PIV in the Car Industry: State-of-the-Art and Future Perspectives

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Abstract. This contribution provides an overview on the applicability of particle image velocimetry (PIV) in an industrial environment as a full-scale automotive wind tunnel and its potentiality in this specific field. Experiences developed in the last nine years in the Pininfarina Wind Tunnel are summarized here. Emphasis is placed on the experimental aspects and the specific problems and unique solutions adopted in this specific field.

1 Introduction

Aerodynamics and aeroacoustics are two highly relevant aspects of car development, since they are directly linked to passengers' safety and comfort and to car fuel consumption. A detailed knowledge of both time-averaged and time-resolved flow structures is required to answer questions posed by aerodynamic and aeroacoustic issues. Furthermore, Computational Fluid Dynamics (CFD) in the automotive field is extending its importance even in unsteady simulations, but it requires validation with experimental measurements.

All these aspects and the growing need to shorten the car development time suggest the use of PIV as a useful experimental technique in automotive wind tunnels. See [1] for further details and references about PIV.

2 PIV in the Car Industry: Requirements

In a full-scale automotive wind tunnel, multihole pressure probes and hot wires are traditionally used to investigate the properties of the flow field around the car body. Even if these probes are extremely accurate, their main drawback is that they are often not able to measure all the three velocity components simultaneously and, furthermore, they are basically point-by-point measurement devices. They can be used to measure extended areas of the flow field with the time-consuming flying-probe technique, by mounting them on a traversing gear, see [2]. In principle, stereoscopic particle image velocimetry is able to overcome these issues, nonetheless, it has to deliver overall better performance and more information than other conventional

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measurement techniques. In order to achieve this result, PIV has to satisfy some operational and performance requirements that usually are in conflict with each other. A PIV system in a full-scale automotive wind tunnel has to measure the three velocity components over large areas of the flow field (typically the order of magnitude is about $1\,\mathrm{m}^2$). The flow field around a vehicle involves wide areas and three-dimensional structures of different scale magnitudes, as wakes and vortices, which are usually responsible for a large amount of energy loss. Therefore, the spatial resolution also has to be quite high, of the order of few millimeters. Moreover, the flow-field structures are usually present in areas with problematic optical access around the vehicle body. Therefore, the PIV system has to be compact and light to be mounted on a traversing system in order to ease the investigation of these areas. While waiting for some technical improvements, a compromise among these issues is currently necessary.

The use of the PIV technique in full-scale automotive wind tunnels is strongly conditioned by the industrial environment itself. In such a facility, the economical and safety aspects are prevalent. For these reasons, the PIV system has to be easy and fast to setup. It is better to have the possibility to do an "offline" calibration outside the wind tunnel test section and, once in the wind tunnel, to measure many areas around the car body, changing as little as possible the system's configuration.

High operational costs of wind tunnels and more and more restricted car time development need fast measurements and fast postprocessing techniques. The improving of computer hardware, with larger memories and faster processors, is moving to the right direction, but the overall performance is still slow for the car industry that requires results "in real time".

All the devices necessary for the measurements have to be motorized and remotely controlled by an operator staying outside the test section, mainly for safety and operational reasons. During the measurement process, the test section has to be completely inaccessible and its windows covered by laser screens.

Laser reflections can give problems not only from a safety point of view but also for image-acquisition reasons. The treatment of this problem will not be addressed in this chapter. Nonetheless, it can be noticed that any successful technique adopted to solve this issue should take into account the size of full-scale tested cars and the peculiarities of industrial environment where people need to work in the wind tunnel test section with no risk to their safety.

The distribution of the PIV tracer particles can be a challenging task too. Sometimes, it is difficult to have a good and homogeneous particle distribution inside a large industrial environment, such as a full-scale automotive wind tunnel, but it is a necessary condition in order to obtain an optimal evaluation of the flow field. Obviously the adopted tracer particles have to be nontoxic, small to better follow the flow but big enough to be detected from a long distance between the observed large area and the recording cameras.

In the Pininfarina Wind Tunnel, olive-oil droplets are injected at the inlet of the contraction area.

3 PIV in the Pininfarina Wind Tunnel

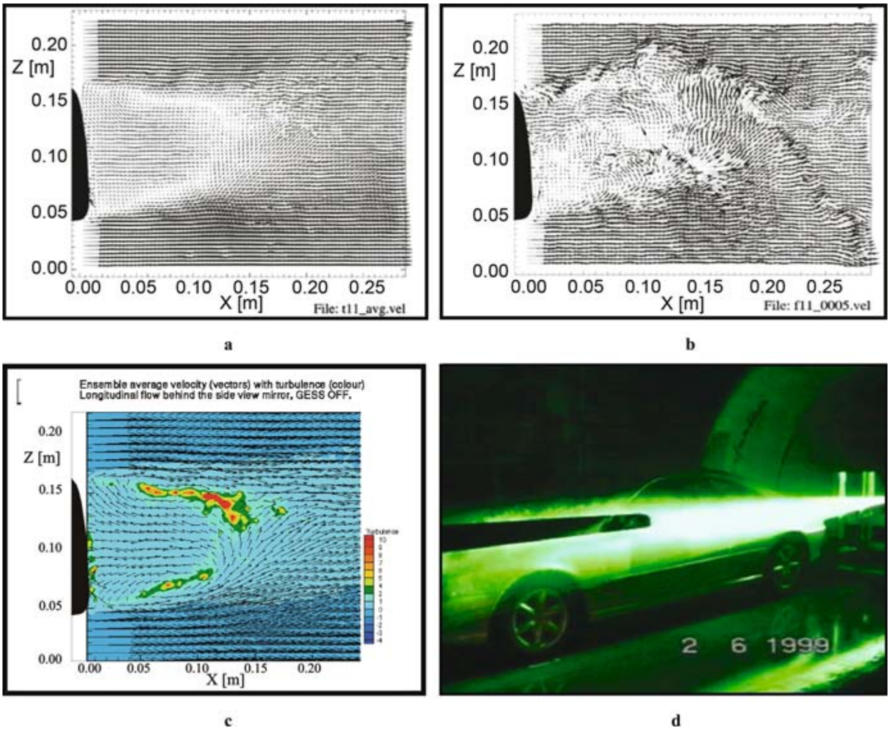
In 1997 Pininfarina became a partner of the PivNet1 Framework as the task manager for the car industry, with the aim of developing the PIV technique in a full-scale automotive wind tunnel. In 1999 Pininfarina, in cooperation with CIRA, hosted a workshop and a demonstration to check the possibility of performing PIV measurements in a full-scale automotive wind tunnel. The demonstration consisted of measuring a longitudinal wake behind a rear view mirror. It was successful, even though the measurements were only two-dimensional and the measurement area was limited to $0.25 \times 0.25\,\mathrm{m}^2$. The instrumentation used was quite bulky, nevertheless, it was confirmed that the PIV measurements were feasible in a complex industrial environment such as a full-scale automotive wind tunnel. See [3] for further details.

In 2000, given the PivNet1 experience and the foreseeable progresses in technology, the Pininfarina Aerodynamics and Aeroacoustics Research Center conceived a 3D-PIV system as a single and compact probe where laser and cameras are enclosed in a unique frame. The Pininfarina 3D-PIV probe was built in the 2001–2005 time frame and was presented at the PivNet2 Workshop held in Pininfarina in November 2005, [4–8]. This workshop marked the line between feasibility and operation of PIV in the car industry on full-scale automotive testing. It has been shown that PIV is now an advanced measuring technique that can be successfully used in the car-development process.

The main topic of interest of the PivNet2 Pininfarina Workshop was to establish a link between the aerodynamic flow field and the aeroacoustic sources of vehicles. These are subjects where theoretical investigation is still relevant and PIV measurements can provide useful data and information about the flow field where noise sources are present. In order to check the possibility to achieve results about the described tasks, a demonstration has been shown. A longitudinal wake behind a rear-view mirror has been measured by the Pininfarina 3D-PIV probe and by 2D time-resolved PIV (see [9]), while the external aeroacoustic noise sources have been measured by the Pininfarina 66-microphone array. Although some qualitative and quantitative results have been shown, at present, fundamental research is very much needed to establish a more solid link between PIV measurements and acoustic-sources identification, [10, 11].

3.1 The PF 3D PIV Probe

Pininfarina Aerodynamics and Aeroacoustics Research Center developed a compact stereoscopic PIV probe composed of two CCD cameras and a pulsed



a b

c d

Fig. 1. Longitudinal wake behind a car rear-view mirror measured during the PivNet1 Pininfarina Workshop; (**a**) mean velocity field; (**b**) instantaneous velocity field; (**c**) turbulence flow field; (**d**) measurement setup

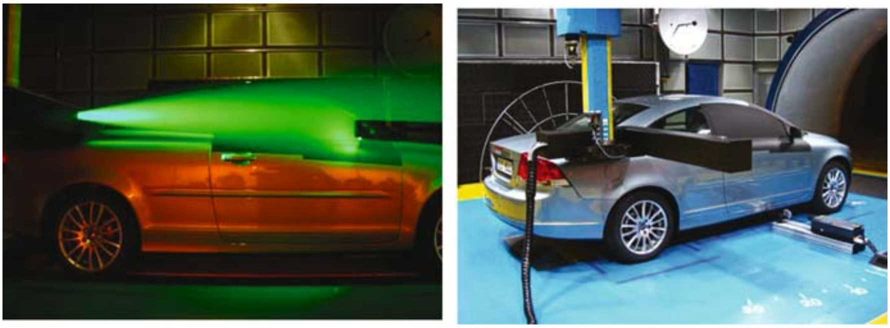


Fig. 2. Demonstration during the PiVNet2 Workshop held in Pininfarina in November 2005

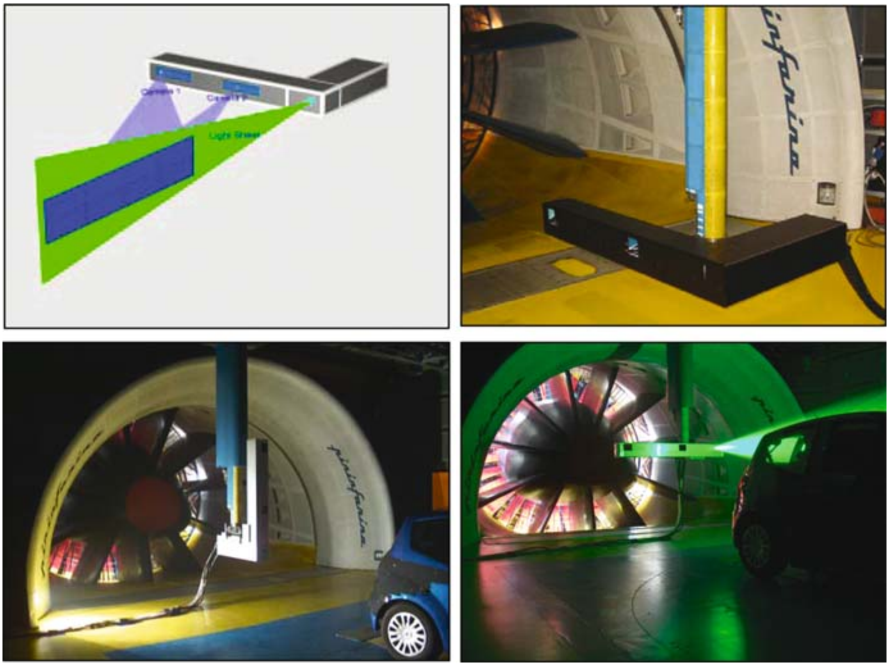


Fig. 3. The Pininfarina 3D-PIV Probe

Nd:YAG laser installed inside a unique aluminum L-shaped frame. All the hardware instrumentation installed in the probe, like Scheimpflug camera angle, focus, aperture and mirrors, is motorized and remotely controlled, while the camera signal is linked by fiber-optic cables to the computer frame grabbers.

Such a system is able to measure the three velocity components of the flow and can be easily and quickly mounted on the main traversing system of the wind tunnel, already present in the test section, in order to investigate different measurement planes around the body, even in areas with problematic access. One of the main advantages of such an arrangement is that the camera angles do not change while moving or rotating the probe with the traversing system. Therefore, only one offline calibration, performed outside the wind tunnel, is required, with a considerable saving of time.

In Fig. 3, the L-shaped Pininfarina 3D-PIV Probe is shown, while its technical data are summarized in Table 1.

3.2 PIV Application: Rear Wake

A typical application of 3D-PIV in a full-scale automotive wind tunnel is the measurement of the flow field of the rear wake of a vehicle. In the experi-

Table 1. PF-3D PIV probe technical data

Probe dimensions (m)	0.8 × 1.45 (L-shaped)
Probe weight (kg)	50
Camera angles to the normal of the light sheet plane (deg)	50 and 70
Max laser energy (mJ)	2 × 200
Laser umbilical length (m)	10
Cameras resolution (pixels)	2 k × 2 k
Camera frame rate (fps)	16
Seeding type	Olive-oil droplets

Fig. 4. Experimental setup to measure the three velocity components of the flow in the near-wake region of a test car in the Pininfarina full-scale automotive wind tunnel. The Pininfarina probe is mounted on the main traversing system. The image of the laser lightsheet is shown for the sake of clarity

ment hereafter presented, the car was mounted in the Pininfarina full-scale wind tunnel on the struts and the tests performed with the Ground Effect Simulation System, see Fig. 4.

The PIV system was mounted on the main traversing system, aligned in order to be at 0.1 m downstream of the vehicle (near-wake), and with the center of the acquisition plane at $Y = -0.5\,\mathrm{m}$ and $Z = 0.5\,\mathrm{m}$ (wind tunnel standard coordinates). The seeding distribution system was located at the wind-tunnel contraction inlet on a traversing system in order to properly optimize the seeding density with respect to the measurement plane.

The calibration was performed offline, before mounting the probe to the traversing system. This is possible since the angles between the cameras and the laser lightsheet remain fixed. The calibration surface was subsequently optimized with the acquired images of the seeding particles.

All the measurements were performed at $V_\mathrm{W} = 100\,\mathrm{km/h}$, with full simulation of ground effect, i.e., spinning wheels, running belts and tangential blowing. In order to avoid laser-light reflections both the wind tunnel and the tested car were properly treated. 640 images were grabbed at a sustained sampling frequency of 7.5 Hz (sampling time about 85 s) and $\Delta t = 30\,\mu\mathrm{s}$.

Standard recursive analysis of interrogation windows was performed, with a final interrogation window size of 32 × 32 pixels. The corresponding spatial resolution is 7.5 mm. The 3D final vectors have been validated with a median and standard-deviation filter.

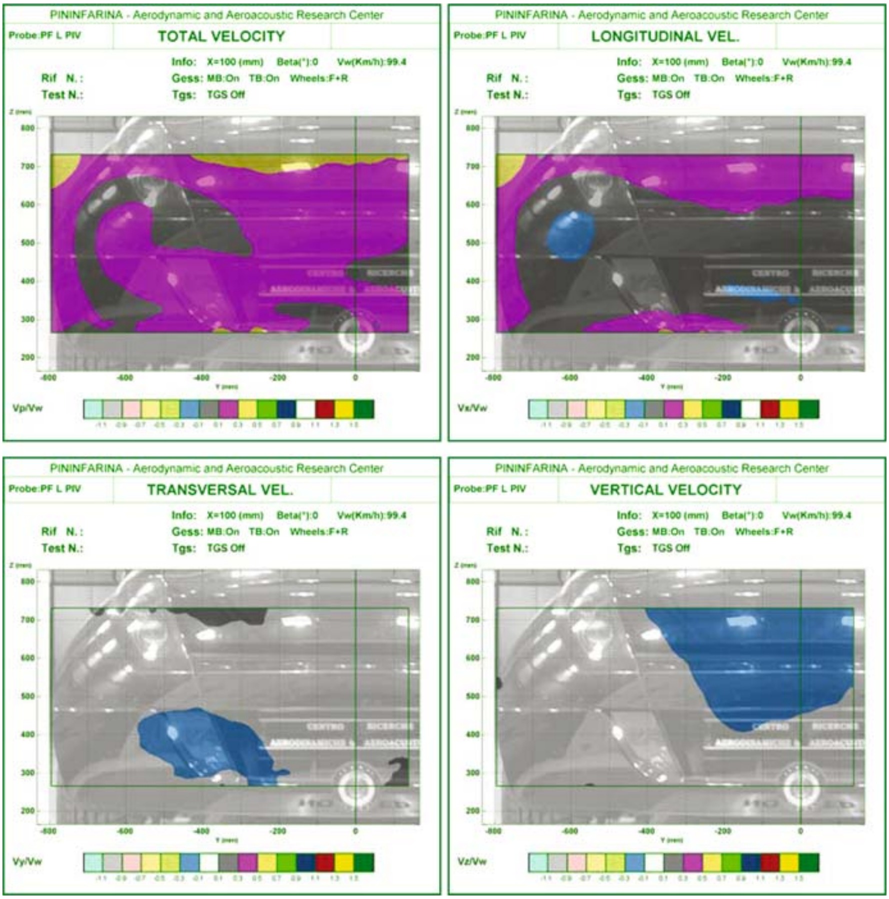


Fig. 5. Velocity maps of the near-wake of test car in the Pininfarina full-scale automotive wind tunnel. The velocities have been normalized to the free-stream velocity, $V_{\mathrm{W}} = 100\,\mathrm{km/h}$. Measurement area is about $0.9 \times 0.45\,\mathrm{m}$

In Fig. 5 the maps for mean total velocity and the corresponding three components are shown.

The measurement area is about $0.9 \times 0.45\,\mathrm{m}$. With a single measurement run, it is indeed possible to measure a meaningful portion of the rear wake. In order to fully cover the rear wake it would have been necessary to repeat the measurement process with the probe properly centered along different positions. This kind of patchwork could be easily performed with the traversing system without even stopping the wind tunnel.

As expected, in the maps in Fig. 5 it is possible to observe a deficit of velocity in the explored portion of the wake of the vehicle. In the longitudinal velocity map some areas of reverse flow are even noticeable. In the vertical

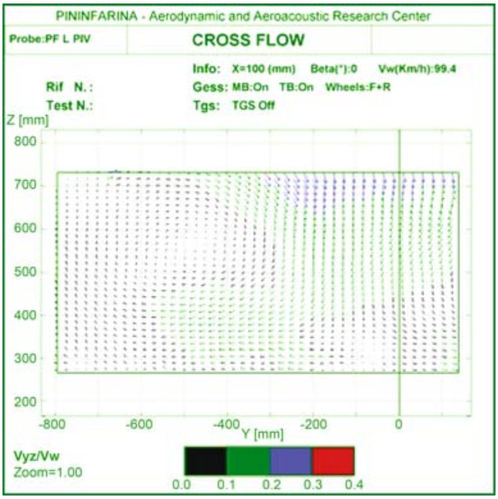


Fig. 6. Crossflow velocity map of the near wake of a test car in the Pininfarina full-scale automotive wind tunnel. A downwash vortex is located at about $Y = -0.5\,\mathrm{m}$ and $Z = 0.55\,\mathrm{m}$

velocity map, an extended region of negative velocity is manifest, showing the typical behavior of the near-wake region.

In Fig. 6 the crossflow map shows the presence of a downwash vortex characteristically shed by passenger cars.

In Fig. 7 the normalized transversal velocity V_{Y}, is plotted at constant height over ground along three lines immediately below, at the center and above the vortex core. It can be noticed that at the vortex core height the transversal velocity changes its direction, as expected.

The measurement of the flow field of the rear wake is only one of the possible applications of stereoscopic PIV in a full-scale automotive wind tunnel. In Figs. 8–11 some other examples are shown.

Another important application consists in adopting PIV measurements to investigate the flow characteristics of the wind-tunnel test section. The Turbulence Generation System (TGS) is a device able to simulate road conditions where the flow upstream of the tested car is conditioned by ambient wind, the wake generated by another car or continuous yawing of the flowCL [12, 13]. The Pininfarina 3D-PIV probe has been successfully used to characterize the turbulent flow produced by the different TGS configurations, see Fig. 12. For further details see [14].

4 Conclusions and Future Perspectives

PIV could be a useful, nonintrusive technique for aerodynamic and aeroacoustic car development. It provides the chance to get more information about the whole flow field around the vehicle, measuring in large areas both time-averaged and time-resolved phenomena.

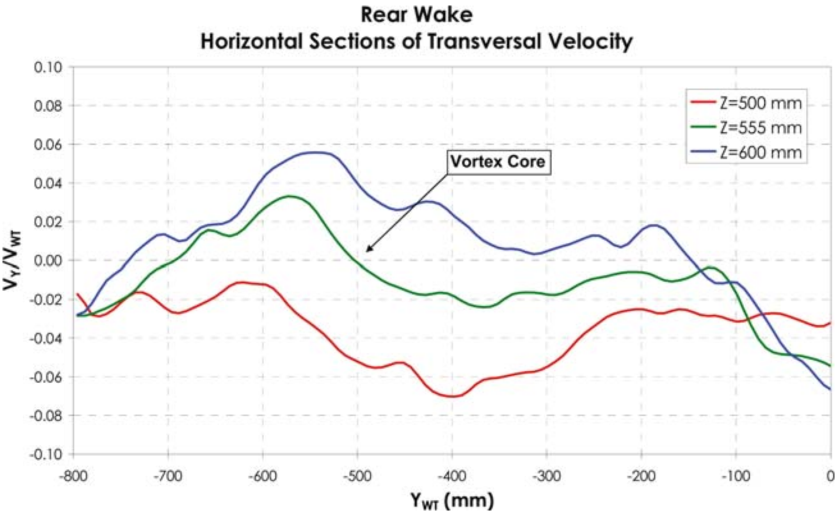


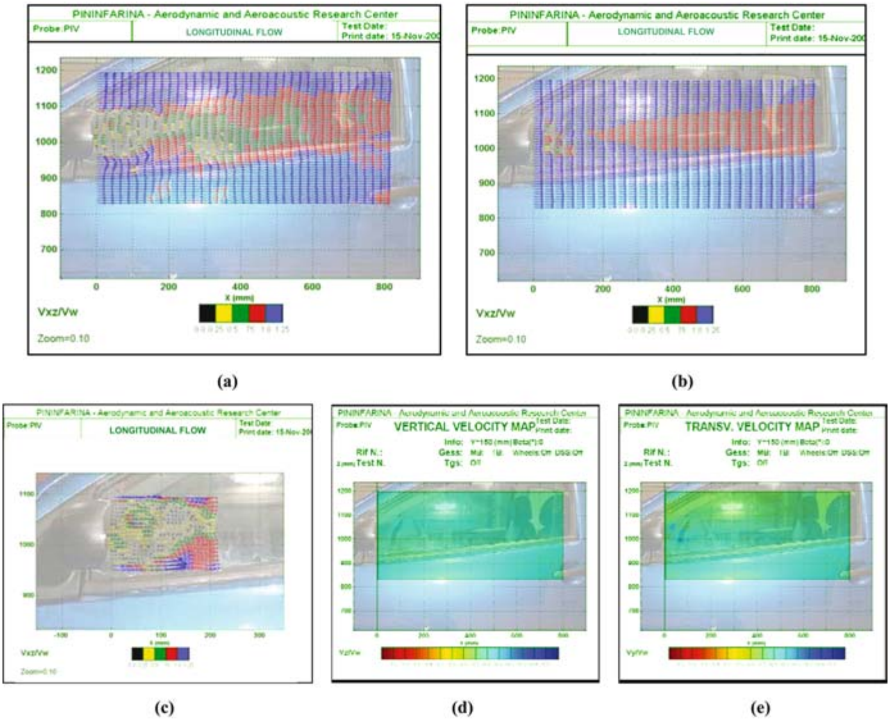
Fig. 7. Normalized mean transversal velocity at three different heights over ground. The vortex core is located at $Y = -0.5\,\text{m}$ and $Z = 0.55\,\text{m}$

However, at present, the adoption of PIV in the automotive car industry is still very limited to a few early adopters, mainly working on scale models. A full-scale automotive wind tunnel is still a challenge for PIV measurements. Typical issues involve the large-area field of view, the spatial resolution and optical accessibility of some measurement areas. Besides, given the cost of such industrial facilities, measurements and results have to be reached in a very short time, despite the mentioned difficulties.

The Pininfarina Aerodynamics and Aeroacoustics Center conceived its 3D-PIV probe in order to solve some of these issues and currently such a PIV system is one of the most advanced in the car industry field. Measurements performed by Pininfarina have been shown in this chapter. PIV is still a complex technique that needs skills and expertise not easily found in the industry. From the technological standpoint the PIV industrial application requires a "plug and play" PIV system and, in order to achieve this target, some improvements are still necessary in all the PIV aspects: hardware, calibration, acquisition and postprocessing techniques.

Hardware progresses are necessary mainly for the application of Time-Resolved PIV (TR PIV). High-frequency measurements are very useful in automotive wind tunnels in order to study fluctuant quantities of the flow field around the car body, but to achieve this task, TR PIV has to be able to measure the three velocity components over large areas.

A very useful tool for aerodynamic and aeroacoustic studies on car development can be given by the interaction of numerical simulation and PIV experimental measurements, especially about the investigation of turbulent and instantaneous flow field. Currently, a fair level of agreement has been



(a) (b)

(c) (d) (e)

Fig. 8. Longitudinal wake behind a car rear-view mirror. Plane XZ (in wind-tunnel coordinate system) and $Y = -0.15\,\mathrm{m}$ from the left-side window: (**a**) Instantaneous velocity field; (**b**) mean velocity field; (**c**) detail of instantaneous velocity field; (**d**) vertical velocity field; (**e**) transversal velocity field. All velocities are normalized to the free-stream velocity

found between these two types of methods and PIV is often used to validate CFD results. In the future, a stronger link is needed with even more complex domain and geometry to gain enhanced knowledge about turbulent and unsteady phenomena, as is more and more required in the automotive field.

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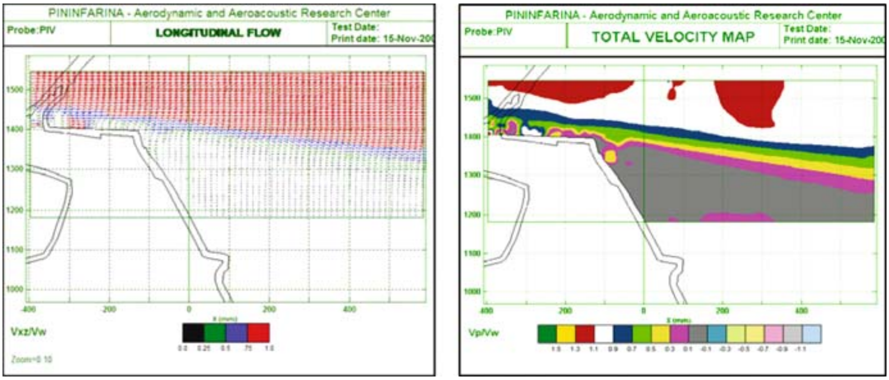


Fig. 9. Mean velocity field of a longitudinal wake behind the car in the plane XZ and $Y = -0.1\,\mathrm{m}$ (wind-tunnel coordinate system). Longitudinal flow (*left*) and total velocity map (*right*). All velocities are normalized to the free-stream velocity

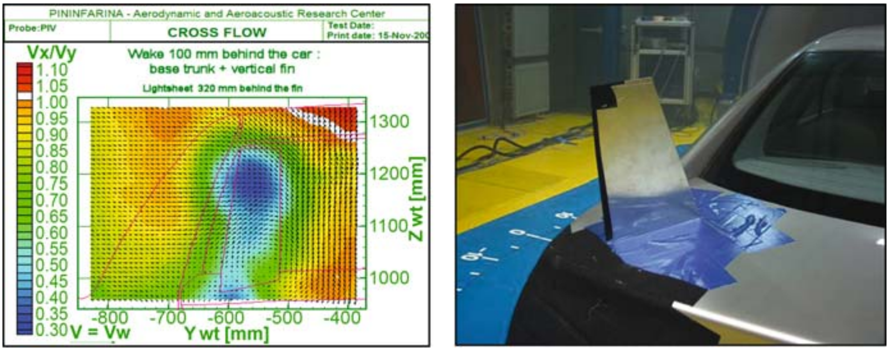
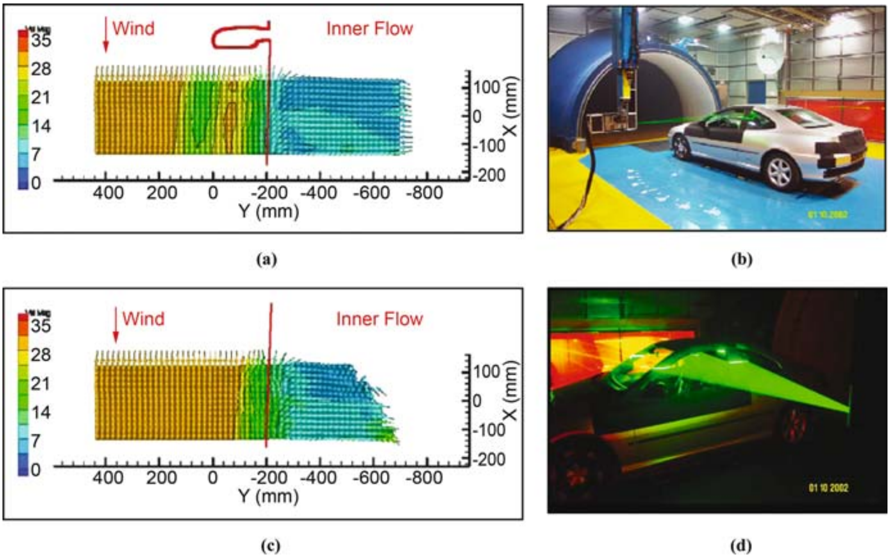


Fig. 10. Crossflow of a wake 0.1 m behind car with vertical fin. Mean velocity field (*left*). Car configuration (*right*). All velocities are normalized to the free-stream velocity



(a) (b)

(c) (d)

Fig. 11. Mean velocity field in a longitudinal area of the front left-side window, with glass lowered. Plane XY, $Z = 1.1\,\mathrm{m}$: (**a**) downstream of the RVM; (**c**) $Z = 1.2\,\mathrm{m}$: higher than RVM. (**b**,**d**) Measurement setup

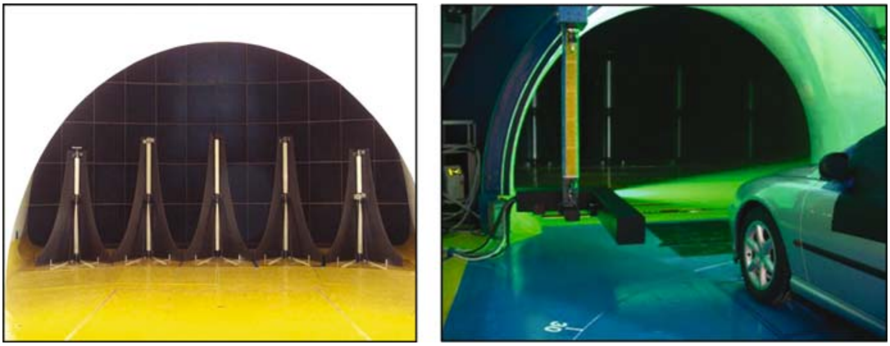


Fig. 12. The Turbulence Generation System (TGS) and PIV measurements setup adopted to investigate the turbulent flows generated by the TGS

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