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Planar Particle Image Velocimetry for Aerospace Research at ONERA

Planar Particle Image Velocimetry (PIV) is a measurement technique that yields the instantaneous spatial structure in a planar cut of a flow. It exists in several forms (two-component, three-component or Stereo, and time-resolved), all of which are now considered to be mature, and as production tools for flow investigation in experimental facilities. This contribution is aimed at showing, through various examples of research activities, how it is currently being used at ONERA, with the idea of extending knowledge on complex flows, and therefore on the performance of complex systems. After a short reminder of the operating principle of planar PIV, applications are presented in the contexts of jet mixing physics, helicopter fuselage drag reduction, reacting flows, industrial wind-tunnels, and acoustics.

Introduction

Particle Image Velocimetry (PIV) is today one of the most widely used measurement techniques in fluid mechanics, in a large variety of situations ranging from fundamental flow physics to various different application fields, such as geophysics, industrial processes, and aerospace sciences. Its success is explained both by its non-intrusive nature, and by the wealth of spatial and, possibly, temporal information that it may provide. The basic idea behind PIV is to spread a fog of solid particles or liquid droplets into the flow to be measured, with constraints on the particle density and size so that they can be considered to be passively entrained by the flow. Illumination of these particles is then performed at two or more consecutive instants separated by short time intervals (possibly as short as less than 1 μs, for the highest flow velocities), and images of these particles at each instant are acquired using CCD or CMOS cameras. Tracking of the particle motion through suitable algorithms then enables the corresponding flow displacement to be determined, and then the velocity field.

For roughly three decades, this measurement technique has motivated very important research efforts in institutes, laboratories and universities worldwide, which have contributed to significantly enriching its capabilities in terms of spatial and temporal flow characterization. This progress has also been made possible by simultaneous advances in light sources and imaging systems. To name but a few, and with no intention of providing an exhaustive account of these research efforts (see for instance [1] or [2], for reviews), PIV started out as a two-component, two-dimension (2C2D), low-frame rate technique, yielding instantaneous snapshots at a low repetition rate (typically 5 to 10 Hz) of two flow velocity components in a plane, and is now available as a three-component, three-dimensional (3C3D), high-frame rate technique, providing volumic snapshots of the three velocity components with repetition rates as high as typically 10-20 kHz [3]. In parallel, dedicated processing approaches have made possible the addition of new analysis features to the initial statistical and instantaneous characterizations. For instance, specific time-resolved (see, e.g., [4], [5], [6]) or Lagrangian tracking approaches [7] have emerged, and, building upon this wealth of information, algorithms able to reconstruct pressure fields from the velocity fields, as well as efforts on objects placed in the flows, are now available (see for instance [8] for a review). In the same spirit, several new strategies for processing 3C3D (possibly partially) time-resolved data are inspired on computational fluid dynamics, thereby bridging the gap between experiment and numerical simulation (see [9], [10], [11], [12], among others). The above mentioned developments and studies, though particularly significant, still only represent a fraction of a very large variety of uses, processing, and applications of the PIV technique among the fluid mechanics community.

In this paper, we choose to focus on illustrating how the most well-mastered form of PIV, i.e., planar PIV (possibly Stereo and/or time-resolved), is used at ONERA as a key ingredient in the aerospace research performed there. Three-dimensional techniques, both of the PIV and Particle Tracking Velocimetry (PTV) type, are also available at ONERA but are excluded from this paper, because they are covered by a companion paper of this volume [13]. Selected examples from recent works at ONERA, each representing a particular context and objective, will be presented, together with the achievements and results made possible by the use of PIV. Note that for conciseness purposes, and in order to focus mostly on applications, only a slight account will be given of the setup and processing details. With regard to the latter point, it can be mentioned that in all examples traditional PIV algorithms based on the cross-correlation of interrogation windows (IW) will be used. With this processing, each of the vectors obtained in the result snapshots corresponds to the average motion of particle patterns contained in the IW defined around this vector. The applications shown will encompass the physical analysis of turbulent jet mixing, helicopter fuselage drag reduction, an overview of the capability of PIV in the context of reacting flows and in industrial wind-tunnels, together with the constraints. A last focus will finally show how PIV can be used to perform aeroacoustic measurements.

TR Stereo PIV for the study of jet turbulence and its control

Jet generated turbulence is a fundamental subject of foremost importance, because it plays a strong role in applications such as mixing, combustion and propulsion, for instance. In the latter domain, it is closely linked to the generation of aeroacoustic disturbances, and underlies the overall furtivity of systems. Several decades of research have enabled the largest scale and the most coherent unsteady perturbations occurring in the mixing layer (the thin region separating the jet from the quiescent surroundings) to be singled out as key ingredients in the global mixing. Among these, axial vorticity fluctuations have received a lot of attention, since they are directly responsible for injections and ejections of fluid, thereby achieving mixing. Understanding their origin and behavior is therefore crucial to propose flow control strategies aimed at enhancing mixing and obtaining complete jet dissipation over a smaller axial distance, for example.

In order to complete the knowledge on mixing mechanisms and to propose more efficient strategies for its control, ONERA recently embarked on experimental studies based on Time-Resolved Stereo PIV on turbulent round jets, at an exit diameter-based Reynolds number of 210,000 [14] [15]. Jets are generated in the open-circuit subsonic wind-tunnel R4Ch, specially designed for fundamental studies on jets and turbulence (see Figure 1). Depending on the contraction ratio of the final nozzle generating the jet, its operating velocities may range from a few m.s^{-1} up to 50 m.s^{-1}. Upstream of the contraction, a portion of the cylindrical pipe, in which a honeycomb with 1 mm-wide cells is placed, can be set in rotation. This enables a component of solid-body rotation to be added to the flow, and the instabilities and unsteadiness present in propulsive jets to be modeled more finely, for instance. Such a capability will be exploited in forthcoming works, given that the present study focuses on non-rotating jets. As depicted in Figure 1, measurement is performed in a cross-sectional plane of the jet, located 2 diameters (D) downstream from its exit. Results are obtained here using the GPU-implemented software FOLKI-SPIV, developed by the departments DAFE and DTIM of ONERA [16].

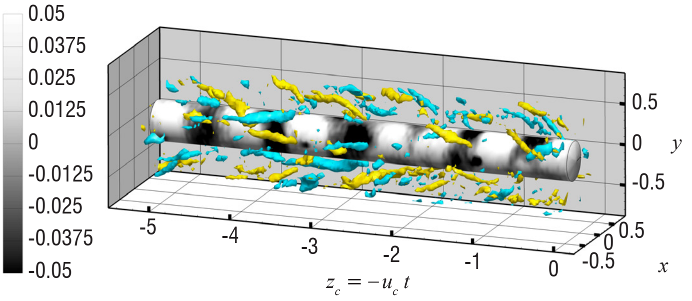


Figure 2 – Pseudo-spatial flow reconstruction in the z direction from time-resolved data. Grey contours identify the axial velocity fluctuation u'_z at $r/D = 0.24$, while yellow (resp. blue) iso-surfaces identify $\omega'_z = 4$ (resp. -4) iso-values of the axial vorticity fluctuation.

Aside from direct three-dimensional measurement, which involves a still complex setup, one way to characterize and investigate the three-dimensional structure of flows can be to rely on Taylor's "frozen turbulence" hypothesis, i.e., in the present case, to assume that turbulent coherent structures do not change while they pass through the measurement plane. Suitable post-processing based on this hypothesis [17] then enables a so-called pseudo-spatial flow reconstruction to be obtained, as shown in Figure 2. This figure evidences the presence of streamwise vorticity fluctuations in the mixing layer region (yellow and blue contours), and of their spatial synchronization with axial velocity fluctuations in the jet core (grey contours), the latter being mostly associated with the well-known axisymmetric Kelvin-Helmholtz vortices [14].

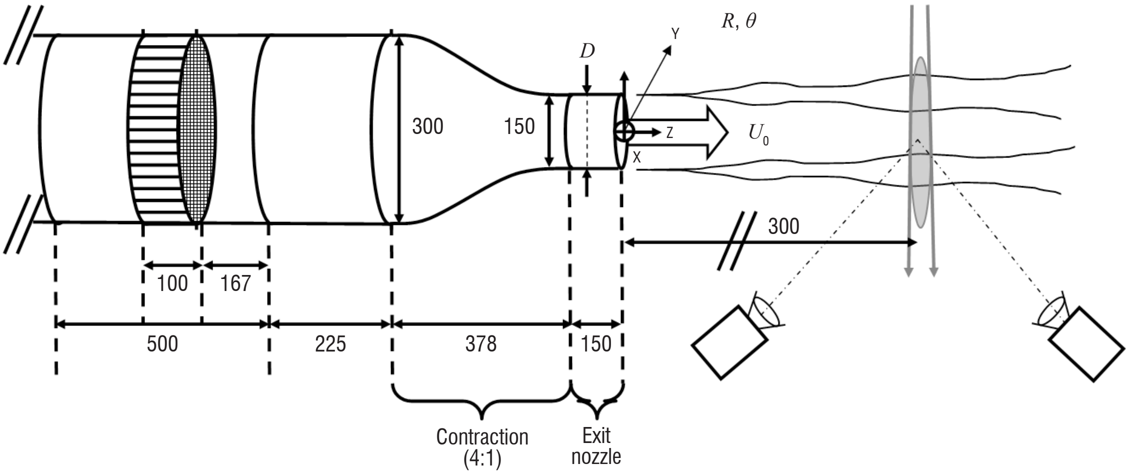


Figure 1 – R4Ch wind-tunnel test section, generated jet and Stereo PIV setup with laser sheet (grey) and cameras.

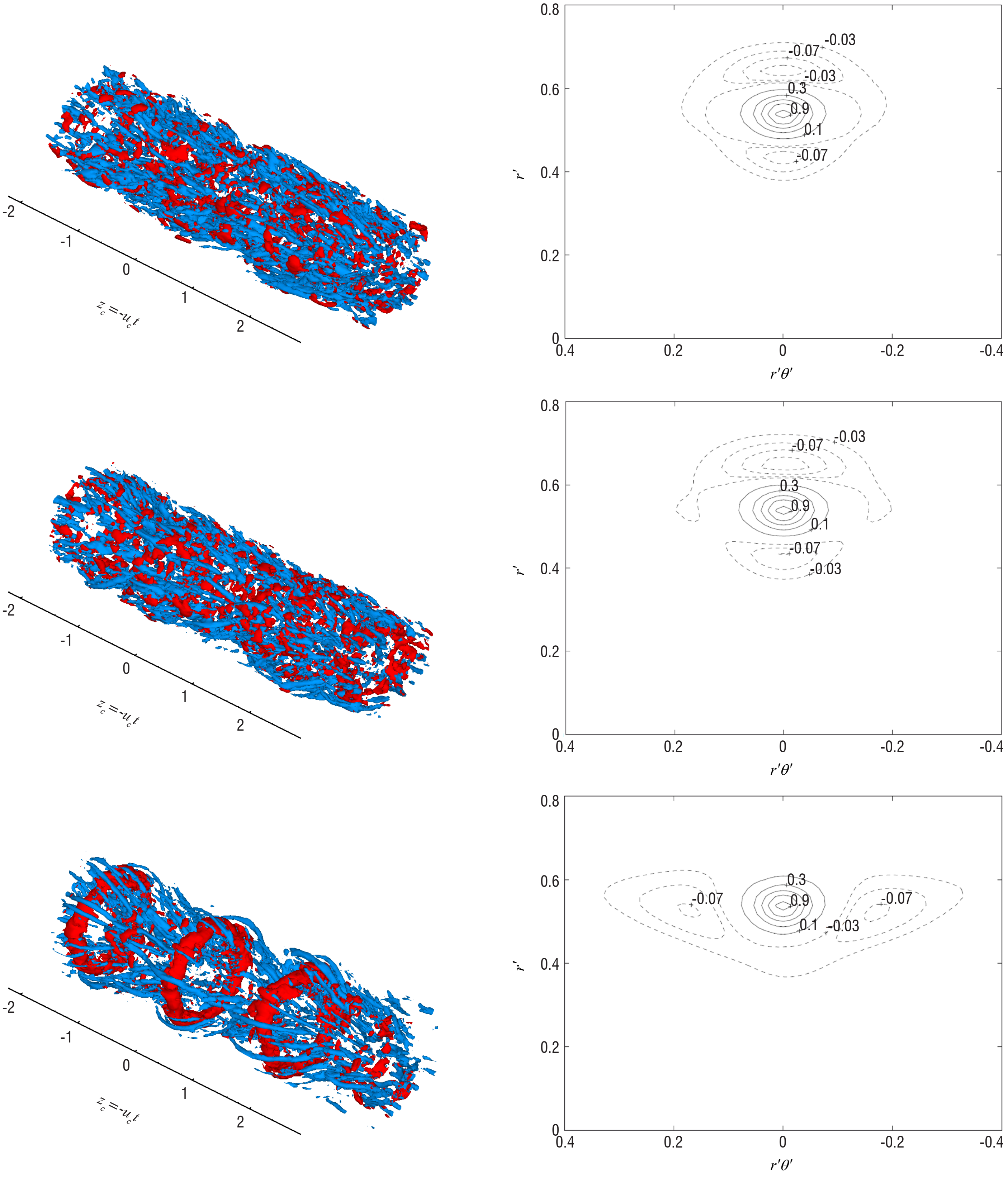


Figure 3 – Jet pseudo-spatial reconstructions (left column) and correlation of the axial vorticity fluctuation taken at reference point $r = 0.52$ (right). Unforced jet (top row), intermediate forcing (medium row), strong forcing (bottom row).

A more in-depth analysis, using spatial auto-correlation of the axial vorticity fluctuation ω_z', helps the statistical spatial structure of the streamwise vortices responsible for mixing to be characterized more finely. The right column of Figure 3 shows iso-contours of this auto-correlation, the sampling point being located in the middle of the shear layer, at a radius $r/D = 0.52$, and distances from that point being denoted by primes. The left column of this figure shows the corresponding pseudo-spatial reconstructions. Three situations are considered: the natural, unforced jet (top row, as in Figure 2), and two intensities of axisymmetric forcing obtained by operating a loud-speaker at the natural jet preferred mode frequency in the wind-tunnel plenum chamber (medium row: medium intensity, and bottom row: high intensity). In the natural situation, one observes that streamwise fluctuating vortices of alternate signs are preferentially piled in the radial direction, which is new and specific to the present Reynolds number [14]. Indeed, past works, on lower Reynolds number jets, have reported piling in the azimuthal direction. As Figure 3 shows, this new spatial organization is robust and strongly linked to the global flow structure. Indeed, it survives a medium level of forcing, as seen in the medium row, and a sufficiently high forcing intensity of the axisymmetric Kelvin-Helmholtz vortices is necessary to retrieve a structure more similar to that of lower Reynolds number flows, as shown in the bottom row. In this case, correlations indeed show negative and positive patches along the azimuthal direction θ', and the pseudo-spatial reconstruction is strongly dominated by Kelvin-Helmholtz vortices (in red).

All of this evidence shows that in sufficiently high Reynolds number jets, streamwise fluctuating vortices and the mixing in general are less influenced by Kelvin-Helmholtz azimuthal vortices than at lower Reynolds numbers. As described in more detail in [14] [15], further pursuing the analysis of flow characterizations and reconstructions offered here by TR Stereo PIV makes it possible to show that the mean shear of the mixing layer plays a larger role, and to propose scenarios for the existence and location of these vortices.

PIV for active flow control: helicopter fuselage drag reduction

The reduction of helicopter parasite drag has become a significant issue as emphasis is placed on speed achievement and on minimizing the impact of the growth of rotorcraft traffic on the environment. The primary source of drag of helicopters is bluff body drag (pressure drag) from pylon/hub/fuselage/landing gear flow separation and interference. Fuselage drag is mainly due to the massive flow separation that occurs at the rear of the fuselage, especially for helicopters with a very pronounced aft loading ramp. A comprehensive experimental investigation of helicopter blunt fuselage drag reduction using active flow control is being carried out within the CleanSky project [18] [19]. The objective is to demonstrate the capability of several active technologies to decrease fuselage drag by alleviating the flow separation occurring in the backdoor area of some helicopters (with pronounced ramp for backdoor loading). The work is performed on a simplified blunt fuselage at model-scale. Several active flow control actuators are considered for evaluation: steady blowing, unsteady blowing (or pulsed jets), and zero-net-mass-flux blowing (or synthetic jets).

The experimental tests of this research program are conducted in the ONERA L1 wind-tunnel located in Lille. This large facility is an Eiffel type wind-tunnel with a return hall. It can reach wind speeds of up to 75 m/s ($Tu \approx 0.3\%$) and its test section is circular with a diameter of 2.4 m. The model is a generic helicopter fuselage (see Figure 4). Its backdoor region is equipped with 8 removable actuators in a U-shape arrangement (see Figure 5). The model is mounted upside down on two struts in the test section, so that the supports do not interfere with the ramp region. Drag, lift and pitching moments are measured, by means of a Monin balance, at various angles of attack. The model is also instrumented with pressure taps and unsteady pressure transducers. In order to complete this usual instrumentation, PIV has been used to obtain quantitative information on the instantaneous and mean topology of the flow around the generic helicopter fuselage.

These PIV investigations have only been focused on the backdoor region of the model and were recorded for different experimental configurations (baseline, with continuous, pulsed and synthetic fluidic actuators). For PIV 2C and 3C measurements, the tracers used are olive oil particles produced by a Multi-Laskin nozzle device located in the return circuit of the wind tunnel. With this seeding system, only a few seconds are necessary to obtain a good and homogeneous concentration of tracers in the test section and, more particularly, in the PIV measurement regions. For illumination of these tracer particles, the light source is a frequency-doubled Nd:YAG laser with two oscillators each supplying two consecutive pulses at 5 Hz frequency with about 400 mJ per pulse. This equipment is located above the test section of the wind tunnel. The light beam emitted by each laser passes through a same set of spherical and cylindrical lenses. It is directed, by means of mirrors, towards the measurement areas, through a window glass located in the roof of the test section. In the laser sheet generator, the angular position of the cylindrical lens allows the measurement plane to be oriented in a direction parallel or perpendicular to the upstream flow. Two high-resolution CCD cameras (2048 x 2048 pixels^2, 12 bits) were used for the recording of PIV images. The frequency of acquisition is limited to 5 double-frames per second. In the pulsed configuration of the actuators, the recording of PIV images is synchronized on

Figure 4 – Simplified blunt fuselage model in the test section of the wind-tunnel

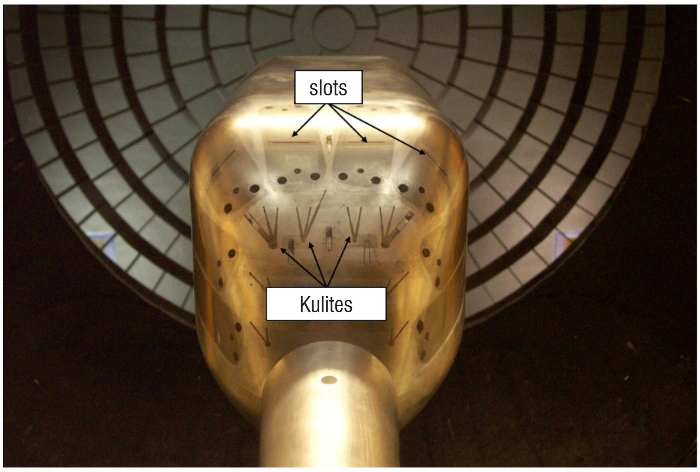


Figure 5 – Removable actuators in the backdoor region of the fuselage.

the command signal of these devices. This synchronization is provided by a programmable sequencer. Under these conditions, all PIV frames of one run are recorded at the same phase chosen in the periodic cycle of actuators. The analysis of all PIV images was carried out by the DaapPIV software developed by the department DAAP. For this evaluation, a local iterative multi-grid cross-correlation algorithm has been applied to all recordings. At the end of this analysis process, the final size of the interrogation windows is 32x32 pixels at a 16-pixel (overlap of 50%) step width in two spatial directions. In the transverse (PIV 3C) and longitudinal (PIV 2C) planes, it corresponds to a spatial resolution, respectively, of 2.4 mm and 1.9 mm.

Figure 6, Figure 7 and Figure 8 present some examples of PIV results obtained on the reference configuration with and without blowing. The streamlines clearly show the topology of flows, the presence of vortices and the effects of the jets on the latter (more information in [18] [19]).

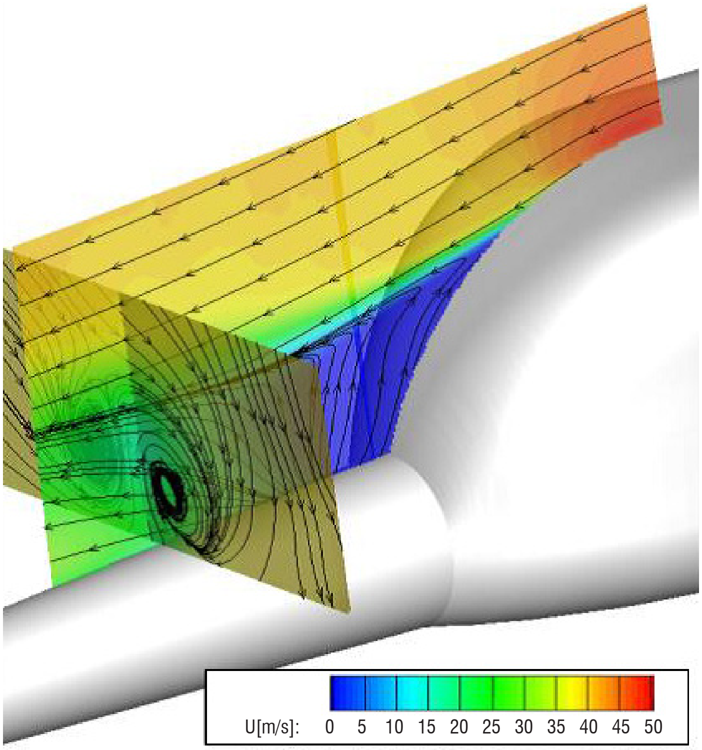


Figure 6 – PIV measurements for $\alpha = +5°$ and baseline (without blowing)

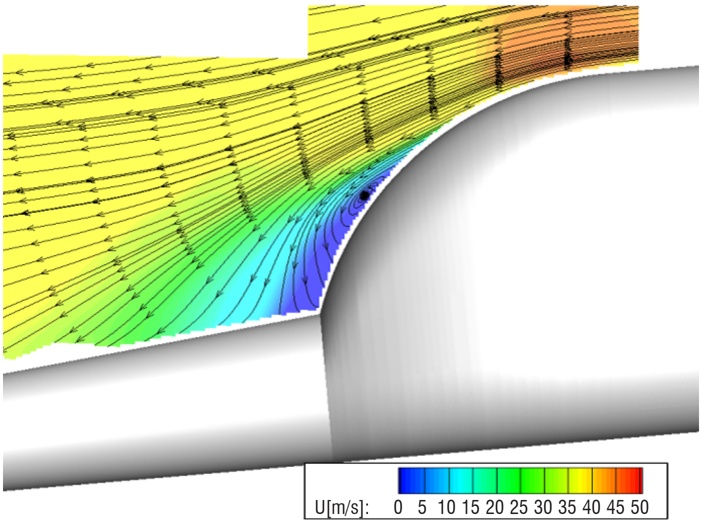


Figure 7 – PIV measurements for $\alpha = -5°$ and baseline (without blowing)

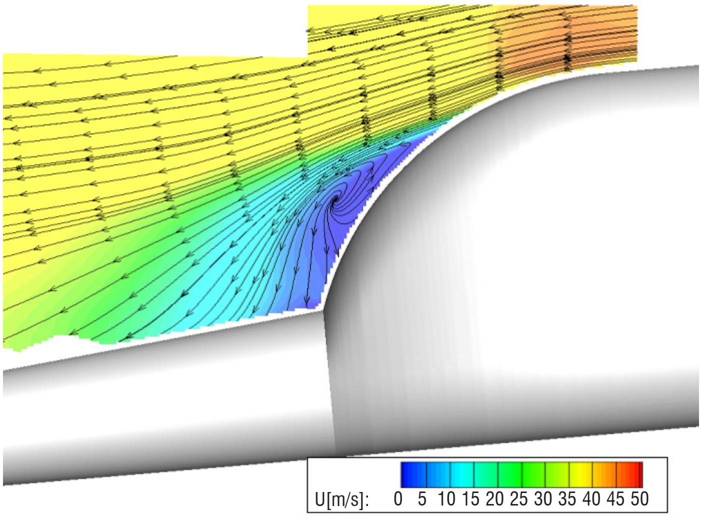


Figure 8 – PIV measurements for $\alpha = -5°$ and blowing

The double topological and unsteady approach accessible by PIV has been a great help in the understanding of the phenomena existing in this type of flow, as well as to evaluate the effectiveness of various fluid actuators studied during the experimental tests [18] [19]. At the present time, major efforts are underway to facilitate the generalization of this measuring technique in the large research facilities of the DAAP and to better meet the demands of its customers.

PIV for the characterization of reacting flows

In combustion experimental studies, the knowledge of the velocity field and its structure is of prime interest, since it plays a key role in the flame stabilization process. Therefore, the development of PIV has allowed significant insight to be gained in reacting flows, with respect to the previously used Laser Doppler Velocimetry (LDV) technique, which provided only a local measurement. PIV has been extensively used in combustion research or development laboratories worldwide. At ONERA, it has also been continuously implemented in air-breathing test facilities located in Palaiseau.

The time development of the research ramjet combustor program conducted at ONERA since the mid-90's illustrates the benefits brought first by the introduction of the PIV technique, and then by the improvement of its technical performance. This research program, supported by the French DGA (*Direction Générale de l'Armement*), was initiated at ONERA with the aim of improving ramjet combustion chamber design and tuning methods by using validated Computational Fluid Dynamics (CFD) codes. A three-dimensional ramjet combustor geometry (combustor model) was specifically defined and built for investigations in hot flow conditions, with combustor operating conditions (pressure, velocity, temperature) comparable to those of real engines. This combustor, a schematic view of which is represented in Figure 9, was designed to be used either as solid-ducted rocket or liquid-fueled ramjet engines.

Experimental investigations of the high-speed flow inside the duct section of the combustor started in 2001, using a 2D-LDV system [20]. However, this required a large number of test runs, in order to be able to reconstruct the mean and fluctuating flow structure through several transverse profiles of the obtained local mean velocities and turbulent correlations, measured at different axial locations along the length of the duct section. Later on, the introduction of the PIV technique allowed, in addition, instantaneous planar flow patterns to be obtained for the first time [21]. An example of the mean flowfield obtained for reacting case conditions is provided in Figure 10a. PIV and LDV data were found to be in good agreement, as shown in Figure 10b. The PIV measurement results then allowed the impact of chemistry description in Large Eddy Simulation (LES) based computations [22] to be studied. However, these first PIV data were obtained with a low repetition rate (3.75 Hz), which did not allow unsteady phenomena to be investigated. This could be done more recently thanks to the development of high-speed or time-resolved PIV systems. PIV was performed at 1,000 Hz and synchronized with visualizations of the OH* chemiluminescence – indicating the location of the reacting zones – at the same repetition rate [23].

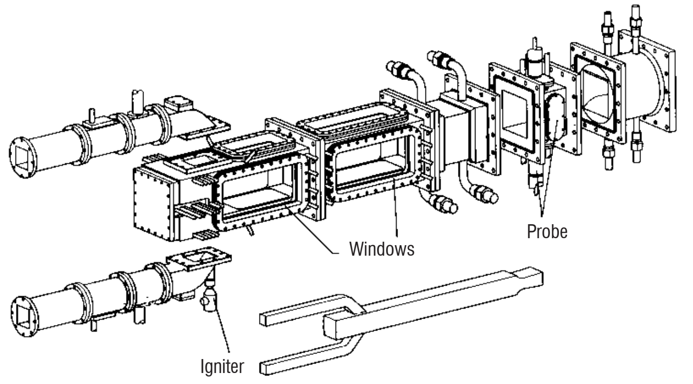
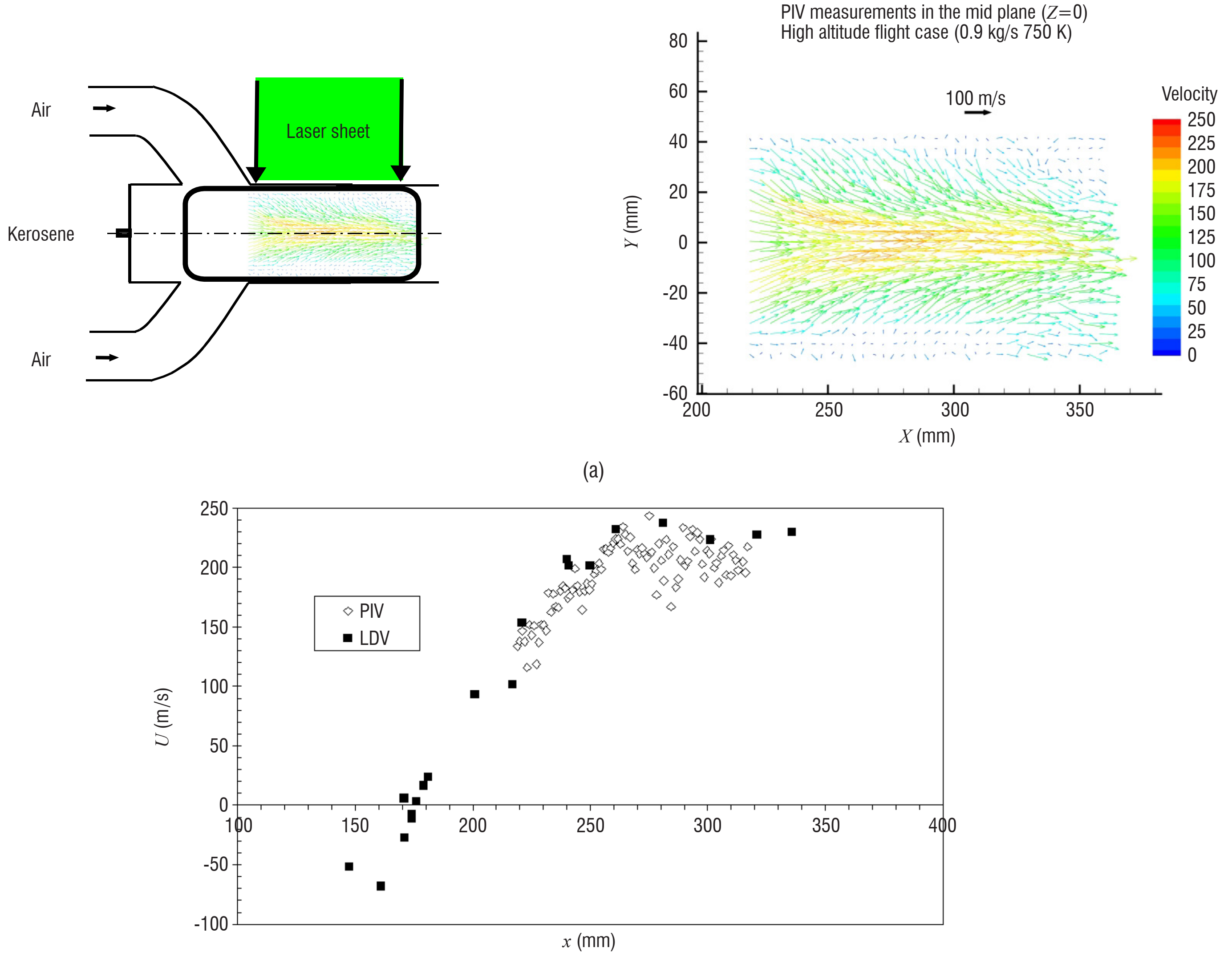


Figure 9 – Schematic view of the research ramjet model [20-21].

Compared to non-reacting flows, the implementation of PIV in reacting flows requires additional technical constraints to be taken into account. The seeding of the flow has to be performed with small (in the micron range) solid particles (usually metal oxides, such as MgO or TiO_2). However, dispersing systems used to generate such



(a)

(b)

Figure 10 – Examples of PIV measurements obtained in the mid-plane of the research ramjet combustor duct section, for a reacting flow case [21]: a) mean flowfield obtained by PIV; b) Comparison with LDV measurements in the axial profile (mean longitudinal velocity component).

particles are prone to unsteady behavior, and precautions must be taken in the operating procedure, in order to limit particle deposits on the windows. Window access on combustion chambers is usually limited due to mechanical and thermal constraints, thus limiting the possibility of using stereoscopic PIV systems. So far, PIV has been conducted in tests with chamber pressure levels limited to 0.2 MPa. The development of a new test rig, named "MICADO", is in progress at the ONERA Palaiseau center (MICADO is a French acronym that stands for "Investigation Means for Air-breathing Combustion using Optical Diagnostics"). This test rig will be dedicated to the study of combustion under test conditions representative of single or multi-sector aeronautical engine combustors, and to the development of the associated advanced diagnostics. The maximum target chamber pressure is 4.0 MPa. One of the main challenges will be to adapt the PIV technique so that it can be used at chamber pressures as high as possible. In particular, beam steering effects are one of the issues that must be addressed. These effects, generated by optical index gradients in the combustion chamber, result in image blurring, and can be very significant in highly turbulent flows at high chamber pressures.

PIV and Stereo PIV in industrial wind-tunnels

Particularities of PIV in industrial wind-tunnels

Over the past years, the PIV technique has started to be used for commercial purposes in large industrial wind-tunnels, at ONERA and elsewhere. This has posed a number of challenges in the progress towards an offer compatible with industry needs. In terms of hardware, the tunnel test-section has a larger size than that needed in most laboratory experiments and offers limited optical access, which requires careful optical adjustments, powerful lasers and suitable seeding techniques. Access to the PIV hardware during the experiment is often difficult and time-consuming due to its out-of-reach position, or pressurization. In addition, the flow often needs to be examined at numerous positions in space. These limitations are progressively overcome by means, for example, of enlarged windows or remote-controlled hardware.

Most of the time, both large and complex flow fields are investigated, which necessitates a compromise to be made between field-of-view and accuracy. Also, depending on the tunnel environment, it may be impossible to position the cameras in the perfect place, to eliminate vibrations and background on the images, to achieve and maintain proper seeding. As a consequence, the flow frequently presents large sub-window movements, zones with small values of the particle displacement, poor particle illumination for at least one camera, and other flaws that can make images challenging to process.

In preparation and during the test campaign, time and cost constraints are significant and a high level of productivity is expected for both the setup and the image acquisition and processing. Last but not least, staff training is crucial to transfer the know-how from highly skilled PIV researchers to people in the wind tunnel performing the measurements.

Examples of 2 recent uses

High-accuracy Clinometric PIV in the F1 pressurized wind-tunnel

The F1 wind tunnel is a low-speed, continuous-flow, pressurized wind tunnel, with a test section 3.5 m high, 4.5 m wide, and 11 m long. It is used by a large number of customers from all over the world for testing aircraft in landing and take-off configurations, as well as for research activities.

Several measurement campaigns have been carried out with PIV, in order to refine our knowledge of the flow angularity (upwash and sidewash) in the empty test section of the F1 wind-tunnel. An original approach, reported in [24], was used to achieve an angle accuracy estimated at ±0.05° and a speed accuracy estimated at ±0.1%. Results have been obtained with various different PIV setups (both 2-component and 3-component) and compared to the techniques historically used to assess angularity and flow speed, i.e., 5-hole, Pitot probing and the model inversion method.

As shown in Figure 11, measurements have confirmed the existence of a moderate upwash of about 0.16° in the test section. For this application, PIV demonstrated important advantages over historical methods: non-intrusiveness, high spatial density of measurements and applicability close to the floor. Measurement provided an unprecedentedly detailed description of non-uniformities in the wind tunnel flow, especially near the floor, therefore securing and improving corrections brought to wind tunnel measurements.

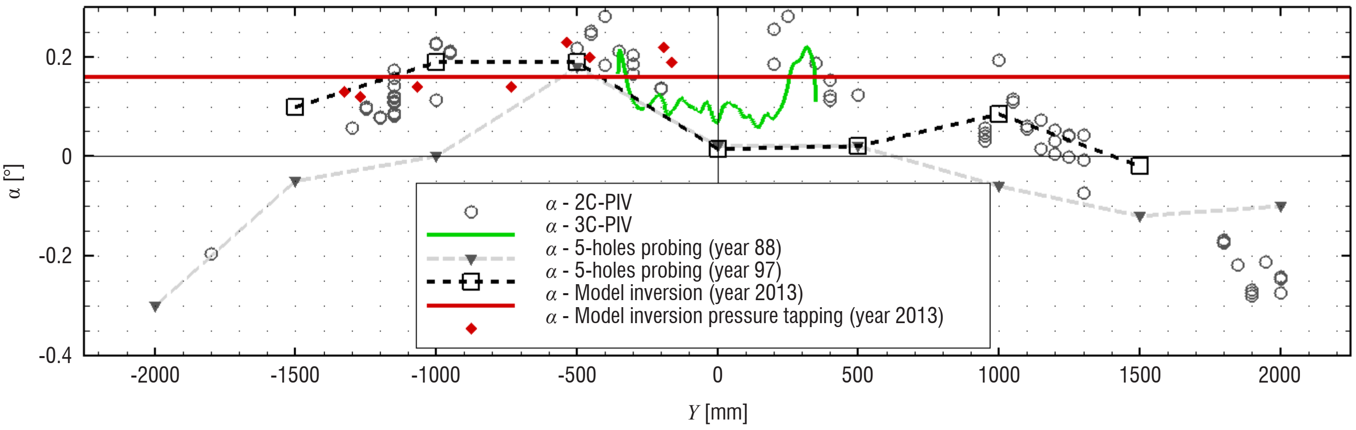


Figure 11 – Distribution of upwash along the spanwise direction at the center of the test section

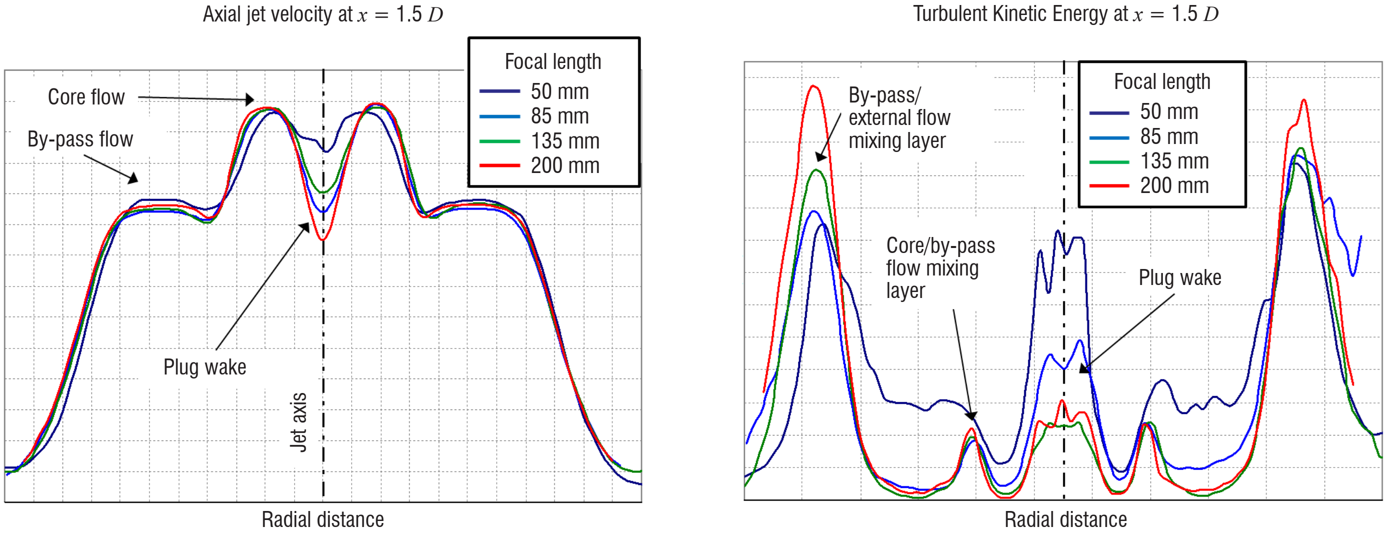


Figure 12 – Radial distribution of mean velocity (left) and TKE (right) in the jet flow. The size of the interrogation windows in pixels is kept the same between different focal lengths

Jet flow characterization in the CEPRA 19 anechoic wind tunnel

CEPRA19 is a large-scale, open-jet, anechoic wind tunnel particularly suitable for aeroacoustic studies of modern dual-stream, high-bypass-ratio engine jets. Besides classical aerodynamic and acoustic measurement, PIV measurements have been carried out several times to characterize jet flows [25]. Beyond the distribution of the mean flow, it is interesting in acoustics to know the intensity of velocity fluctuations because they are strongly related to the generation of noise. To serve that purpose, a recent campaign was performed to improve the measurement accuracy of the TKE (Turbulent Kinetic Energy) [26].

As an example of the results of these investigations, a comparison of measurements with increasing focal length for camera objectives (hence increasing the spatial resolution) is presented in Figure 12. It can be seen that the mean axial jet velocity is easily captured in almost all cases. On the contrary, properly measuring the TKE is more challenging and only the larger focal lengths provide valuable results. This kind of measurement is highly interesting to validate unsteady flow simulations and to understand the physical mechanisms behind the noise reduction offered by nozzle devices such as chevrons or micro-jets.

Future needs

Industrial applications of PIV will naturally benefit from the probable continuation of the increase in computing power and camera resolution, but there are also some more specific needs. An immediate need is to better quantify the uncertainty of the PIV measurement. Considering the discrepancy between and across images (due both to flow features and to the imaging technique), a local uncertainty assessment is desirable. Generalization of remote-controlled hardware, possibly automated, is also desirable to reduce the time to set up the hardware and to be able to make adjustments at the tunnel startup or during the run (e.g., to correct deviations of the laser beam trajectory). Adaptation of wind-tunnels should be continued, in order to foster easier preparation of the tests. Interesting flow features can be found close to the model surface, but it is often difficult to perform reliable measurements in this area, because of laser reflection (despite the care taken to paint the model), model movements, the extreme close-ups demanded due to cameras being located far away, and optical access in a concealed area. Any progress in this direction would be welcome. Finally, in order to gain attractivity, a more elaborate outcome of the PIV measurements than velocity mapping should be sought. Examples include drag and lift analysis performed from wake surveys, or aeroacoustic applications.

TR-PIV for the measurement of acoustic velocities in a turbulent duct flow

Context

The development of non-intrusive measurement techniques for in-flow acoustic pressure and velocity estimations is necessary to better characterize and analyze the response of aeroacoustic surface treatments, such as acoustic liners. Over the past decades, several optical methods have been proposed [27]. Particularly, Minotti *et al.* [28] successfully developed at ONERA an approach based on Laser Doppler Velocimetry (LDV) allowing the extraction of both acoustic and turbulent flow velocities. Assuming no correlation between flow turbulence and acoustic perturbations, their approach was based on an estimation of the acoustic velocity components through spectral cross-correlations between the measured velocity signals and an unsteady pressure measurement performed on the wall of the duct in which multi-sine acoustic waves are generated. Other methods based on Doppler Global Velocimetry were later proposed [29], but with very limited spatial resolutions. In the literature, the use of PIV for similar purposes mainly relies on using phase-averaging approaches [30] [31], which is a non-trivial task when dealing with multi-sine acoustic waves. The present work demonstrates the applicability of the method developed by Minotti *et al.* [28] to the measurement of acoustic velocities in highly turbulent duct flows using TR-PIV.

Experimental Setup

In order to validate the TR-PIV acoustic velocity measurement approach proposed, a simple test case was selected. Measurements were performed with the ONERA aero-thermo-acoustics bench (B2A) in Toulouse. A schematic view of the bench is provided in Figure 13, the test cell having a square section of 50 mm x 50 mm. The bulk Mach number was set to Mb = 0.1 and the flow temperature was regulated at T = 20 °C. A simple acoustic plane wave was prescribed upstream at a frequency fac = 800 Hz and at various sound pressure levels above 130 dB. TR-PIV measurements were performed at a frequency of 3 kHz in the horizontal plane (xy) located in the middle of the test section. Turbulent intensities of about 5% were observed in the measurement window, leading to a signal-to-noise ratio of -12 dB for an acoustic wave at a sound pressure level of 138dB (results presented in Figure 14). For validation and comparison purposes, LDV measurements were performed under the same conditions on the test cell centerline.

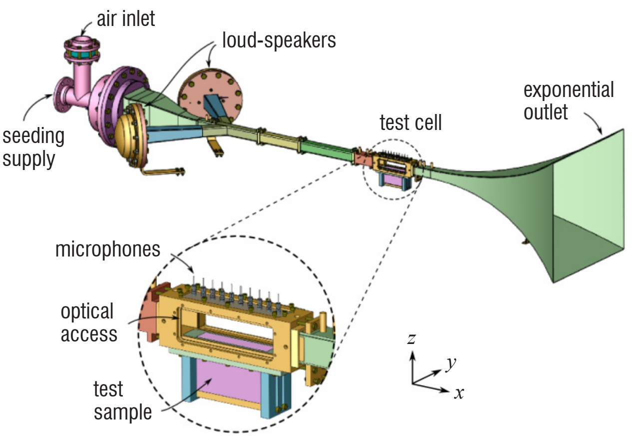
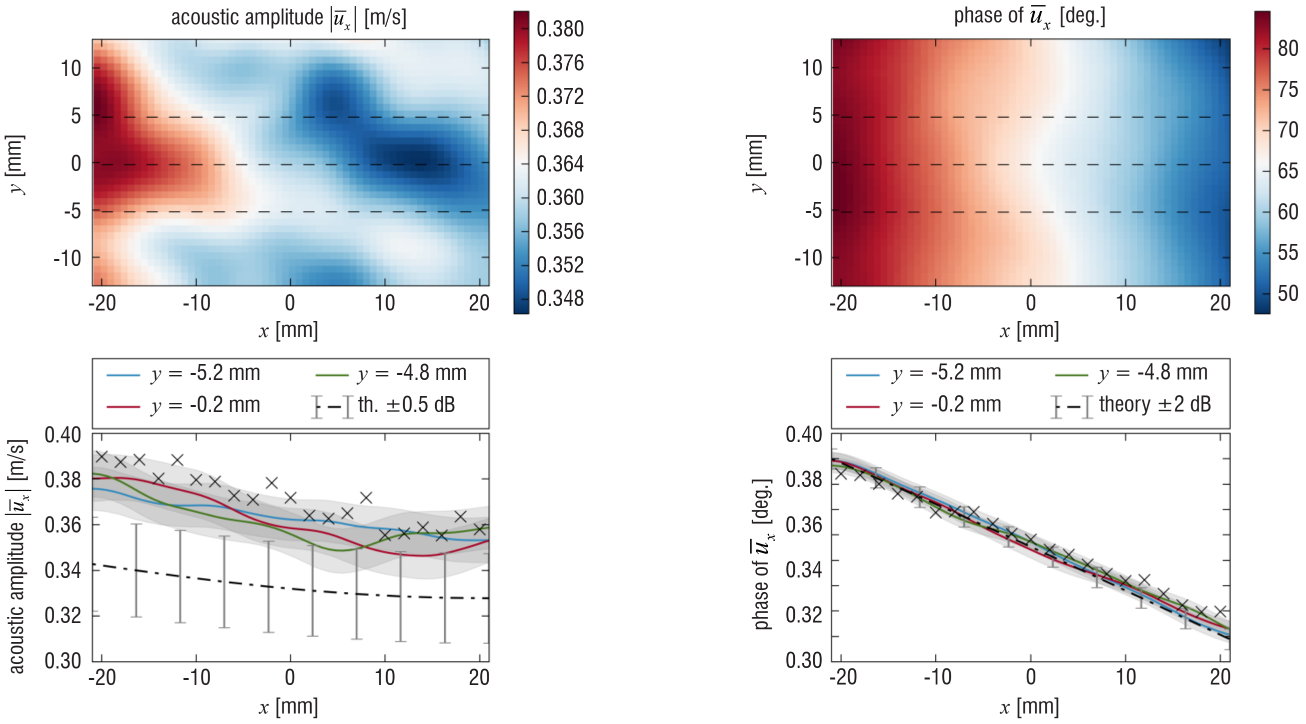


Figure 13 – Diagram of the aero-thermo-acoustic bench (B2A) used for experimental liner investigations.

Results

The results of both the TR-PIV and LDV campaigns were post-processed using the turbulence rejection method previously mentioned [28]: acoustic amplitudes and phases with respect to a reference signal, here the loud-speaker input, are evaluated using cross-power spectra estimates. For TR-PIV measurements, 30,000 pairs of images were acquired for every test condition, with a 1 Mpx camera. Such a large number of samples is necessary to provide accurate estimates, given the signal-to-noise ratios at play. Post-processing of TR-PIV measurements was performed on GPU using the FOLKI-SPIV software [16]. A comparison between the acoustic amplitude and phase estimations obtained using the two measurement techniques on the test case L = 138 dB is provided in Figure 14. As observed, an excellent agreement is obtained for both quantities, with satisfactory statistical confidence intervals.

From these results, it appears that TR-PIV measurements can provide valuable estimates of the acoustic velocity components, which can then be complementary to LDV measurements. Indeed, the latter are not as restricted in terms of acquisition frequencies, but are time-consuming when a fine spatial resolution is required. Further developments on the TR-PIV approach will address near-wall measurements and sound pressure levels lower than 130 dB.



(a)

(b)

Figure 14 – Maps of acoustic (a) amplitude and (b) phase estimations yielded by TR-PIV measurements for an acoustic wave of 138 dB; comparisons with the corresponding estimations yielded by LDV (cross symbols) and the theoretical results obtained using a simple model considering plane waves in a uniform flow (dash-dot lines with 1 dB error bars) are provided in the bottom plots.

Conclusion

In this paper, examples selected from various applications studied at ONERA have been presented, in order to highlight the role played by planar PIV in aerospace research. In these studies, two-component, Stereo PIV and Time-Resolved PIV have been applied to gain better understanding of jet mixing physics, assess the efficiency of actuators to reduce helicopter fuselage drag, characterize the flow structure in a ramjet combustor, provide a precise characterization of flows in industrial wind tunnels and, finally, extract acoustic velocities from turbulent flows. In all of these applications, it is the wealth of spatial and, in the case of TR-PIV, temporal information that has been determinant in obtaining the results and contributing supplementary knowledge to the field.

Most of the results above have been obtained using well-validated approaches, which can be considered as traditional nowadays. PIV, TR-PIV and 3D PIV processing algorithms are still a very active field of research, with substantial effort being directed at estimating the measurement uncertainty, and extracting indirect and/or difficult quantities from the measurements, such as pressure fields and forces exerted on bodies, for instance. Since these constant developments contribute to enriching the trust placed in the measurement, as well as the spectrum of its capabilities, there is no doubt that the use of PIV in wind tunnels will continue to develop strongly in the next years, confirming its place as a major contributor to aerospace research ■

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Acronyms

PIV	(Particle Image Velocimetry)
IW	(Interrogation Window)
LDV	(Laser Doppler Velocimetry)
TR-PIV	(Time-Resolved Particle Image Velocimetry)
TKE	(Turbulent Kinetic Energy)
CFD	(Computational Fluid Dynamics)

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