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Investigation of the small scale statistics of turbulence in the Modane S1MA wind-tunnel

(part ESWIRP project)

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\+ Carine Fourment and Joel Delville perished in a sad car accident on their way back from Modane, where the experiment presented in this document was carried out. This has been a terrible human and scientific loss for all of us.

1 Introduction

The first scientific observation of *turbulence* probably dates back to Leonardo Da Vinci [1], who named, for the first time in history, *turbulenza* the complex swirling motion of water. Leonardo's drawings already emphasize two of the main properties of turbulence: its randomness and its multi-scale aspects, with small random eddies being embedded in larger ones. Since then, although our understanding of the phenomenon has significantly progressed, no complete framework has yet emerged which is able to fully explain the origin and the dynamics of turbulence. Reynolds has shown that turbulence appears whenever the viscous forces are small compared to the driving forces. In practice this includes most macroscopic natural and technological flows, what makes turbulence an enormous challenge for the future. Beyond its fundamental interest, piercing the mysteries of turbulence, may indeed help improving aerodynamics design, weather forecast, understanding of stars evolution, models of blood flow, and a thousands of other applications.

Paradoxically, an exact theory for turbulence does exist, though the mystery remains: Navier-Stokes equations are indeed expected to actually rule the motion of flows, even in the turbulent regime. However, the complexity of these equations (in particular due to its non-linearity and non-locality properties) seems to have ruled out any hope of ever finding an analytical solution to the problem. The alternative strategy is then to characterize, as precisely as possible, the main porperties of the unknown *solutions* of these equations. Because turbulence is random, this description is to be statistical. Most ongoing researches in turbulence are done in the perspective of finding such an accurate statistical description of turbulence.

The first stone in building a statistical description in modern history of turbulence starts with Richardson, who proposed in the 1920s a multi-scale description of the phenomenon in terms of an energy cascade, where turbulence appears as a hierarchy of random eddies with sizes ranging from the scale where energy is injected (which could be hundreds of meters for atmospheric flows for instance) down to the scale where it is dissipated by viscosity (which could be microns). This range of scales (between injection and dissipation) is known as the inertial range of turbulence. This qualitative description was put in a more quantitative framework by A. Kolmogorov in 1941 [2] who developed a phenomenological description of the turbulent cascade, based on dimensional considerations and assuming homogeneous and isotropic turbulence (HIT) with a self-similarity of statistical properties of eddies within the inertial range of scales. In Kolmogorov 1941 phenomenology (known as K41) the statitiscal properties of turbulence are mostly characterized by one single parameter : $\langle\varepsilon\rangle$ the average energy dissipation rate (which in stationnary conditions equals the average enrgy injection rate). One of the big successes of K41 is the prediction of the spectrum of the kinetic energy of turbulent eddies (the celebrated $k^{-5/3}$ law). However, as rapidly objected by Landau, K41 fails predicting one important statistical property of turbulence known as *intermittency*. This appears as the fact that energy dissipation (which is related to the viscous friction between fluid elements at small scales) is highly unevenly distributed in space. To account for intermittency, Kolmogorov proposed in 1962 [3] a

refined version of his self-similar phenomenology, including Obukov suggestion that the energy dissipation rate exhibits strongly non-Gaussian fluctuations. However the description of intermittency and its origins are still mysterious, and its modeling remains an active field of research [4,5] whose development still requires accurate experimental (reference measurements for intermittency date back to the 90' [6]) .

Traditionnal approaches (including Kolmogorov phenomenology) of turbulence are done in the so-called *Eulerian* framework, which aims at describing statistical properties of the turbulent velocity field from spatial obervations. The necessity of accessing a description of turbulence as complete and accurate as possible has recently renewed the interest of the complementary *Lagrangian* approach. In this approach, one is not interested in velocity as a field with spatial statistical fluctuations, but as a dynamical quantity associated to fluid elements along their trajectories. While an *Eulerian* measurement of turbulence is done with a probe at a fixed location, *Lagrangian* measurements require the capacity to track fluid particles and to analyze their trajectories. From the modeling point of view *Lagrangian* approaches are related to stochastic models, which offer numerous mathematical tools for modeling for instance turbulent diffusion phenomena, such as mixing and particle dispersion. Hence, not surprisingly, first important use of *Lagrangian* approach of turbulence was proposed by Taylor in the 1920s in the context of turbulent diffusion, in analogy with brownian motion. However, *Lagrangian* measurements remained almost impossible in real turbulent flows until very recently, thanks to development of high speed imaging technologies and high resolution acoustical particle tracking. In the past decade, the first *particle tracking* measurements of turbulence have shown that the intermittency phenomenon already known from *Eulerian* investigations has its *Lagrangian* counterpart which appears as the fact that the forcing acting on a fluid particle (revealed by the measurement of particle acceleration) is unvevenly distributed along particle trajectories and has highly non-gaussian fluctuations with extreme events occuring with a probability orders of magnitude larger than for a gaussian distribution [7,8,9]. Wether and how *Lagrangian* intermittency is related to *Eulerian* intermittency remains a mystery which starts to be tackled thanks to multi-fractal models of turbulence but which still requires accurate measurements of small turbulent scales (with both high time and space resolution) to get a deeper insight.

To finish this brief description of the state of the art of turbulence we also mention one of the most important applications of turbulence which its ability to mix. The mixing problem is usually referred to as the *passive scalar* problem. It corresponds to the investigation of the diffusion of a scalar (for instance the concentration field of a dye, or a temperature field) which does not affect the main carrier flow. The statistical characterizaton of the passive scalar field in turbulent conditions also reveals a strong small scale intermittency, with important and uneven fluctuations of the scalar dissipation. The origins of this intermittency and its connection to intermittency (either Eulerian or Lagrangian) of the carrier flow remains mysterious. Concerning the scalar, other important question remain open, such the rate at which the mixing process is accelerated by the turbulence and the influence of the Reynolds number of the carrier flow on this process.

In this context, there is a strong need from the community for high quality data, suited to test, validate and calibrate models and simulations of turbulent flows (for the Eulerian approach, the Lagrangian description and the passive scalar problem). The demand is particularly important concerning homogeneous and isotropic turbulence (which remains

the field of predilaction to investigate fundamental properties of turbulence) at large Reynolds number (for which asymptotic limits are generally investigated to derive scaling laws of turbulent dynamics). State of the art strategies to produce high Reynolds numbers in laboratory experiments consist in injecting a huge mechanical energy in a small volume of fluid. One of the most studied configurations of this type is obtained by considering the flow between two counter-rotating impellers in a cylindrical vessel full of water (the so-called von Karman flow). Such swirling flows have been extensively investigated in the turbulence community [7,10,11]. However this geometry has several drawbacks the main one is the strong anisotropy of the flow which make any comparison to models and simulations complicated and ambiguous. The second is that the small scales at which effects as intermittency become important are extremly small (of order of microns for space scales and fractions of milliseconds for time scales), and at the limit of the resolution of classic instrumentation. Another recent strategies of achieving high Reynolds number turbulence rely on cryogenic flows using liquid Helium which has a very low viscosity. However, fluid dynamics measurements in such cryogenic conditions are still in their childhood. The best state of the art configuration to produce HIT remains the grid-generated turbulence in wind-tunnels [12]. This turbulence is produced by the interaction of the wake from the rods forming a grid with appropriate geometry. However the limited dimensions of academic wind-tunnels only allow moderate Reynolds numberds to be reached, and limits the possibility to finely explore Reynolds number effects on inertial scalings and intermittency.
The goal of our project is to contribute to the effort in untangling the statistical description of turbulence (with a particular focus on intermittency effects, Lagrangian-Eulerian connections and passive scalar diffusion) by offering to the scientific community a unique database of fully resolved experimental data of turbulent flow in homogeneous and isotropic conditions at large Reynolds number.

2 Goal of the project

The objective of this project is to provide a complete and fully resolved experimental characterization of high Reynolds number turbulence in order to build a unique and unprecedented database of high-resolution turbulent statistics. In the mid-term, this database is intended to become « open – source » and to be made available to the scientific community. It will be a precious tool at several levels : (i) as a reference and a standard of turbulence properties for validation and calibration of other experiments and direct numerical simulations (DNS) ; (ii) for the fundamental comprehension of turbulence physics and (iii) for the development, tuning and calibration of accurate models. Building such a database requires the ability to measure accurate scale by scale statistical properties of turbulence, with high space and time resolution over the entire range of relevant scales, including inertial scales and small dissipative scales. This considerations motivated our project to produce and investigate grid-generated turbulence in the S1MA windtunnel in Modane. The unique size of this facility (typically one order of magnitude larger than usual academic wind-tunnels) allowed to produce high Reynolds number turbulence with fully resolvable dissipative scales and fulfilling the double condition $\eta << L << D$: (i) a dissipation scale η much smaller than the

energy injection scale L, as required to develop real inertial range scalings and (ii) an injection scale L much smaller than the size of the facility D in order to avoid undesired wall effects from the walls. A large scale grid (10m in diameter, with a mesh size of 0.625m) was used as turbulence generator, as it is known to produce canonical homogeneous and isotropic turbulence. Building and installing such a large grid was one the major challenges of this project. This required not only to design a unique grid using inflatable strucutres technology, but also to adapt the S1MA windtunnel in order to install the grid in it.

Besides, in order to build a databse as complete as possible, many different complementary measurements have been implemented during the experiment, giving access to Eulerian and Lagrangian description of turbulence statistics :

1. Hot-wire anemometry
2. Laser cantilever anemometry
3. Lagrangian particle tracking
4. Vortical acoustic scattering
5. Micro-pitot tubes

This document is built as follows : section 2 details the main preparation stages of the experiement and section 3 details the measurements which have been performed and the preliminary results. We finalize with a conclusion and opening remarks. The experiment took place from July 7th to 11th 2014. At the moment this report is being written, the acquired data has therefore not been fully processed yet and only preliminary signal samples will be presented.

3 Preparation of the experiment

Preparing this experiment required several challenging tasks to be solved. First, such a high dimension grid turbulence experiment has never been performed before and no precedent existed on how to manufacture such a large scale grid. Second, intoducing such a grid in S1MA represents a much higher pressure drop than with usual models. This constraint needed to be taken into account in the design of the experiment. Third, as previously highlighted many simultaneous experimental diagnosis were expected, requiring a dedicated instrumentation platform. The following sections briefly discuss the main aspects of the experiment preparation.

3.1 The grid

Initially, the grid was supposed to be a metallic strucuture of about 8 m in diameter, mounted at the entrance of the test section. Empirical laws for turbulence generation [12] required a solidity of the grid between 30 and 40%. It became rapidly evident that such an obstruction ratio represented a pressure drop going far beyond the usual working point of the wind-tunnel. Reasonable pressure drops would require to lower the solidity of the grid around 20%, in which case turbulence generation becomes very inefficient. The solution found was to place the grid not at the entrance of the test section, but in the convergent of

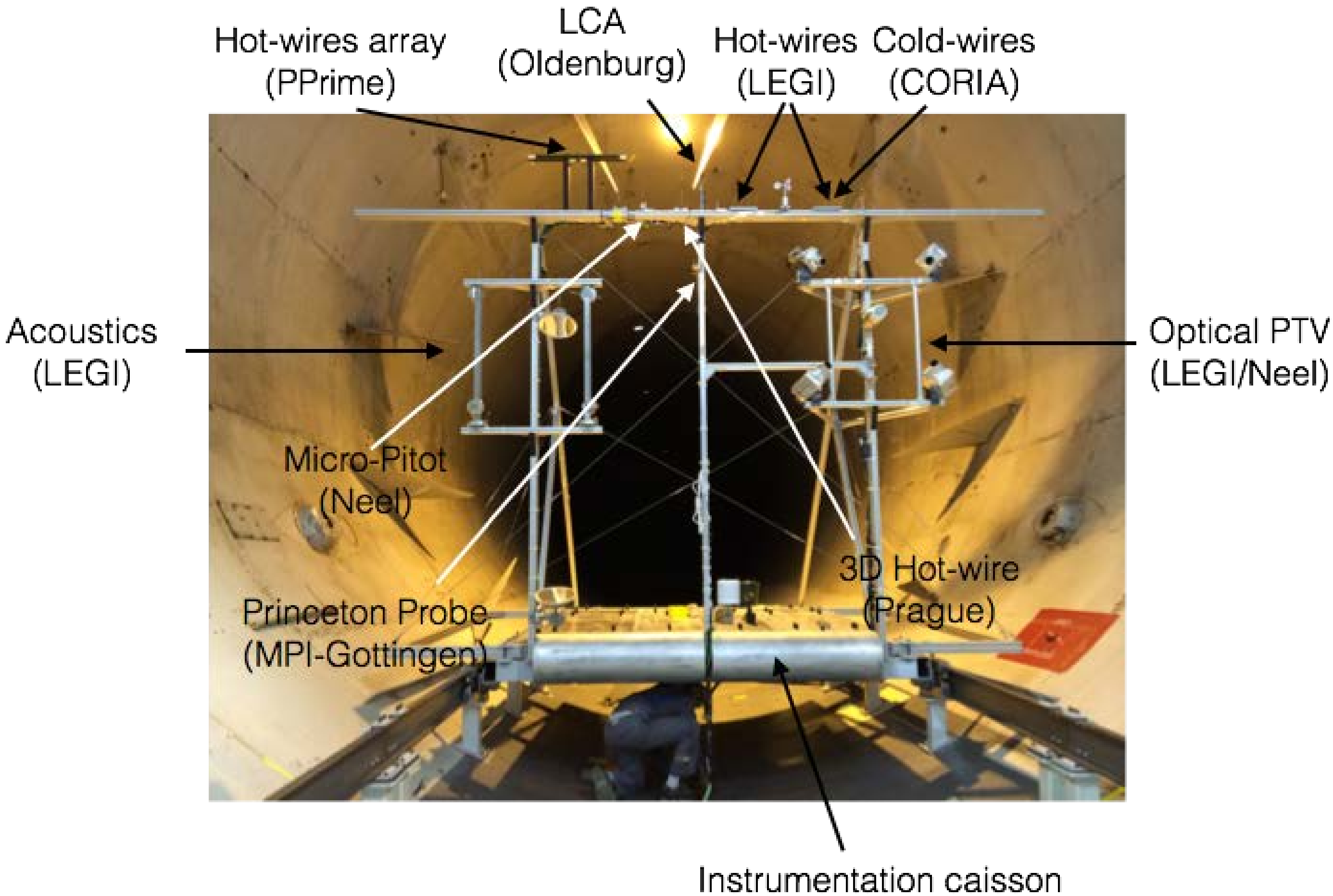
the tunnel, with a diamter ratio from 8 to 10m, the pressure drop for a given solidity being then reduced by about 35%. The problem then moved from an aerodynamic issue to a structural issue as building a heavy metallic grid (the estimated weight for an aluminium sturcture was of the order of 2 tons) in the convergent of S1MA would require a huge effort. Therefore we explored the possibility to built a light inflatable structure. The study of this solution was given to CERTEC, a french company specialized in inflatable strucutures at all scales, in close collaboration with LEGI partner and ONERA. The feasilbility of the project was rapidly confirmed. The final design consisted is an infaltable grid, with a solidity of 33%, made of cylinders with diameter of 120mm and a spacing of 625mm, with one plane of horizontal cylinders and one plane of vertical cylinders. The pictures below shows the first test of assembly of the grid, in september 2013 and the grid in its final position in the convergent of S1MA.

Test assembly of the grid

The grid mounted in the convergent of S1MA

3.2 The instrumentation platform

A dedicated instrumentation platform capable of hosting all the planned sensors and apparatuses for the diagnosis of the turbulence was specially designed for the campaign. Many sensors and probes required to have their corresponding instruments (amplifier, anemometer, conditionner, etc.) as close as possible, to limit cable length and hence improve signal to noise ratio, resolution, etc.. This required to design an instrumentation caisson below the platform, with an apropriated aerodynamic profile, to limit pressure drop. The picture below represents the instrumentation platform during the test, with most of the sensors on it (for each sensors we have indicated the responsible institution).



3.3 Adapting S1MA for the project

The unusual configuration of the experiment, compared to usual model tests in S1MA required several adaptations to be performed :

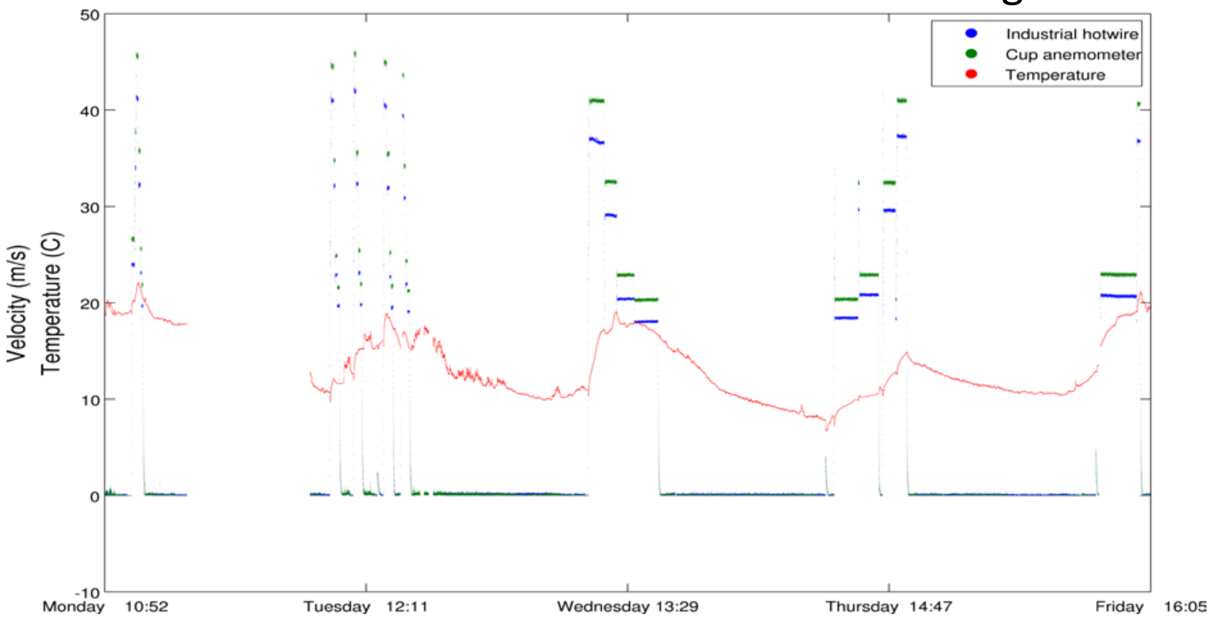
1. Installing the grid in the convergent required to set 7 vertical cables in the convergent, to fix the grid and hold seven 500kg weights underneath in order to tend the cables and limit the deformation of the grid. This was the most complex required adaptation of S1MA.
2. Installing the platform (which needed to be mobile along the streamwise direction) required to install dedicated rails inside the test section
3. Particle tracking experiments required to fix particles generators upstream the measurement volume. This was done thanks to 2 vertical cables mounted accross the test section, where droplet generators and bubble generators were fixed.

4 The measurements

4.1 Global view of the measurement campaign

The main goal of the experiment was the characterization of the smallest scales of homogeneous isotropic turbulence. Hence most of the measurements were carried with the instrumentation platform at the farthest position downstream the grid (corresponding to nearly 40 grid meshes), were the turbulence is fully developped, with optimal homogeneity and isotropy properties. However, an interesting input is also given by the decay of turbulence downstream the grid. Therefore, some measurements have also been carried at several positions between the entrance of the test section (corresponding to about 12 meshes from the grid and the final position). These measurements will allow to study for instance the evolution of the mean square velocity as a function of the distance from the grid, what gives a direct estimation of the turbulent dissipation rate, a key quantity to estimate turbulent temporal and spatial scales. The study of the decay rate is not finalized yet.

The figure below gives an interesting global view of the wind-tunnel operation during the 5 days campaign. It can be seen for instance that the first 2 days where dedicated to short runs at given velocities (each velocity was repeated for the different positions of the instrumentation platform) while the last 3 days where dedicated to long runs for each velocity (the instrumentation platform being fixed at its farthest downstream position), in order to achieve the best possible statistical convergence for a highly resolved characterization of small scale fluctuaitons. Velocity plateaux as long as 2 hours of continuous runs at a given wind speed were carried. To understand the necessity of such long runs, we can recall that the typical correlation scale of the studied flow is given by the mesh size (a fraction of it in the present case due to the contraction effect). If we take 30 cm as an order of magnitude, a run of 2 hours at the velocity of 30 m/s therefore warrants that $30 * 3600 / 0.3 = 3.6*10^5$ correlation scales of the flow are effectively sampled, what ensures an excellent statistical convergence.



The following sections give some details of the different complementary measurements performed for the turbulence characterization. Note that the experiment was carried in July 2014 and that tens of Tera-bytes of data were collected. The building and processing of this gigantic datbase is still in progress. Results presented here are therefore preliminary and parcelar, although they already indicate that the campaign has been scientifically successful.

4.2 Hot-wires

4.2.1 Methodology

Hot wire anemometry remains the most classical high resolution measurement for the accurate characterization of the velocity flucutations in a turbulent flow. The principle is very simple : a small conducting wire (typically a few microns in diameter and less than a millimeter in length) is over-heated (compared to ambient temperature) ; the convective heat transfer induced by the surrounding flow then tends to cool the wire and hence to modify its electrical conductivity which is monitored and whose fluctuations give access to the veloclity after a proper calibration has been done. The most common measurement protocol consists of a CTA (Constant Temperature Anemometry) : the wire is inserted in a Weastone bridge, which is kept balanced with a feedback loop of the electrical current which is dynamically adjusted so that Joule dissipation in the wire dynamically varies to mantain the wire at constant temperature. As a consequence the voltage feeding the bridge flucutates, reflecting the velocity fluctuations of the velocity around the wire. The relation between voltage fluctuations and velocity can be calibrated according to the so called King's law. Each wire needs to be individually calibrated. Besides the calibraiton parameters depend on the ambient temperature, what requires, either to have an accurate temperature dependent calibration or to re-calibrate the sensors for each given experimental condition. This justifies the fact that several ramps of velocity were performed all along the measurement campaign : these ramps will be used to test the calibration of the hot-wires and recalibrate theme if necessary.

The space and time resolution of the measurement is directly related to the dimensions of the wire. The smallest the wire the better the spatial resolution, but also the better the time resolution as smaller wires have less thermal inertia and hence respond faster to the turbulent fluctuations. Besides, in order to have an apropriate directional measurement (giving access to a well defined velocity component) the length to diameter ratio of the wire is empirically known to be of the order of 100 or more. For instance a wire with diameter 5 microns must be at least 500 microns long. The effective spatial resolution is therefore limited by the lenght of the wire.

In the present experiment several types of hot-wires were used :

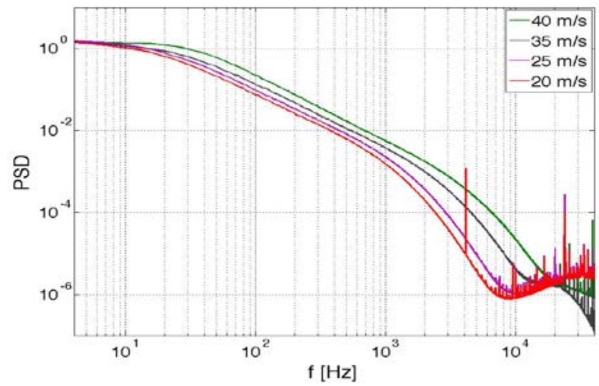
- 6 single wires from LEGI , with diameter between 1.25 and 5 microns (6 such wires were simultaneously recorded)
- 1 triple cross wire from the Prague group, with diameter 5 microns, giving access simultaneously to 3 components of the velocity
- A nano-fabricated wire from Princeton with very high resolution was also tested by the Gottingen group (which has a separate partnership with the Princeton group developping this sensor).
- An array of 23 single wires with logarithmic spacing, giving access to transverse correlations of velocity flucutations, from the Poitiers group.

In the following we briefly describe the first preliminary results from these different hot-wires measurements.

4.2.2 Single wire measurements

6 single wires, sensitive to the longitudinal component of the flow were simulatneously monitored using a Dantec – Streamline CTA anemomenters. The main goal of these measurements was to obtan high resolution measurements of turbulent fluctuations (one point and two points correlations). Two points statistics are traditionnally obtained in grid generated turbulence from a Taylor hypothesis, were the temporal fluctuations of the recorded signal are interpreted as spatial fluctuations as the turbulent field is rapidly swept by the main stream accross the sensor. The Taylor hypothesis is valid for flows with low turbulent levels (defined as the ratio between the rms velocity and the average velocity), what applies to the present situation were this ratio is of the order of 2.5%. The single wires measurements are therefore devoted to access longitudinal statistics of the streamwise component of the velocity field.

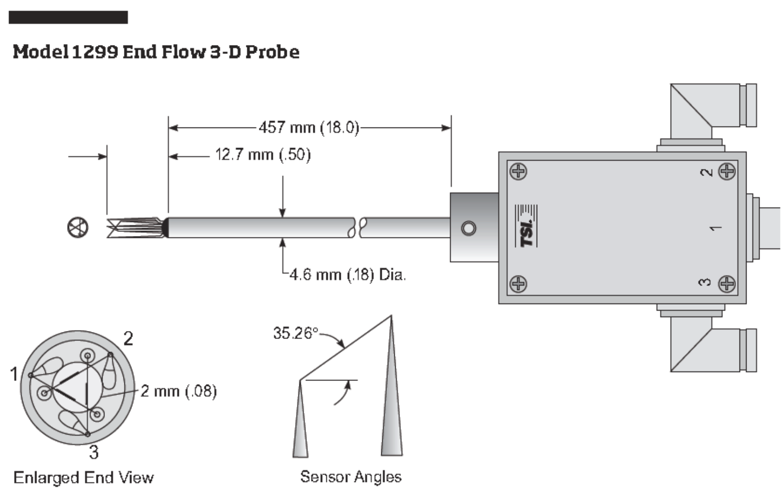
Preliminary results show that indeed, not only the inertial range, but also the smallest dissipative scales of the flow were correctly resolved as it can be seen in the sample spectra below.



Temporal spectra of the recorded velocity signal. The inertial range of turbulence is clearly visible at intermediate frequencies while the dissipative cut-off is clearly visible at higher frequencies (of a few kHz), with, as expected, increasing frequency cut-off for higher wind-speeds.

4.2.3 3 components crossed-wires

We performed measurements of the full velocity components using a 3 components crossed-wires (probe TSI 1299 – 3 perpendicular hot film sensors, measuring point 2 mm dia).

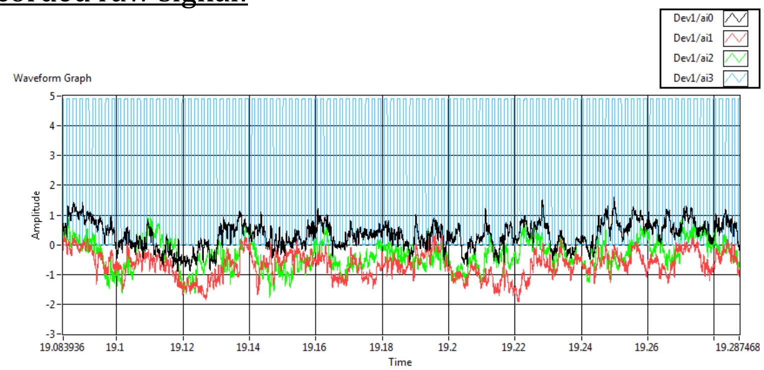


The probe was oriented towards the flow with variable temperature of the sensors. All regimes available during the measuring campaign were recorded. (Over 3 hundreds records). In isothermal conditions time series of all 3 velocity components in the measuring point (*u*,*v*,*w*) are to be evaluated. Velocity, temperature and directional calibrations are to be applied. We are using generalized Collins-Williams cooling law formulation.

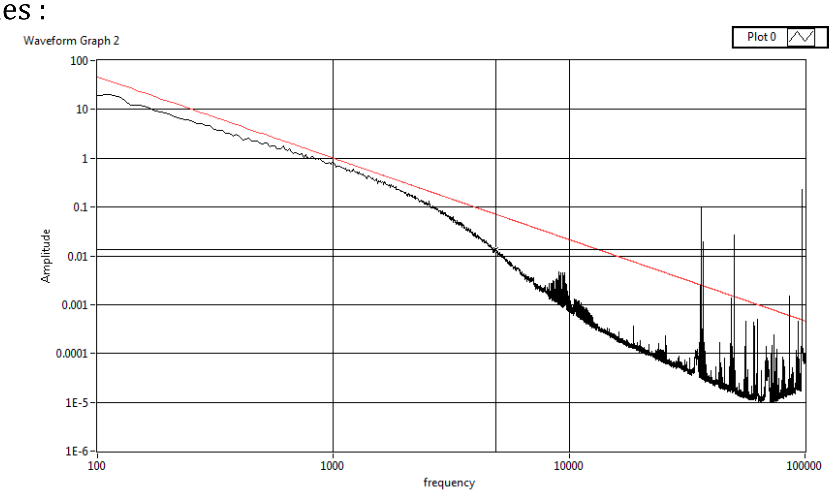
A special method for non-isothermal flow statistical characteristics evaluation is to be used. For this several measurements for one regime were acquired for several temperatures of hot elements (from 100 to 300 degrees). The method allows for evaluation of the following statistics:

- 1st order statistics: time-mean values of velocity components and temperature (*U*,*V*,*W*,*T*)
- 2nd order statistics: variances *u*,*v*,*w*,*t*, correlations *uv*, *uw*, *vw*, *ut*, *vt*, *wt*

Example of the recorded raw signal:



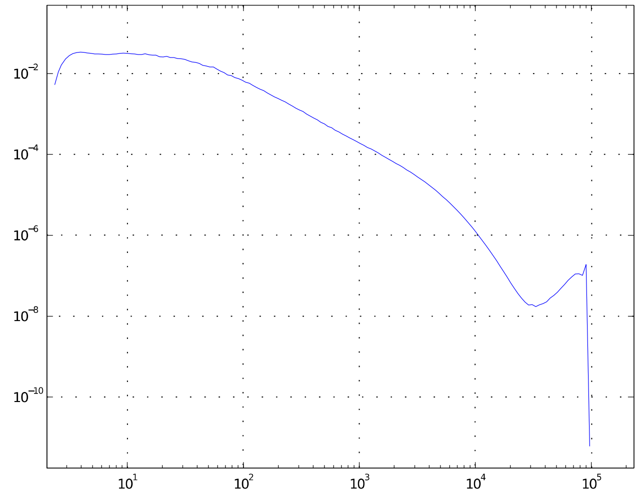
Example of corresponding turbulent spectrum, showing resolution of the inertial range and dissipative scales :



Note that resolved scales with the 3 components probe are consistent with single wire measurements.

4.2.4 Princeton nano-probe

The Nano-Scale Thermal Anemometry Probe (NSTAP) [13] is a hot wire probe developed at Princeton University especially designed for high Reynolds number flows. It is at least one order of magnitude smaller than commercially available hote wires, which are usually not shorter than half of a millimeter. The shortest NSTAPs can be as small as 100 nm x 300 nm x 30 µm providing a unique possibility to fully resolve the smalles scales in highly turbulent flows. These probes can be used in conjunction with a standard Dantec CTA circuit in basically the same way as classical hot wires with the exception of the NSTAPs providing greatly improved temporal and spatial resolution.



Typical energy spectrum of a short (4 minutes) dataset for a 45 m/s flow, recorded by a NSTAP at 200 kHz. At 30 kHz electrical noise from the CTA-circuit is starting to corrupt the signal.

As seen in the figure above the NSTAPs are able to resolve all relevant scales in the flow, with porbably a higher signal to noise ration compared to classical wires (although this statement still requires a better analysis). This is true for all speeds the tunnel was running at. The most natural focus of the analysis should lie in the small scale statistics of the turbulent flows and the direct comparison of the NSTAP sensors with the other technologies used in the experiment. Especially the comparison on the differences of different measurement methods in the vicinity of the Kolmogorov scale should give important new insights.

4.2.5 Multi-probe array

The group in Poitiers had prepared a unique measurement device composed of 23 hot-wires (2.5 microns in diameter, 600 microns long) with logarithmic separation along a linear array.

Our colleagues from Poities were victim of a fatal car accident in their way back from Modane after the campaign. This loss have been a terrible shock for the group. Beyond the terrible human tragedy, we are doing all our possible to recover the data from their unique measurement instrument.

4.3 Cold-wire thermometry

Cold-wire thermometry is a high resolution technique to measure fluctuations of temperature induced by turbulent mixing. In conventional case, a mandolin is used to generate a temperature gradient, and thus we follow the temperature evolution through the wind tunnel. In the present case, the extreme dimension of the facility did not allow us to design an adequate mandolin to inject controlled temperature fluctuations. Hence only natural turbulent fluctuations of temperature were measured. We used a constant current anemometer (CCA), with a single wire probe. This kind of measurements is very sensitive to the shape and length of the wire. The first tests were made with the optimal probe, using Platinium-Rodium totally etched wire of 0.63 µm diameter. The sensitive length to diameter

ratio was about 880. The CCA operated at low overheat (hence the cold wire name), where the current intensity was 0.1mA, in order to minimize the contamination by velocity fluctuations.

Several attempts were made, but a critical problem appeared, probably related to a small residual pollution by pollen filaments in the tunnel which destroyed the very thin cold wires.

A thicker wire diameter (1.25 μm) was tested, but the results were not satisfactory. The spectra of temperature fluctuations extend only over two decades, whilst the velocity fluctuations spectra extended overs more than seven decades. This can be attributed to two factors: (1) the wire diameter was not really adapted (too thick), causing a cut-off frequency smaller than the true value ; (2) the temperature fluctuations in the wind tunnel were most likely very low, in comparison with those produced by a classical mandolin.

4.4 Laser Cantilever Anemometer (LCA)

The 2d-Laser Cantilever Anemometer has been developed at the University of Oldenburg [14] as an alternative to commercial x-wires. It fea- tures a spatial resolution of about 160μm and a temporal resolution of about 100kHz.

4.4.1 Measuring principle

The underlying principle utilized in the 2d-LCA is the detection of the de- formation of an one-sidedly fixed microstructured cantilever that is exposed to a fluid flow. For a straight inflow, i.e. a flow direction perpendicular to the cantilever surface, the deformation is a response to the drag force F_{drag}, that is given by:

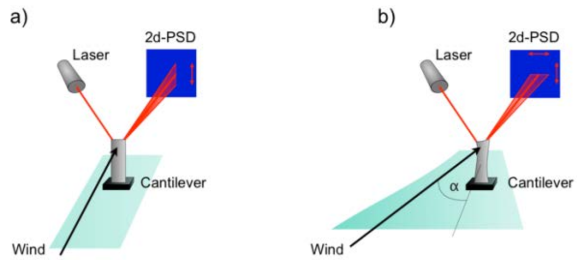
$$F_{drag} = c_d(u)\rho A u^2.$$

Here, $c_d(u)$ is the drag coefficient, ρ is the density of the fluid and A is the area of the cantilever that is facing the flow. For an oblique flow, i.e. flow at an angle of attack $\alpha \neq 0$, the total deformation of the cantilever is observed to be a superposition of bending and twisting. In that case the quantities A and $c_d(u)$ become functions of α and eqn. above becomes:

$$F_{drag} = c_d(u,\alpha)\rho A(\alpha) u^2.$$

The detection of the deformation is accomplished by means of the laser leaver arm principle that is also used in atomic force microscopy. For that purpose, a laser provided by a laser diode (λ_{laser}= 660nm, Power = 5mW) is focussed onto the tip of the cantilever.

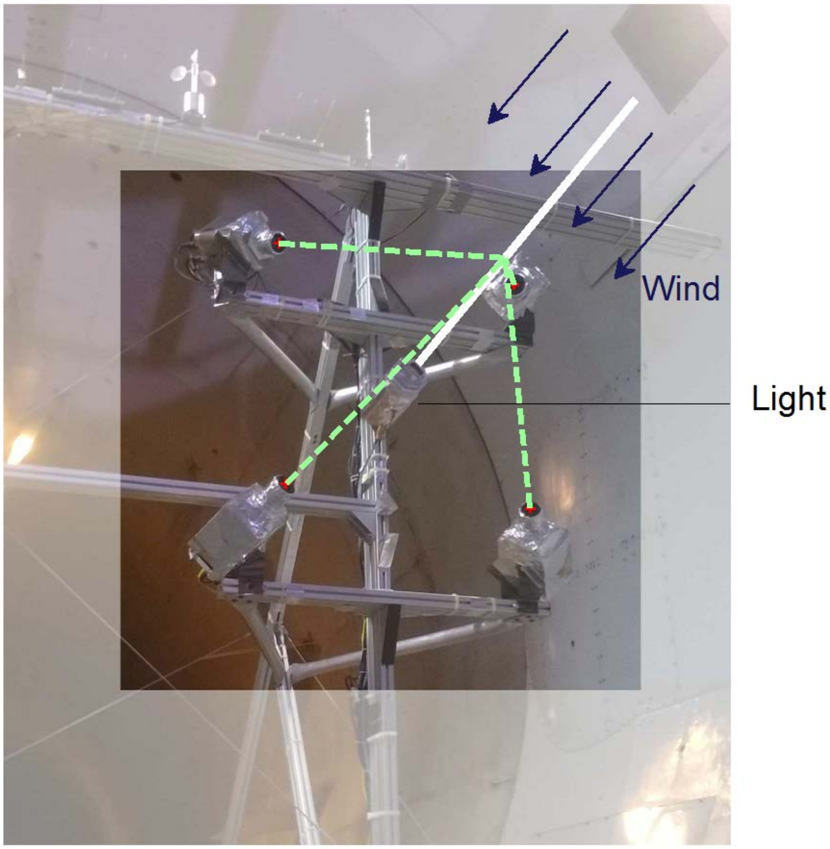
The resulting reflection beam is tracked using a 2d-position sensitve device (2d-PSD) with an active area of 4mm x 4mm. This principle is schematically illustrated in figure below for both deformation modes.



The deflection paths of the reflecting spot along the active area due to bending and twising are decoupled and follow two perpendicular directions. After calibration, each position of the reflecting spot along the active area can be unambiguously assigned to a flow velocity and an angle of attack, from which the longitudinal and transversal velocity components are easily calculated. That way, simultaneous measurements in two dimensions are possible. LCA data is still being analyzed.

4.5 Lagrangian particle tracking

This part of the installation (see figure below) is dedicated to the direct visualization of the air flow from the analysis of the trajectories of very light particles called tracers. Two types of tracers have been used : water droplets (diameter ~ 100 μm) and millimetric soap bubbles. The tracers are released in the flow upstream from two nozzles supported by cable placed inside the wind tunnel section.



Particle tracking setup. The sight of the four cameras (dashed lines) correspond to the edges of a square-based pyramid. The opening angle of the cameras allow for an observation of trajectories of 80 cm. The tracers are enlightened by a beam light coming from a LED (switched o on the image).

The measurement of the tracers trajectory is made about one meter upstream to the carriage. The observation region corresponds to a cylindrical volume with length 80 cm, diameter 15 cm and aligned with the wind flow direction. The volume is light by a high power LED allowing for the observation with 4 fast cameras of the sub-millimetric tracers at the mean velocity 50 m/s.

The acquisition of the tracers trajectories is made simultaneously by the 4 cameras in sequences of 2 seconds at a frame rate around 10 kHz. The location of the particle image on the cameras sensors is extracted from an image analysis of each frames. The 3D coordinates of the tracers in real space is obtained from an home made algorithm that use the information of

- the 4 cameras location and orientation
- the coordinates on the 4 cameras sensors of each particle found in the image analysis.

Once a list of particles have identified for each frames, the trajectories are reconstructed step by step by linking the closest neighbours in a given frame and the following. The cables holding the nozzles were at the middle of the wind tunnel. This means that the Particle tracking experiments were running the last two days only, when the

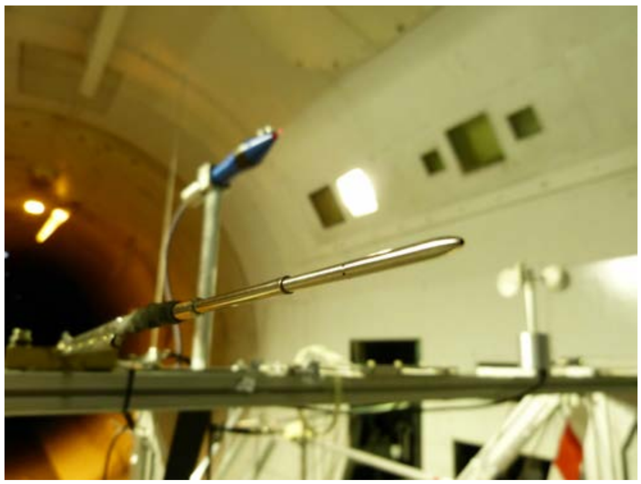
instrumentation platform was at its farthest position from the grid (16 m). In addition to this first limitation, it was actually not possible to run any experiments on the last day because the LED used for the lightening failed.

4.6 Vortical acoustic scattering

Acoustic measurements have not been processed yet.

4.7 Miniature Pitot tubes

Two miniature Pitot tubes anemometers have been specially designed and installed alternatively in Modane S1 wind-tunnel to measure the mean velocity and its more energetic fluctuations during the first 4 days of the experiment (7/7-10/7). The picture shows the probe labelled #1 mounted in Modane S1 wind-tunnel.

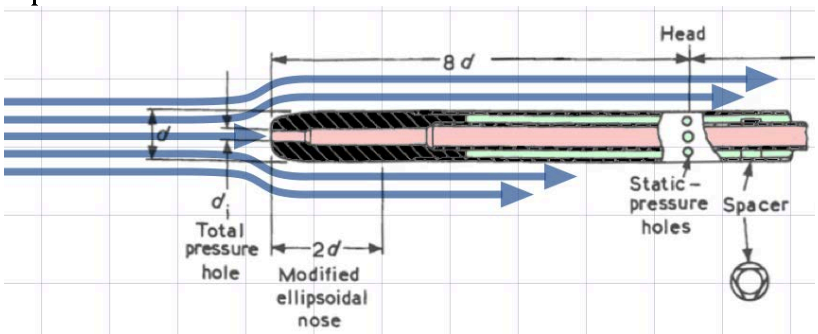


Special interest of miniature Pitot tubes Compared to how wire anemometers, the key advantages of the miniature Pitot tubes are their robustness (in particular to particles impinging the probe) and their no-need of calibration. Their main limitations are space and time resolutions, which is typically few millimetres over a bandwidth up to few kHz. Given the typically velocity range in this experiment, the bandwidth limitation is the most stringent one.

The expected physical outcome includes the assessment of the flow turbulent intensity independently of the actuator and electronic sensitivities, and cross-check of the other sensors based on different velocity-measurement mechanisms (hot films and wires, cantilever, ultrasonic, cup anemometer,…). Another objective is to validate in a turbulent flow the specific sensor design, which is compatible with cryogenic helium, and was developped as part of the Euhit CE projet (WP21).

Pitot tube #1 The nozzle (external diameter of 3 mm) and pressure reference taps of the Pitot #1 are following the NPL modified ellipsoidal-nosed standard (norm BS1042 and french norm AFNOR NFX10-112). See figure 2. Its Helmholtz resonance was around 4.2 kHz with a typical quality factor of 7. This Pitot tubes evidenced very good immunity the acoustic and environmental electromagnetic noise. Indeed, the detectable disturbances were the voltage-noise of the preamplifier (see below) and the Johnson-Nyquist thermodynamical noise from sensing resistors, both significantly below the velocity signal.

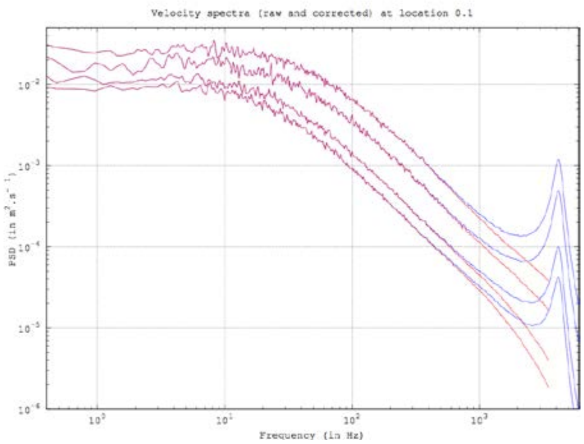
Zeroing of the probe at null velocity was performed several times everyday to compensate for a slight drift. This Pitot tube #1 was used the first three days (7/7-9/7) of the experiment.

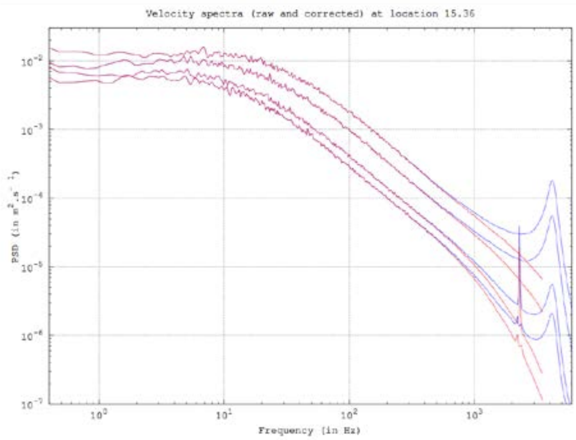


Pitot tube #2. The #2 Pitot tube was operated only during one day (10/7). Unfortunately, it picked up an energetic parasitic acoustic noise around 400 Hz, which prevented us from benefiting from its dynamics range which was three times better than Pitot #1 (first intrinsic resonance at 13 kHz). The noise source may have been caused by the gas jet of the bubble seeding apparatus. Hence, the data processing focussed on the first Pitot tube. We acknowledge support from the Onera machine shop in the making of this probe.

Mounting, **Electronics and data acquisition** Special attention was dedicated to the probe mountings both in term of stiffness, damping of vibrations from the support and flow invasively. In particular, the « rule of 10 » was respected : the pressure taps of the Pitot tube where located at a distance 10 x L upstream from the L-wide-bars of the mounting frame. The probe was located on the top horizontal bar of the probe rack, near the centre of it.
The electronics powering circuitry consisted of the battery-driven DC voltage source and a temperature-compensation resistive bridge aimed at compensating the residual temperature dependence of the piezo-resistive Wheatstone bridge of the pressure transducer. On the measuring side, a preamplifier was inserted before one 16-bits ADC card operated by the LEGI. Given the sharp cut-off of the Pitot tube signal above its first Helmholtz resonance, and the sampling frequency (>200 kHz), no anti-alias filter was used. On the first day (7/7), the preamp was set to a AC input preventing access to the mean velocity, while it was set to a DC position during the 4 other days of measurements. The multi-channel ADC card used to acquire data was shared with other probes : a cold wire from the CORIA, a thermometer, a cup-anemometer and 2 hot-wires from the LEGI.

Preliminary post-processing. As illustrated by two spectral plots at minimum and maximum distance from the grid, an accurate estimation of the flow kinetic energy is possible from the velocity spectra since the most energetic part of the spectra is well resolved in all conditions. Hence, a precise assessment of the turbulence intensity (with upper and lower bounds) should be possible using data from Pitot #1 acquired during Day 2 and 3.





5 Conclusion

From a scientific point of view, although the acquired data just started to be processed, we can say the campaing has been successful. The first analysis show indeed that the smallest scales of the flow were well resolved, what was the main challenge. The different diagnosis are consistent within each other, with different levels and ranges of noise. The combination of the data recorded with the several instrument should improve the overall quality of the measurements. The coming months will be devoted to a deep quality assessment of the acquired data, in order to quantify precisely the actual resolution of the several performed measurements and to built a complete database, ought to become open to the scientific community within a period 2 years starting from the completion of the database.

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