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QUANTITATIVE FLOW FIELD VISUALIZATION IN WIND TUNNELS BY MEANS OF PARTICLE IMAGE VELOCIMETRY

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Abstract

The instantaneous and non-intrusive measurement of the flow velocity in a 2-dimensional plane of a flow field can be performed by means of a new experimental technique, called Particle Image Velocimetry (PIV). An experimental set-up for the application of PIV in wind tunnels has been developed. Results of the investigation of flow fields in a low turbulence wind tunnel at U = 10 m/s are presented. Furthermore, PIV has been applied to jet flows up to Ma = 1. Problems affecting the operation of PIV in a large wind tunnel are discussed.

Introduction

In todays aerodynamic research the interest is more and more directed to problems where unsteady separated flow fields are dominant. Thus, for aerodynamic investigations in wind tunnels the measurement of the time dependent component of the flow velocity in the boundary layer of the model and in the whole flow field downstream of the model becomes increasingly important.

Up to now in most wind tunnels pressure probes are utilized for the measurement of the flow velocity. Due to the fact that the flow field may be changed by the presence of a probe (especially at high speed flows), and that the flow velocity is measured only at a single point, the application of this measuring technique is restricted to stationary or slowly time-varying flows.

Being an optical method the laser Doppler anemometer technique (LDA) allows non-intrusive measurements of the flow velocity. The flow velocity is obtained by measuring the velocity of small tracer particles within the flow. It is assumed that these particles will accurately follow the flow, provided, they are small enough. The volume concentration of the particles, achievable in large wind tunnels, results in sampling rates of the typical order of some hundred measurements per second. Thus, the measurement of the three-dimensional flow velocity vector with 'limited' time resolution is possible by the LDA technique. However, in order to obtain information on the spatial structure of the flow, the flow field has still to be scanned point-by-point sequentially in time. If the spatial structure varies with time, correlation methods (correlation in time of signals originating from two spatially separated points in the flow) have to be applied to get some information on the structure of the flow field.

Thus, it becomes obvious that for the investigation of flow fields with rapid temporal or spatial changes or for investigations in wind tunnels in which measurements are possible only during a short time interval (blow down wind tunnels, shock tubes) new experimental techniques are needed. These techniques should give information on the spatial structure of the total *instantaneous* velocity field.

One of these methods is 'Particle Image Velocimetry (PIV)', or as it is sometimes called 'Pulse Laser Velocimetry'. 'Laser Speckle Velocimetry' is a somewhat different method. The basic principles of the PIV method have been explained in detail elsewhere [e.g. 1-5] and shall only be briefly summarized here.

To illustrate the principle of PIV it can be best compared with the classical method of flow visualization by means of tracer particles. The flow must be seeded with small particles (Fig. 1). A thin sheet of the flow field is illuminated by pulsed laser light (two pulses within a short time interval). The light scattered by the tracer particles within this sheet is recorded on a photographic plate. On this photographic plate we will observe particle images due to the first and second illumination of an individual particle. If the time interval between the two light pulses and the magnification of the recording camera are known, the 2-dimensional flow velocity vector (in the plane of the light sheet) can be calculated from the displacement of the images refering to the same particle. The advantage of PIV over classical methods is that nowadays methods are available which allow to evaluate the velocity data within a reasonable time.

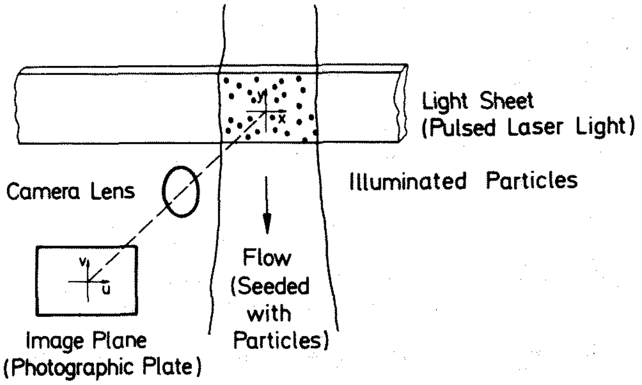

Fig. 1 Principle of Particle Image Velocimetry.

Experimental set-up

In this paper some examples of the application of PIV in wind tunnels shall be presented. Therefore, only a short description of our experimental set-up will be given here. Details of the PIV arrangement we use can be found in [6].

Illumination of the light sheet

For the illumination of a 2-d plane in the flow a Nd:YAG laser system is utilized. The output of the laser consists of two short laser pulses (at a wavelength of $\lambda = 532$ nm), separated by a delay continuously variable between 0 and 10 ms. These features have been achieved by mounting two Nd:YAG oscillators on a common base. Due to the two-oscillator arrangement, the output energy of both pulses (2x70 mJ) is excellently controllable and stable. The repetition rate of the double pulses is 10 Hz; it may be increased up to 50 Hz. In the experiments described in this paper a single shot option was used.

Transmitting and recording optics

For operation in large wind tunnels the transmitting optics, which is needed to transform the circular, pulsed laser beam into a thin light sheet, must produce a focal plane with a long waist at a distance determined by the dimensions of the wind tunnel (typ. 2-5 m). With our optical arrangement we obtain a thin light sheet with an almost uniform thickness ($\approx$ 0.5 mm) and an almost constant height ($\approx$ 70 mm) in the flow area of interest at a distance of $\approx$ 5 m from the laser. The light scattered by the tracer particles is recorded in a plane parallel to the light sheet by means of a 35 mm camera.

Data reduction

As we work in the high image density range according to the definition given in [3] it is difficult to resolve individual image pairs (corresponding to the first and second illumination of a single particle). Therefore correlation methods have to be applied to obtain the displacement vector. For this purpose the photographic plate is divided into a great number of interrogation points. At each point only a small area (typ. 0.5x0.5 mm^2) of the PIV recording is considered. It is assumed that between the two exposures all particles within this area have moved the same distance and in the same direction. A 2-dimensional autocorrelation would yield the local displacement vector at each interrogation point. As such algorithms are time consuming, even with modern computers, a well known relationship between autocorrelation and Fourier transformation is used, i.e. the inverse Fourier transformation of the power spectrum of an image is equivalent to the 2-d autocorrelation of the same image.

The power spectrum at each interrogation spot can be obtained easily by illuminating the interrogation spot with coherent laser light and performing the 2-d Fourier transformation by means of a lens, resulting in a pattern of equally spaced fringes (Young's fringes method). This analog method, based on the principles of coherent optics, has been described e.g. in [2]. The subsequent digital inverse 2-d Fourier transformation of the Young's fringe pattern, which is performed in an image processing computer, is rather time consuming. With our system the data reduction necessary to obtain one 2-dimensional velocity vector in the flow field lasts $\approx$ 25 seconds to $\approx$ 80 seconds, depending on the desired resolution. However, with faster systems as utilized by other authors it is possible to reduce this evaluation time to less than one second. Finally, the positions of the peaks within the 2-d spectrum have to be determined. (These peaks are equivalent to those of the 2-d autocorrelation). The data in image co-ordinates are converted into velocity data and plotted. The procedure runs automatically for the whole PIV recording.

Flow facility

The experiments were carried out in the DFVLR low turbulence wind tunnel (TUG), which is of an Eiffel type (Fig. 2). Screens in the settling chamber and a high contraction ratio of 15:1 lead to a low turbulence level in the test section (cross section 0.3x1.5 m^2). Our experiments were carried out on the center line of the wind tunnel. Near the end of the nozzle different grids can be installed in order to generate turbulence. The basic turbulence level in the TUG of Tu = 0.04 % may be increased by this modification [7].

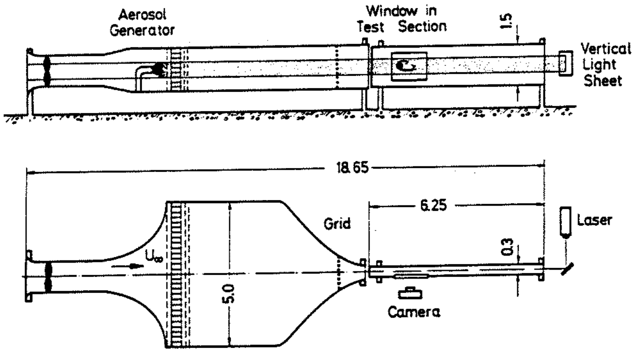

Fig. 2 Low turbulence wind tunnel (TUG) with experimental set-up for PIV (all dimensions in m).

Tracer particles

The flow velocity is calculated from the displacement of the tracer particles. Thus, the particles must truly follow the flow. Especially for applications in high speed flows particles with a very small aerodynamic diameter are necessary. However, in order to increase the light scattering efficiency the particle diameter must be as large as possible. Our particles, which consist of olive oil droplets, are generated by means of a Laskin nozzle. Their aerodynamic diameter is approximately 1 μm. Such a diameter is widely recommended for use in high speed flows (flow velocity $\approx$ 100 m/s).

Seeding

A low turbulence wind tunnel is best suited to study the problem of seeding a flow. At first a location within the wind tunnel for the proper insertion of the particles had to be selected. The flow is usually seeded a short distance upstream of the model, still within the test section or - sometimes - in the settling chamber. However, our earlier experiments carried out by means of laser Doppler anemometer or flow visualization have shown that flow disturbances at the nozzle of the seeding apparatus may occur. The flow field under test can be influenced by such fluctuations. Moreover, these fluctuations lead to a nonuniform distribution of the tracer particles in the measuring plane. To avoid these difficulties we had to seed the flow upstream of the screens used to reduce the turbulence of the flow.

Experimental results

Laminar flow

At first PIV recordings of the undisturbed flow in the test section of the TUG (time delay between light pulses = 80 μs) were taken. The purpose was to get an idea of how the velocity data will scatter if there is only a very small turbulence level present in the flow. After the PIV recording had been evaluated and the flow field had been plotted (see Fig. 3a), it was found - as expected for laminar flow - that all velocity vectors (u,v) were obviously parallel to each other and had the same length. (The u-component of the velocity vector was chosen to be parallel to the flow direction). The size of the flow field shown in the plot is approximately 8.2×3.9 cm². The resolution is 50×24 grid points. At each interrogation point at which an evaluable fringe system was found the velocity vector was plotted. To find any differences between the flow velocity vectors, the fluctuations had to be enhanced. This was done by subtracting 90% of the mean flow velocity U (obtained by averaging the u-component of all vectors) from each local flow velocity vector (u,v). The plot of the resulting 2-d velocity vector field (u-0.9U,v) can be seen in Fig. 3b. For comparison a reference vector is also plotted, whose length corresponds to 10% of the mean flow velocity U, which was 10 m/s in this experiment.

Finally, the mean flow velocity U was totally subtracted to yield the velocity vector field (u-U,v). Fig. 3c gives a good impression how the velocity data scatter in laminar flow. At some grid points only a small point symbol has been plotted instead of the vector symbol. At these points the length of the velocity vector, if plotted, would have been smaller than the fixed length of the tip of the vector symbol. It can be seen that direction and magnitude of the fluctuating velocity vectors are not distributed randomly. Instead of this, small areas exist in which the vectors have similar direction and length. This indicates that small turbulent fluctuations, still present in the laminar flow, are responsible for this kind of scatter of the data. Random fluctuations which will occur during the evaluation process due to limited numerical resolution are believed to be smaller than the length of the tip of the vector in this scale ($\leq 1\%$ of U). No calculation of the over-all accuracy of our data evaluation has been done up to now. However, we think that the evaluation of the PIV recording of a laminar flow field, presented here, has shown that the accuracy is of the order of 1%. This value is also given by other authors.

Turbulent flow

Another set of PIV recordings was made after a grid had been installed upstream of the nozzle of the TUG (see Fig. 2). Thus, the turbulence level in the test section was increased from $\approx 0.04\%$ to $\approx 1.2\%$. The distance between the grid and the flow area to be investigated was ≈ 1.3 m. The flow velocity field (u,v) at U = 10 m/s, plotted in the same scale as for the laminar case, is presented in Fig. 4a. A comparison between Fig. 3a and 4a shows that indeed the turbulent fluctuations have been increased. This fact becomes more evident if - in the same manner as in the case of the laminar flow - the velocity vector field (u-0.9U,v) - as shown in Fig. 4b - or the velocity vector field (u-U,v) - as shown in Fig. 4c - are calculated. The dimensions of the grid (diameter = 8mm, mesh size = 28 mm) are indicated at the right hand side of Fig. 4c. Hot-wire measurements, performed under the same experimental conditions, had already shown that the turbulence had not yet become isotropic at this distance from the grid [7]. PIV, moreover, shows that the turbulent fluctuations have an obvious spatial structure of a size comparable to the dimensions of the grid.

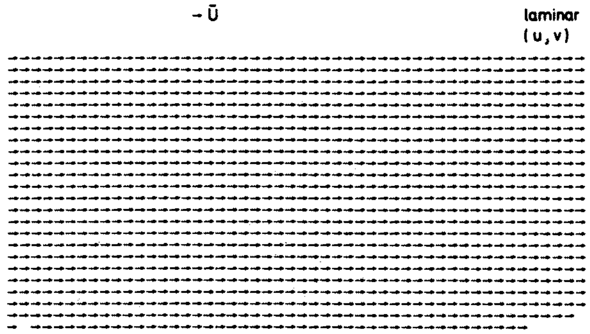

Fig. 3a Map of instantaneous 2-d laminar flow field (U = 10m/s); the velocity vectors (u,v) are plotted.

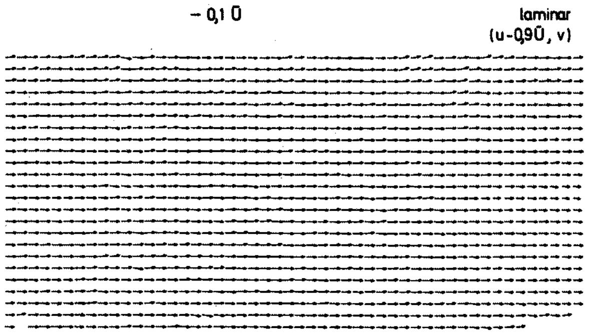

Fig. 3b Map of instantaneous 2-d laminar flow field (U = 10m/s); the velocity vectors (u-0.9U,v) are plotted.

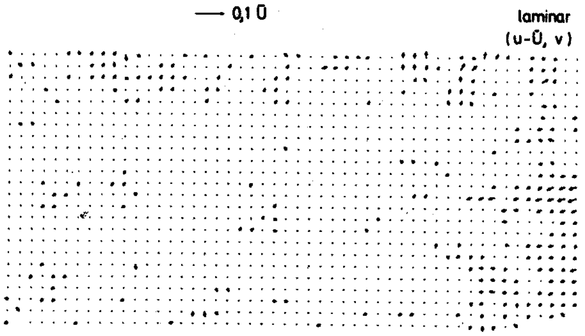

Fig. 3c Map of instantaneous 2-d laminar flow field (U = 10m/s); the vectors of the fluctuating velocity component (u-U,v) are plotted.

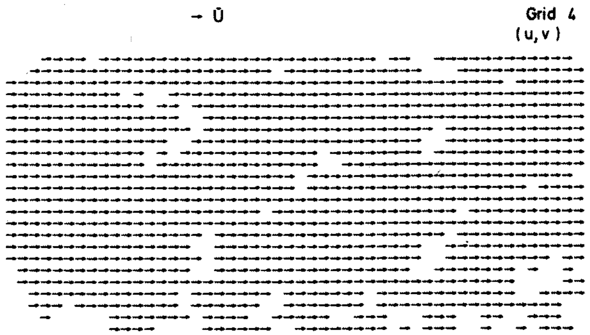

Fig. 4a Map of instantaneous 2-d flow field in a distance of 1.3 m behind a grid (rod dia. 8 mm, mesh size 28 mm); U = 10m/s; the velocity vectors (u,v) are plotted.

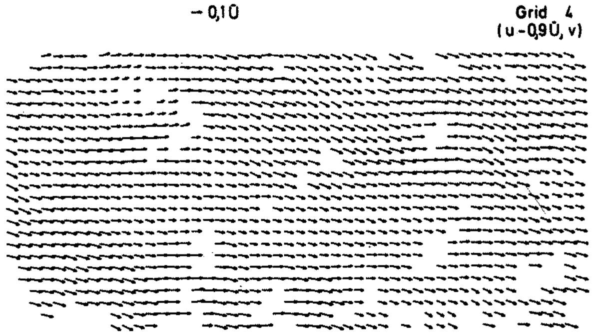

Fig. 4b Map of instantaneous 2-d flow field in a distance of 1.3 m behind a grid (rod dia. 8 mm, mesh size 28 mm); U = 10m/s; the velocity vectors (u-0.9U,v) are plotted.

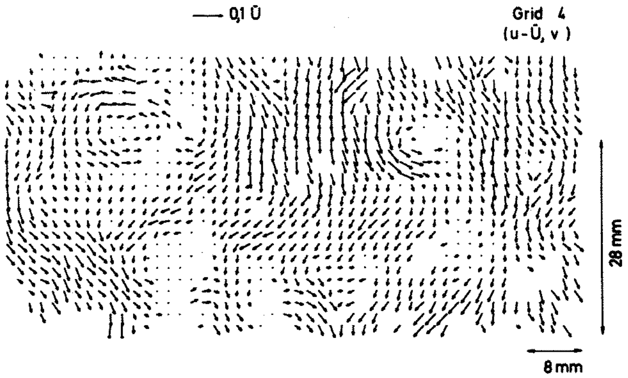

Fig. 4c Map of instantaneous 2-d flow field in a distance of 1.3 m behind a grid (rod dia. 8 mm, mesh size 28 mm); U = 10m/s; the vectors of the fluctuating velocity component (u-U,v) are plotted.

Vortical flow behind a cylinder

PIV recordings were taken of the wake flow behind a cylinder (D = 10 mm, U = 10 m/s, Re = 6600). The time difference between the two laser pulses was 60 μs. Fig. 5 presents the data as evaluated from a typical PIV recording. Due to experimental difficulties when seeding the flow, the distribution of the tracer particles is not uniform. Thus, no data can be given for the flow field directly behind the cylinder and at some other areas in the wake because no tracer particles were present in these regions. But nevertheless, large vortical structures may be recognized. The original PIV recording also showed some small scale structures. These could not yet be resolved due to the fact that the size of the interrogation spot (over which the data are averaged) was larger than the size of these structures at this special example. For the same reason the boundary region between flow areas having different flow directions (i.e. the edges of the large vortical structures) cannot be detected as exactly as would be desired. A higher magnification when imaging the flow will be necessary to resolve such details. Other authors have studied similar flows by means of PIV, e.g. the temporal evolution of the flow past a circular cylinder [8]. However, there were different experimental conditions at that investigation: water towing tank, diameter of cylinder 25.4 mm, towing velocity 22 mm/s, Re = 550. Thus, problems of non-uniform seeding were of no importance.

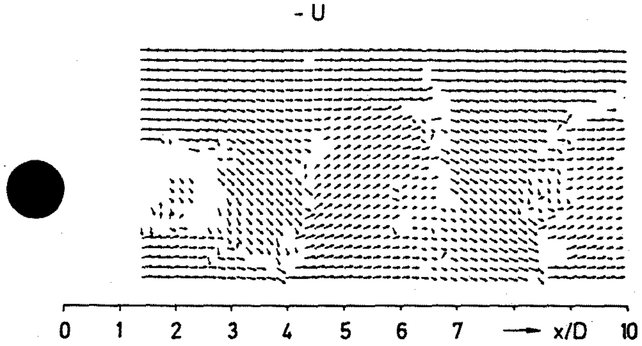

Fig. 5 Map of instantaneous 2-d flow field behind a cylinder (D = 10mm; U = 10m/s; Re = 6600), the vectors of the local flow velocity (u,v) are plotted.

Jet flow

For experiments at high flow velocities a jet flow facility with a nozzle (diameter = 15 mm) in front of a plenum chamber was utilized. PIV recordings could be taken up to a Mach number of 1. Fig. 5 shows the the instantaneous flow field of a jet at a jet exit velocity of U_j = 180 m/s. In this case the time delay between the two laser pulses was only 3 μs. To emphasize the vertical velocity component of the jet, 80% of U_j has been subtracted before plotting the flow velocity vector field (u-U_j,v). For the PIV recording, the data of which are shown in Fig. 5, the tracer particles were inserted in the plenum chamber. Thus, only the jet itself is seeded with particles. Nevertheless, the vortical structures in the shear layer of the jet can be detected.

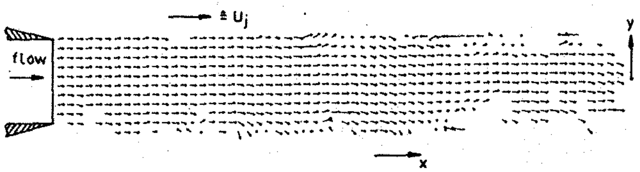

Fig. 6 Map of instantaneous 2-d flow field of a jet; (nozzle diameter = 15mm; U_j = 180 m/s; internal seeding), the velocity vectors (u-0.8U_j,v) are plotted.

Conclusion

The results presented so far have demonstrated the application of PIV in a low turbulence wind tunnel with low flow velocities in the range of 10 m/s to 20 m/s and to jet flows at high flow velocities (U = 180 ... 300 m/s).

Of course, there are still a number of problems to be solved before routine operation of PIV in wind tunnels is possible. Some of them shall shall be briefly mentioned:

- Uniform distribution of the particles,
- accessibility of the test section of the wind tunnel,
- appropriate size of the tracer particles,
- width of the light sheet (observation field),
- resolution of the velocity data (turbulent flows).

However, our experiments have shown that PIV will be a useful tool for aerodynamic investigations in wind tunnels, especially for the investigation of instantaneous velocity fields or in blow down wind tunnels. The time needed for a PIV recording is of the order of $\approx$ 100 μs. This fact helps to reduce the operating time and hence the costs of the wind tunnel. From a single PIV recording more than several thousand instantaneous 2-d velocity vectors can be obtained. The evaluation of a PIV recording is carried out later on in the laboratory and is independent of the measurement. The time necessary for the evaluation of a PIV recording will further decrease in future, due to the availability of faster computers. Thus, it will be possible to a great extent to compare experimental data of the instantaneous velocity field directly with data obtained by numerical calculations of the flow field in order to improve theoretical flow models.

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