, it is useful to plot non-dimensional graphs, the jet exit velocity and diameter being used as characteristic velocity and dimension. To make the comparison quantitative, profiles of quantities along transverse and axial directions must be derived, for example along the jet axis and orthogonally to this axis. As usual, an evaluation of measurement errors is required in order to comment differences with reference data. It is quite difficult to compute exactly errors in PIV, due to the high number of quantities involved. The simplest approach considers the flow field without any jet and measuring the two velocity component standard deviations in this condition, which in theory should be zero. These values give a minimum value for the error in different regions of instantaneous flow fields, which is added to the statistical error for average fields.

Images of the jet are acquired with a camera shutter time small enough to “freeze” the moving vortical structures, so being possible to use vortex identification criteria on instantaneous images to investigate their generation and interaction. The simplest method is to compute vorticity (possible with centered differences), which however partially hidden the single structures in case of strong velocity gradients as in shear layers. Thus, the method of Hussain, described in lecture notes, which is based on velocity differences invariants, can be used.

EXPERIMENTAL FLUID-MECHANICS

Laboratory Practice N°5: Infrared Thermography



Objectives:

Mandatory

- Set-up the Thermo-camera (using a thermometer on a given surface).
- Acquire images of a microchannel heated from below.
- Save images and derive statistical moments of the temperature field (mean and standard deviation).
- Acquire images for different flow rates and heating temperature.
- Compare computed mean and standard deviation temperature fields.
- Evaluate errors (calibration, readings and oscillations).

Additional

- Compare quantitatively the data by evaluating temperature profiles in horizontal and vertical directions.
- Evaluate temperature fields in unsteady conditions, during heating.
- Plot temperature behavior in time at selected points.
- Investigate the effect of the number of images on the derived results.

References:

- Handbook of the Infrared Thermo-camera.
- G.M. Carlomagno, G. Cardone, Infrared thermography for convective heat transfer measurements, *Experiments in Fluids*, Vol. 49(6), pp.1187–1218, 2010.
- AA.VV., Handbook of Experimental Fluid Mechanics, Springer-Verlag, 2007, Chapter 7.

Practical notes:

Infrared Thermography (IT) is a non-intrusive optical measurement technique able to determine temperature fields with high spatial resolution. Every object with a temperature over the absolute zero (0 Kelvin = -273,15 °C) emits Infrared Radiation (IR), which in the electromagnetic spectrum is close to the visible red light (from 760 nm to 1 mm). The human eye is not sensitive to these wavelengths (unless temperature is over 500°C), whereas a thermal imager detector can reveal IR radiation emitted by an object. Based on the intensity of the IR radiation, the detector records the thermal image and converts it into an electric signal proportional to such intensity, giving an output image in which each pixel has a color scale proportional to the temperature, this process being referred as IT. The thermal sensor detects the surface temperature of the object and not the internal one.

However, the picture is not so simple because the dependence of IR intensity on temperature is also a function of the radiation wavelength, as also the transmittance in air. Starting from Planck law, the wavelength (λ) of maximum radiation intensity is inversely proportional to the temperature (T) as expressed by the Wien law, so that the lower the temperature of the object to be measured, the larger is the wavelength for maximum radiation. In addition, the level of transmittance of IR in air is also dependent on radiation wavelength. It could be useful to integrate the spectral radiation intensity across all wavelengths for the case of a black body (perfect emitter and receiver), the resulting value being independent on the radiation wavelength, but only on the fourth power of the temperature (Stefan-Boltzmann law, SB). In the case of an object different from a black body, the SB law is modified by means of the emissivity of the investigated object ε

$$I(\lambda, T) \propto \varepsilon(\lambda, T) \sigma T^4$$

(σ is the SB constant). This correlation shows the significance of the object emissivity on measured temperature, dependent on material, surface temperature, wavelength and measuring arrangement. It is normalized to the emissivity of a black body, so that it varies from 1 for the black body (by definition, independent on the wavelength) to lower values (skin 0.95, glass 0.75-0.95, water 0.85, Plexiglas 0.86, metal less than 0.1), in this cases dependent on wavelength. In order to get the best performances, the imager must be tuned in a specific range of λ and a calibration is required to get the correct proportionality.

The objective of this practice is to measure the thermal field over a microfluidic device heated from below, in which water is flowing in order to control the heat transfer from the surface. Image acquisition is performed by following the increase of temperature of water when passing close to the heated surface. So far, it is possible to acquire instantaneous temperature fields and to perform either a statistical average in time or to follow the variation of temperature in time in unsteady conditions. Measurements are performed by changing the flow rate inside the microfluidic device and by changing the temperature of the bottom heating plate. Measurements can be also compared to results obtained at selected points by single-point thermos-couples.