Comparisons between 3D-LDA measurements and TR-PIV data in the separated flow of a circular cylinder

by

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ABSTRACT

In the wake of a circular cylinder vortices are being periodically shed thus forming a vortex street. For Reynolds numbers larger than ~400 additionally a sequence of smaller vortices is appearing in the separated shear layer as a result of the Kelvin-Helmholtz instability. In the present paper a time-resolved PIV technique has been used to investigate the interactions of the primary vortex street and the vortices originating in the shear layer for Reynolds numbers of 5000. The time-resolved PIV with a resolution of up to 500 fps allows the monitoring of Kelvin-Helmholtz vortices in the separating free shear layer flow and in the formation region of the primary vortices where their influence on the deterioration of the primary vortices can be detected. From these results the impact of the shear layer instability on the turbulence production can be determined.

1. INTRODUCTION

In the wake of a circular cylinder the development of the flow during the transition process from laminar 2D flow to turbulence can be studied as an example for the wake flow behind bluff bodies in general. For technical applications, such as car aerodynamics and flows in heat exchangers, the bluff body wake has major importance. The transition process influences the wake which, for example, can result in decreased drag forces or in improved mixing efficiencies in chemical applications. As the most simplified setup of a bluff body the circular cylinder has been chosen to investigate the typical transition scenario.

Being a standard experiment the cylinder wake has been investigated frequently in the past, many transition phenomena have been identified. With increasing Reynolds number Re= U d / ν, based on the cylinder diameter d, the velocity of the oncoming flow U and the kinematic viscosity ν , the first periodic shedding of primary vortices is being observed for Re > 45. For Re > 160 secondary vortices appear, which are oriented in streamwise direction. The vortex structures of the secondary vortices is three dimensional and was determined using time-series PIV images (Brede, Eckelmann, Rockwell 1996). A detailed review of the primary and secondary vortex structure in the cylinder wake can be inferred from (Williamson 1996). For higher Reynolds numbers the separated shear layer becomes unstable before it is rolled up to a primary or secondary vortex due to the Kelvin-Helmholtz instability of the shear layer. This phenomenon was first observed in 1964 for Re > 1000 as additional high-frequency fluctuations in the hot-wire signal (Bloor 1964), but the periodic movement of the separated shear layer has been observed down to Re = 350 (Gerrard 1978, Brede and Leder 1999). Later, the velocity profile development in the separated shear layer has been investigated using hot-wire anemometry by Unal and Rockwell (1988). In Prasad and Williamson (1997) a physical explanation is given for the frequency law of the shear-layer vortices. Recent research focus has been put on the influence of the shear layer instability on the turbulence properties measured in the wake. While these efforts have been accomplished by 3D-LDA (Brede and Leder 2001) the time-resolved PIV method allows it to observe the effects of the shear-layer instability and the shedding of the primary vortex in real time.

In the present paper the time-resolved PIV (TR PIV) method is used to monitor the development of small scale shear-layer vortices. The TR PIV method used here is a setup which allowed it to obtain PIV vector fields in the wake with a frequency up to 250 Hz. From the velocity data the frequency and the location of the shear layer vortices could be

determined. The results have been compared with phase averaged 3D-LDA data as well as with ensemble averaged 3D-LDA data selected for the event of an unstable shear layer.

2. TIME-RESOLVED PIV and 3D-LDA EXPERIMENTAL SETUP

The experimental setup for the Time-Resolved PIV measurements is displayed in figure 1. A circular cylinder with a diameter of 20 mm and an aspect ratio L/d of 29 is placed in the test section of a Goettingen type wind tunnel perpendicular to the oncoming flow. On both ends of the cylinder endplates are mounted to cut off disturbances from the ends of the cylinder. All measurements were performed in a plane perpendicular to the cylinder on the symmetry plane between the endplates. The plane of view covers the wake from $x/d = 0.9$ to 3.4 and from $y/d = -1.0$ to 1.0 in cross-stream direction.
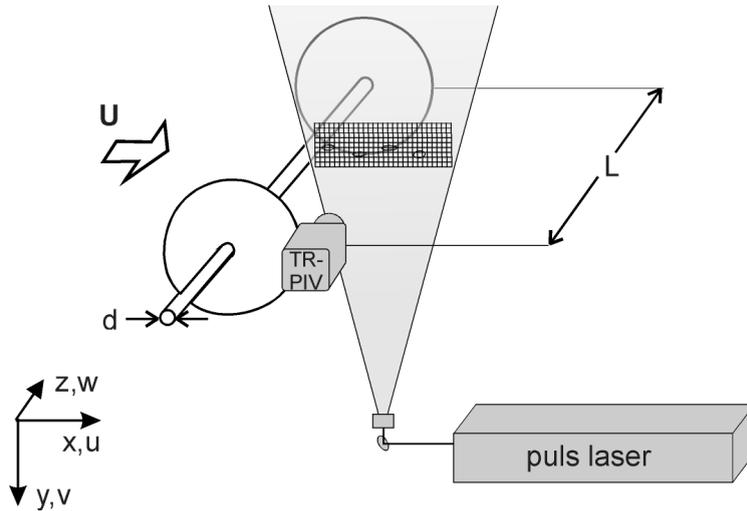

Fig. 1. Experimental setup for the TR-PIV measurements in the wind-tunnel

The TR PIV measurements were made with a standard type setup for PIV measurements with the light sheet introduced from below as shown in figure 1. The light sheet optics is mounted on the laser and the light sheet is diverted upwards by a mirror. Crossing the cylinder, there is no PIV data available above the cylinder, of course. The light sheet was approx. 2 mm thick. The image acquisition was performed with a CMOS type high speed camera at rates of 500 and 1000 frames per second, resulting in 250 Hz and 500 Hz PIV, respectively. At 500 fps the camera can record at 1k x 1.25 k pixels. At 1000 fps the camera field of view is 0.5 k x 1.25 k pixels. In this paper mainly the 500 fps results are reported. The pixel pitch is 12 µm. The camera was fitted with a 50 mm Nikkor lens used at #F2.8, matching the light sheet thickness. The distance between the light sheet and lens front was 450 mm. With a Nikkor 11A spacer ring (8 mm thick) the full field of view was 107 by 134 mm, or 5.4 d x 6.7 d. The camera has a 1Giga pixel memory allowing for 511 full frame data sets to be recorded. The laser is a 50 W diode pumped, Q-switched Nd:YAG laser. At 250 Hz PIV rate, a pulse pair of each 12 mJ with a distance of $\Delta t=400$ µs have been used. This results in a particle displacement of 14 pixels at 3.75 m/s. Using an ultrasonic atomizer, the diameter of the seeding particles (a mixture of water and glycerin) is about 2 µm.

For each Reynolds number 500 PIV images have been acquired. For each single image the velocity vector components in the PIV-plane were determined using an adaptive cross-correlation scheme. The interrogation area used is 32 x 32 pixels, corresponding to a measurement volume (interrogation area size x light sheet thickness) of 3.4 x 3.4 x 2 mm³. Therefore the interrogation area has a characteristic dimension of 0.17 d x 0.17 d. The vorticity component perpendicular to the plane has been derived. From the image series these quantities can be calculated as average values (conventional time averaging) or as phase averaging splitting the primary shedding cycle into phase intervals. For the phase averaging of the PIV-data the single frames were sorted into phase bins. The phase of each frame was calculated from the time stamp and the shedding frequency observed over the entire sequence.

For comparisons an extensive series of 3D-LDA data has been used which was obtained previously with the experimental setup depicted in figure 2. The cylinder and the wind tunnel are identical to the TR PIV setup. The velocity data were obtained using a 3D-LDA setup composed of an Ar-Ion laser driven 2D LDA probe and a NdYAG cw-laser driven 1D probe. The resulting measurement volume with a diameter of approx. 0.2 mm was automatically moved on the measurement grid. Two series of measurements have been performed with 3D-LDA. The first one with a grid spacing of 0.1 d covering the cylinder wake from the cylinder downstream to $x/d = 3.3$ and the second series only observing the separated shear layer with a grid spacing of 0.05 d to resolve the flow details. On each grid position approx. 50000 LDA-burst have been recorded in coincidence mode. A trigger mechanisms was employed to obtain real time information
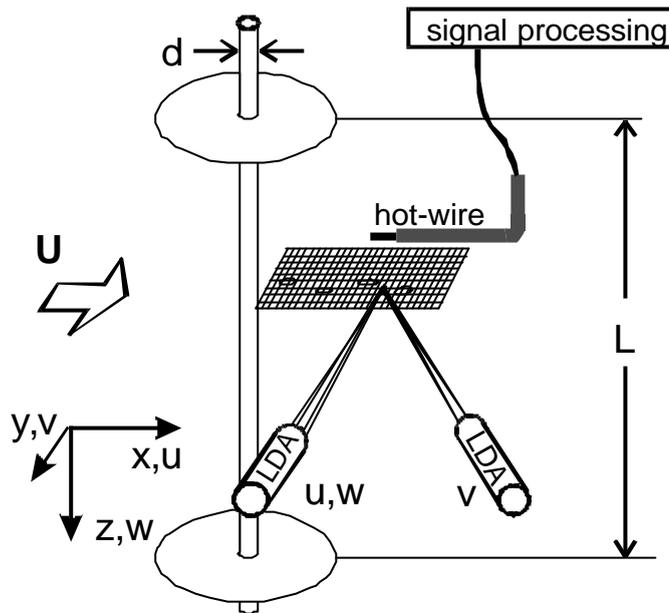

Fig. 2. Experimental setup for the phase- and event-triggered 3D-LDA measurements in the wind-tunnel

about the shedding process simultaneously to the 3D-LDA measurements. The trigger mechanism analyzes a signal from a hot wire placed in the cylinder wake. The trigger called "phase trigger" detects the phase of the primary vortex shedding and supplies a trigger pulse for every shedding cycle to the phase trigger input of the LDA burst spectrum analyzers (Leder and Geropp 1988).

The phase triggering technique allows the phase averaging of the data. Thus one primary shedding cycle can be represented as a sequence of 16 phase intervals. Due to the averaging within each phase interval, the small scale structures and processes with frequencies outside the primary shedding frequency are not visible in the data. From the 3-D LDA data first the mean velocities and the Reynolds-stress tensor have been calculated. Also three properties from the budget of the turbulent kinetic energy (TKE), the turbulence production, the viscous diffusion and the turbulent convection can be derived. From these the turbulence production P_{turb} is particularly interesting.

3. RESULTS

The two measuring techniques, TR PIV and 3D-LDA allow a variable observation of the cylinder wake. By using the Time-Resolved PIV method the instability development in the separated shear layer can be monitored in sequences of PIV images. These images allow the observation of the velocity vector field as well as the vorticity component ω_z perpendicular to the plane of observation. Due to the instantaneous character of the measurement, all details of the wake are being displayed in each frame. Additionally the phase of the separation process of the primary vortices can be determined from the velocity field allowing a phase averaging of all velocity fields within the same phase interval.

The spatial and temporal periodicity of the cylinder wake at Re = 5000 is shown in fig. 3. Obviously the periodicity of the flow is concentrated in both free shear layers, separating from the circular cylinders. These shear layer flows induce the primary vortices, which are shedding at Re = 5000 with a frequency of f = 37 Hz. This results in a Strouhal Number of Str = 0.197.
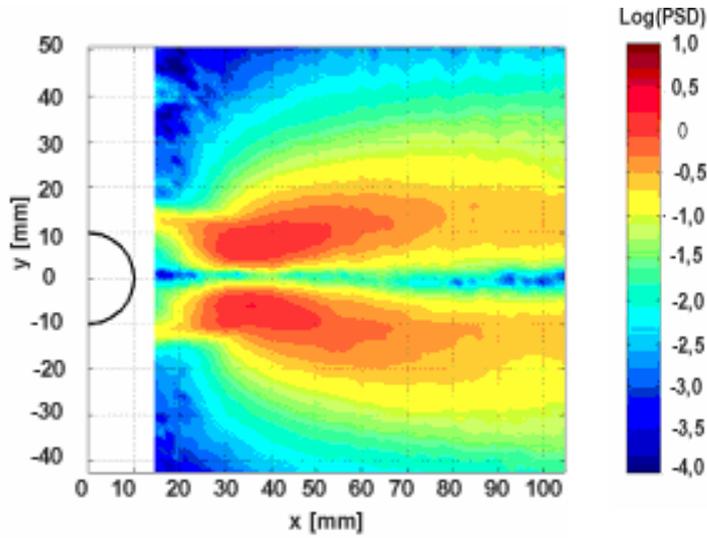
Fig. 3. Results of TR-PIV wake flow measurements behind a circular cylinder concerning the spatial distribution of the power spectrum at f = 37 Hz (Re = 5000).

In figure 4 we compare a sequence of TR PIV image in the right column with a sequence of phase averaged fields from 3D-LDA measurements in the left column. The colour coding in both cases represents the vorticity component ω_z. The scale is kept constant for all panels. The velocity components in the plane are presented as velocity vectors.

In the direct comparison of the sequences, in fig. 4 first the averaging effects are noticeable. For the phase-averaged fields obtained with LDA (left) the different regions in the wake can easily be distinguished. These are the separated shear-layer, the emerging vortex (dark/blue), the separating vortex (light/red) and the recirculation region. In the sequence of instantaneous PIV-frames (right) the wake structure is far more complex. Particularly for the separating shear layer small scale vortex structures can be observed. The large scale wake structure however is very well matching the structure observed with phase-triggered LDA, for the location of the shear layer and the primary vortices as well as for the temporal development. A second effect caused by the averaging in the LDA data can be seen in the amplitude of the vorticity component ω_z. In the TR PIV single frames the amount of the peak vorticity level is about 30% larger than that in the phase averaged LDA fields, where local small scale maxima disappear by the averaging process.

A closer look on the small scale vortex structure in the fields obtained with TR PIV reveals certain differences to the phase averaged LDA results. The small scale vortices develop from a wave disturbance of the separated shear layer (panels 1/16 and 3/16 right column in figure 4) and are wrapped around the emerging primary vortex (7/16 and 9/16, right column in figure 4). This ring of small scale vortices around the primary vortex shows significantly higher vorticity values than the vortex itself. In the phase averaged fields obtained with LDA (left column) the small scale vortices can not be detected, the maximum of ω_z is here observed in the vortex core. Also further downstream a continuous decrease of the vorticity can be recognized. In the matching TR PIV fields the primary vortex is found to deteriorate in these regions. This process happens as the small scale vortex structures embedded in the primary vortex cause a disintegration of the primary vortex into smaller vortex structures. This mechanism can not be observed in the phase averaged 3D-LDA data directly, but only from the decay of the vorticity and Reynolds stress components (not shown here).

4. DISCUSSION

In the previous section the cylinder wake has been investigated as an example for an unsteady three dimensional separated wake flow. The cylinder wake in the observed Reynolds number range shows two independent instability mechanisms leading to the formation of two independent vortex structures, the periodic primary vortex street and the intermittently periodic shear layer vortices. The primary and the shear-layer vortices interact and cause a turbulent disintegration of the large scale structures. To observe these features measurement techniques with a maximum spatial and temporal resolution are required. Results have been presented which have been obtained by using two different optical measurement methods.

Two measurement techniques were applied to the cylinder wake flow. First, the 3D-LDA method was used; the LDA velocity data were complemented by phase trigger informations. Second, a time-resolved PIV system was installed to acquire velocity fields in the cylinder wake with a rate of 250 Hz.

Using the TR PIV technique it is now possible to obtain a sequence of instantaneous velocity fields for the unstable separated shear layer in addition to the statistical analysis derived from triggered 3D-LDA. While the development of the vortex structures in the wake can be observed in the velocity and vorticity fields from TR PIV sequences, the distribution of the turbulence production allows an assessment of the influence of the vortex interaction on the
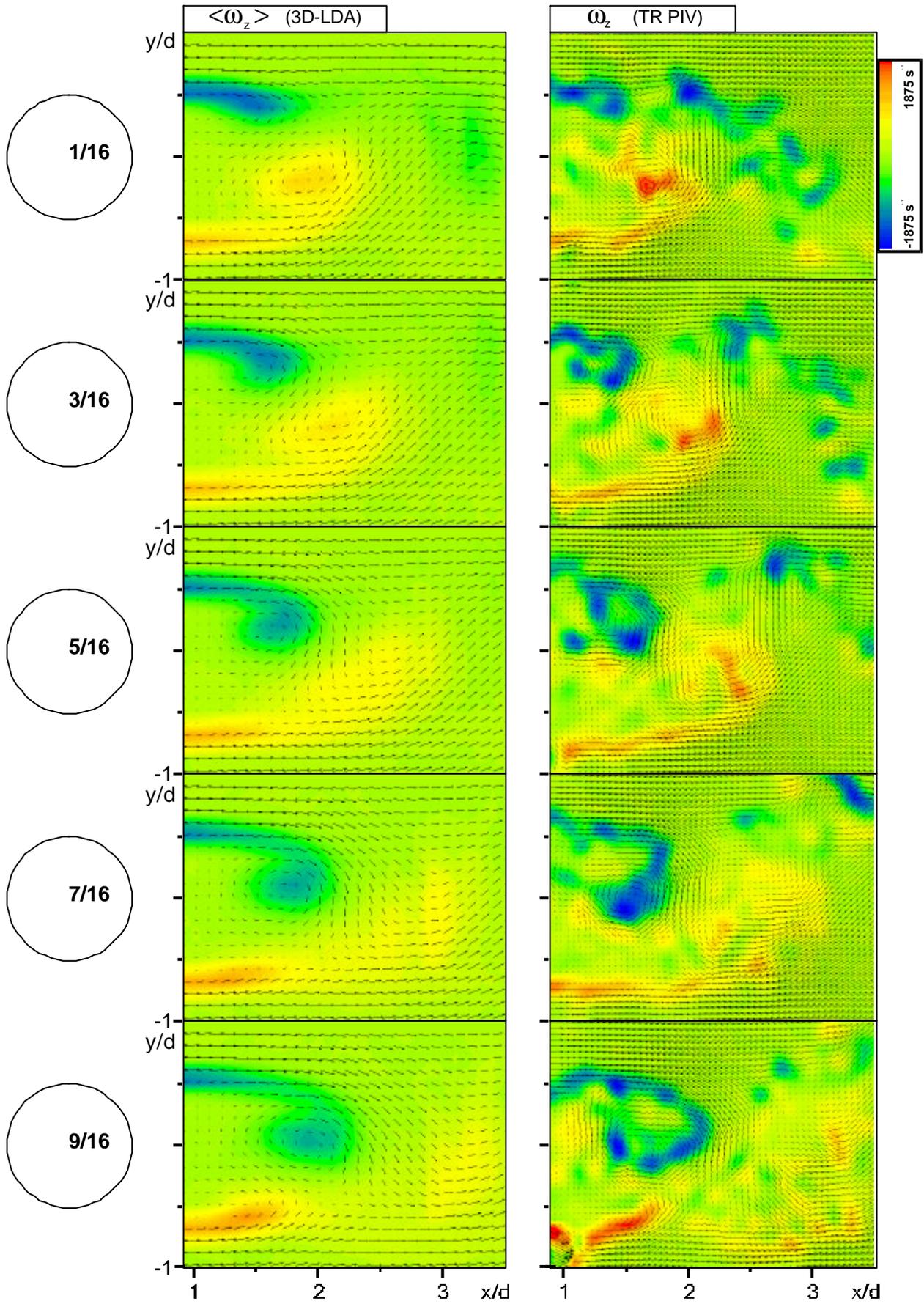
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Fig. 4. Velocity vector field and vorticity component $\mathbf{w}_Z$ (color) in the cylinder wake for Re = 5000, left column: phase- averaged 3D-LDA data, right column: TR PIV (250Hz) for a selected consecutive event

turbulence development. Comparing phase averaged 3D-LDA with TR PIV results it is essential that the large scale wake structure is in good accordance while of the small scale vortex structure measured with the TR PIV technique is must more complex than in phase-averaged LDA-data plots.

Here it is recognizable that the shear-layer vortices are first being wrapped around the cores of the primary vortices. A few cylinder diameters downstream, the primary vortex disintegrates incorporating the small scale vortices.

In the future the use of TR PIV with higher frame rates and larger number of frames will considerably improve the possibilities to perform statistical data analyses.

REFERENCES

Bloor S (1964) The transition of turbulence in the wake of a circular cylinder, J. Fluid Mech. 19, 290-304

Brede M; Eckelmann H; Rockwell D (1996) On secondary vortices in the cylinder wake, Phys. Fluids 8, 2117-2124

Brede M; Leder A (1999) Dreidimensionale Wirbelstrukturen im transitionellen Zylindernachlauf, In Pfeifer H J, Schäfer H J; Ruck B; Dopheide D; Leder A (Editors): Proceedings of the seventh conference "Lasermethoden in der Strömungsmeßtechnik", Saint-Louis, France, paper 27

Brede M; Leder A (2002) On the structure of turbulence in the transitional cylinder wake. In: New Results in Numerical and Experimental Fluid Mechanics III, Notes Numer. Fluid Mech. 77, Springer, Berlin

Brede M (2003) Measurement of the turbulence production in the cylinder separated shear-layer with event-triggered Laser-Doppler anemometry. Submitted to Exp. in Fluids

Gerrard J H (1978) The wakes of cylindrical bluff bodies at low Reynolds number, Phil. Trans. R. Soc. Lond. A 288, 351-382

Leder A; Geropp D (1988) Phase-averaged LDA measurements in turbulent separated flows. In: Duräo, D.F.G. (Editor): Proceedings of the fourth International Symposium on Applications of Laser-Anemometry to Fluid Mechanics, Lissabon, Portugal, paper 3.3

Prasad A; Williamson C H K (1997) The instability of the shear layer separating from a bluff body, J.Fluid Mech. 333, 375-402

Schlichting H; Gersten K (1997) Grenzschicht-Theorie, Springer, Berlin

Unal M F; Rockwell D (1988) On vortex formation from a cylinder. Part 1. The initial instability, J. Fluid Mech. 190, 491-512

Williamson C H K (1996) Three-dimensional wake transition, J.Fluid Mech. 328, 345-407

Westergard C H; Brede M; Leder A (2003) Time-space analysis of time resolved PIV data, PIV03, 5th intl. Conference on PIV, Busan, Korea, September 2003, paper P3214