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Feasibility of Particle Image Velocimetry (PIV) in High Speed Flow Tunnels

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Abstract

Experimentation regarding high speed flows became very important now-a-days. So, there is a need of accurate and complete information regarding the desired flow from final results. Existing Flow Visualization techniques like Schileren and Shadowgraph gives information related to density and some other parameters of the flow. Sometimes these results are not sufficient for validation with numerical results and analysis of flow visualization becomes difficult. PIV technique as it is a non-intrusive flow visualization technique which gives information regarding velocity of the flow in global domain along with other existing techniques can increase the accuracy and gives complete information regarding the flow. In this paper results of various experiments conducted in high speed tunnels along with PIV arrangement are discussed and its validation, feasibility results are presented.

Keywords: Particle Image Velocimetry technique (PIV), Schileren & Shadowgraph techniques, High speed flows.

1. Introduction

Particle Image Velocimetry is the newest entrant to the field of flow measurement and provides instantaneous velocity measurements over global domains. The PIV represents a quantitative extension of the qualitative flow visualization. The PIV technique may be an efficient way of measuring gross velocity structures of a flow region compared to other available techniques. PIV technique gives the measurement of fluid mechanic quantities like mean and rms velocities, temporal and spatial velocity moments, various velocity correlations, vorticity, circulation of the flow. Frequently used techniques like Schieleren, Shadowgraph techniques in high speed flow tunnels give flow parameters related to density which is sometimes not sufficient for some flow evaluation. In order to completely validate the flow measurements, the addition of this PIV technique with the existing techniques can bring a appreciable desired change[1],[2],[3],[4]&[5].

This paper mainly discusses about feasibility of this new technique in high speed flows by taking the cases of experimentation already performed in various parts of the world. So taking these cases as a reference a new experimental model with PIV and Schileren or Shadowgraph arrangement can be established for Improved experimentation. Section 2 discusses the feasibility of PIV in supersonic flow tunnels, section 3 about transonic flows, section 4 regarding shock tubes and shock tunnels, section 5 gives experimental issues of PIV & section 6 summarizes and concludes the paper.

2. Feasibility of PIV in Supersonic flows

2.1 1st Case

Tomographic particle image velocimetry and proper orthogonal decomposition are used to investigate the three-dimensional instantaneous flow organization of an incident shock wave/turbulent boundary layer interaction at Mach 2.1. Experiments were performed in the blow-down transonic-supersonic wind tunnel (TST-27) of the High-Speed Aerodynamics Laboratories at Delft University of Technology. The facility generates flows in the Mach number range 0.5–4.2 in a test section with maximum dimensions of 270mm×280mm.[6](Humble etal.,2007) The Mach number is set by means of a continuous variation of the throat section and flexible nozzle walls. The tunnel operates at unit Reynolds numbers ranging from 30×106 to 130×106m-1, enabling an operating use of approximately 300s. In this study, the tunnel was operated at a nominal Mach number of 2.1 ($U\infty$=503m/s) with a stagnation pressure of 282kPa and stagnation temperature of 273K.

Flow seeding and illumination constitute critical aspects of PIV in high-speed flows. A 10mm diameter probe was inserted into the settling chamber to seed the upstream boundary layer. Titanium dioxide (TiO2) particles with a nominal diameter of 170nm and a bulk density of 200kg/m3 were adopted as tracers. The particle relaxation time across the incident shock wave(based on particles with a nominal diameter of 50nm) has been determined to be τp~2μs, corresponding to a frequency response fp~500kHz. The seeded flow was illuminated by a Spectra-Physics Quanta Ray double-pulsed Nd: Yag laser, with 400mJ pulsed energy and a 6ns pulse duration at wavelength 532nm. A probe inserted into the flow downstream of the test section provided laser light access, and shaped the light beam into a volume using light optics. Before light entered the probe, a knife-edge slit filter was used to remove the low-energy fringes present, and to give a better approximation of a top-hat light intensity distribution. To minimize reflections, illumination was almost tangent to the wall. The laser pulse separation was 2μs, allowing a particle displacement in the free stream of approximately 1mm (≈20 voxels).

The tomographic results for revealing 3D instantaneous structure of the interaction are found out which shows a series of uncorrelated measurements volume containing instantaneous streamwise velocity. Results are very much sufficient here to validate with all velocity measurements. The only problem lies in selecting seeding particles for the flow. This is very difficult because there are many factors in the flow which drifts the motion of particles in the flow.

2.2 2nd case

Before the Space Shuttle could return to flight after the loss of Columbia, NASA was required to validate the computational fluid dynamics (CFD) codes that it uses to predict the trajectories of debris that may be shed from the vehicle during launch. To meet this and other requirements, NASA conducted two tests of a 3% scale model of the Shuttle ascent configuration in the NASA Ames 9×7ft2 Supersonic Wind Tunnel (9×7 SWT)[7] (raffel et al., 2007). In these tests, Dual Plane Particle Image Velocimetry (PIV) was used to measure the three components of velocity upstream of the Orbiter wings where debris shed from the External Tank (ET) would be convected downstream. The measurements were made in four cross-stream vertical planes located at different axial positions upstream of the Orbiter and above the ET. The measurements were made at two Mach numbers (1.55 and 2.5) over a range of model attitudes. The high stream velocity necessitated the use of the dual plane technique. These measurements revealed a complex network of interacting shock waves and a region of turbulent, separated flow on the ET just upstream of the Orbiter-to-ET attach point ("bipod"), where foam broke loose during Columbia's final flight.

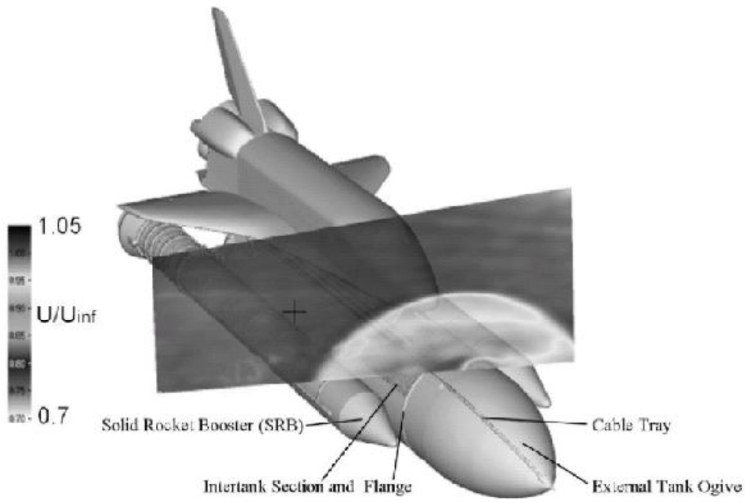

Figure 1: Sample plot of normalized axial velocity in the most upstream measurement plane $Ma_\infty = 2.5$, $\alpha = 0^\circ$, $\beta = 0^\circ$.

Figure1 shows average axial velocities in the most upstream measurement plane for a typical case. Higher spatial-resolution measurements were made in a single vertical plane in the separated-flow region above the Intertank section of the ET. More than 7000 samples were acquired at a single test condition to allow computing turbulence statistics. Figure1 clearly shows the bow shock-wave from the nose of the External Tank (ET). The data are not laterally symmetric because the measurement plane was not perpendicular to the flow (it was yawed 15◦). In addition, the cable tray on the starboard side of the ET ogive (Figure1) probably induced flow asymmetry.

3. Feasibility of PIV in transonic flows

The application of PIV in high-speed flows (e.g.: transonic flow above airfoil)[7] yields two additional problems: the resulting behavior of the tracer particles and the presence of strong velocity gradients. For the proper understanding of the velocity maps it is important to know how far behind a shock will the tracer particles again move with the velocity of the surrounding fluid. Experience shows that a good compromise between particle behavior and light scattering can be found if this distance is allowed to be of the order of one or two interrogation areas. Strong velocity gradients in the flow will lead to a variation of the displacement of the images of the tracer particles within the interrogation area. This influence can be reduced by application of image shifting. This is especially important if autocorrelation and optical evaluation methods are applied as in this case it is required to be able to adjust the displacement of the tracer particles to the range for optimal evaluation (i.e. ≈200 μm). Strong velocity gradients are present in flow fields containing shocks. Figure2 shows such an instantaneous flow field above a NACA 0012 airfoil with a chord length of Cl =20cm at $Ma\infty$= 0.75. By subtracting the speed of sound from all velocity vectors the supersonic flow regime and the shock are clearly detectable.

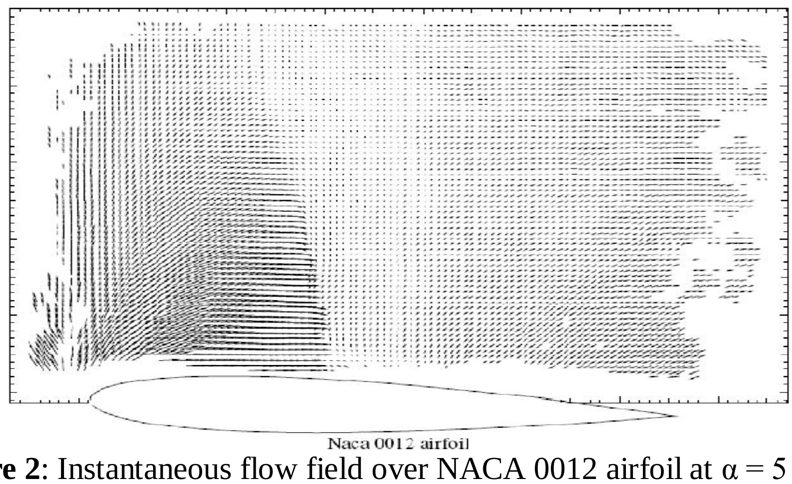

Figure 2: Instantaneous flow field over NACA 0012 airfoil at α = 5 degree

4. Feasibility of PIV in Shock tubes and Shock tunnels

Shock tubes and shock tunnels generate compressible flows that are characterized by short time durations and large gradients. Therefore, these flows are a challenging application for all kinds of measurement systems. Additionally, a high information density is desirable for each experiment due to short measurement times. During recent years, particle image velocimetry (PIV) was therefore extensively tested and successfully applied to different flow configurations in the shock-tube department at “French-German Research Institute of Saint-Louis (ISL)”. It turned out that one difficulty common to all shock-tube or tunnel applications is a good timing and triggering of the PIV system. An appropriate seeding is another crucial factor. The latter is particularly difficult to manage because, in contrast to continuous facilities, no assessment of the seeding quality is possible before and during the experiment.

Particle seeding was accomplished by a smoke generator burning incense resin that gives a typical smoke particle diameter of approximately 1 μm.[8] Both the open-end tube and the ambient air near the opening were seeded before each experiment. The PIV system was triggered by a pressure transducer located close to the shock-tube opening. The experimental setup is given in figure 3.

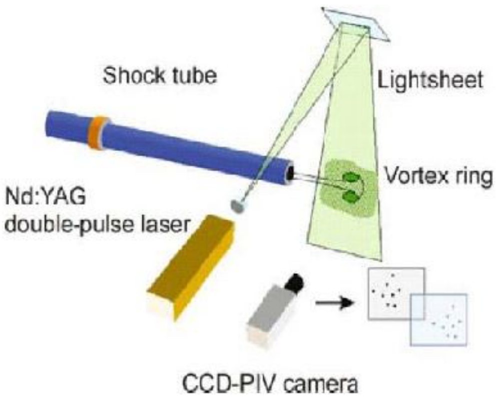

Figure 3: PIV setup.

PIV has been applied to a large variety of simple and complex flows in short duration facilities (shock tunnel and shock tube) at ISL. For rather simple flow fields with a low level of turbulence the instantaneous PIV results represent the flow field very well even with rather large interrogation window sizes. Velocities up to nearly 2km/s have been measured in a shock tunnel with an accuracy of a few per cent comparing the experimental results with analytical and theoretical values. This confirms the ability of PIV to be used for CFD validation even in a very high velocity range. This Proves the evolution of PIV became very useful in shock tubes and shock tunnels. Now-a-days the use of shock tunnels and shock tubes became very useful in analyzing high speed flows with higher mach numbers. Existing techniques like Schieleren and Shadowgraph techniques are that suitable because of incomplete results even though they are accurate. From this case, we can converge to a fact that PIV provides useful, accurate sophisticated results. So addition of PIV arrangement to schieleren or Shadowgraph arrangement in shock tubes and tunnels can be useful.

5. Experimentation Issues of PIV

As high speed flows are not easy to analyze because the reaction time is very less. So very high technical equipment is required (for ex: high speed image processing equipment like CCD cameras with high spatial and temporal resolution). Another important factor for PIV flow visualization technique is particle selection. Depending upon the flow, particles need to be chosen. In gas flows, the increased difference in density between the gaseous bulk fluid and the particles can result in a significant velocity lag. Health considerations are also more important since the experimentalists may inhale seeded air, for example in wind tunnels with an open test section. The particles which are often used are not easy to handle because many liquid droplets tend to evaporate rather quickly. Solid particles are difficult to disperse and tend to agglomerate. Very often the particles must be injected into the flow shortly before the gaseous medium enters the test section. The injection has to be done without significantly disturbing the flow, but in a way and at a location that ensures homogeneous distribution of the tracers. Since the existing turbulence in many test setups is not strong enough to mix the fluid and particles sufficiently, the particles have to be supplied from a large number of openings. Distributors, like rakes consisting of many small pipes with a large number of tiny holes, are often used. Therefore, particles which can be transported inside small pipes are required.

A number of techniques are used to generate and supply particles for seeding gas flows. Dry powders can be dispersed in fluidized beds or by air jets. Liquids can be evaporated and afterwards precipitated in condensation generators, or liquid droplets can directly be generated in atomizers. Atomizers can also be used to disperse solid particles suspended in evaporating liquids or to generate tiny droplets of high vapor pressure liquids (e.g. oil) that have been mixed with low vapor pressure liquids (e.g. alcohol) which evaporate prior to entry in the test section. For seeding wind tunnel flows condensation generators, smoke generators and monodisperse polystyrene or latex particles injected with water-ethanol are most often used for flow visualization. Every flow visualization techniques have got some limitations. Even PIV technique has got it, but beyond these limitations it is very useful.

6. Conclusion

As PIV is the newest entrant to this fluid flow visualization field, there are some limitations which can be overcome very easily as technology improving day by day. From the cases discussed in this paper we can come to a conclusion that PIV results are accurate, useful and can be easily validated with numerical simulation methods. But at the same time it is also very clear that experiment arrangement of PIV is not as easy as expected. So budget allocated for the experimentation is more or if we need accurate and complete results for validation it will be a good step to consider the PIV technique. Otherwise there is another option taking PIV technique with other flow visualization techniques to get complete results as it is done in Transonic Wind Tunnel (TWG) of the German Dutch wind tunnel (DNW) in Gottingen[9] to in order to derive quantitative flow velocity and density data of a wing tip vortex generated by an airfoil model of a modern large transportation aircraft. There they used BOS (Background Oriented Schieleren) with PIV to get complete results. So these types of arrangements are improving day by day and results from these dual techniques are very accurate enough and that too especially in high speed flows.

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7. Conclusion

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