QUASI-PERIODIC GENERATION OF COHERENT VORTICAL STRUCTURES BEHIND A SURFACE-MOUNTED OBSTACLE

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ABSTRACT
The paper describes the investigation of the shear layer behind a surface-mounted prismatic obstacle placed in a fully developed water channel flow with rectangular cross-section. In the shear layer the formation of three-dimensional coherent vortical structures is investigated at Reynolds numbers of $24{,}000 \leq Re \leq 72{,}000$ related to the obstacle height. A double structure of turbulence in form of primary and secondary vortices can be observed by flow visualization. With different measurement techniques the characteristics of the vortex shedding is further quantified. For a better insight into the spatial distribution of the vortical flow phenomena, a time-resolved PIV-technique is applied. It can be stated that they are still present and coherent at high Reynolds numbers. Additionally, the auto-correlation of single point velocity data in combination with a conditional sampling technique indicates the quasi-periodic generation of the primary and secondary vortices.

INTRODUCTION
Coherent flow phenomena are essential features in the development of turbulent mixing layers. The underlying physics is governed by a three-dimensional unsteady motion with distinct vortex structures. Brown and Roshko (1974) published work on the behavior of large-scale spanwise vortices. These two-dimensional structures, referred to as primary vortices, are a result of the Kelvin-Helmholtz instability caused by the velocity gradients within the shear layer. Between two successive spanwise vortices, streamwise streaks are produced by counter-rotating secondary vortices. Bernal and Roshko (1986) investigated the streamwise vortices and determined the critical Reynolds number at which they can be visualized. A topological model of this double structure of vortices was developed by Hussain and Hayakawa (1987) for the near-wake behind of a circular cylinder (Fig 1). Although these latter authors contributed to the understanding of the shear layer phenomena, many aspects remain speculative, including the dynamical role and the spatial and temporal relationship between successive vortical structures at high Reynolds numbers.

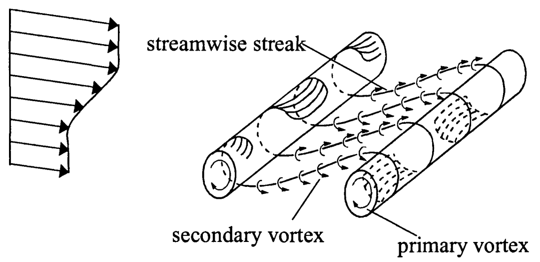

Figure 1: Topological model for the double structure of shear-layer vortices according to Hussain and Hayakawa (1987)

FLOW CONFIGURATION
The investigated flow configuration is the turbulent shear-layer behind a surface-mounted rectangular obstacle of size h = 12 mm (see also Fig. 3). The flow height and width is H = 84.1 mm and B = 120 mm respectively. In the test-rig flow velocities of $2.0\ m/s < u_{ref} < 6.0\ m/s$ are produced, giving a Reynolds number of $24{,}000 < Re < 72{,}000$ related to h.

VISUALIZATION OF COHERENT STRUCTURES
For a detailed investigation of coherent flow phenomena, usually a flow visualization is performed. With a reduction in free stream pressure, the cores of spanwise and streamwise vortices can be set down to vapor pressure so that they fill with gas and vapor. In the present investigation, the cavitating flow indicates the regions of small hydrodynamic pressure due to vortical motion. Cavitation acts as an adequate visualization tool since other methods cannot be applied due to the high Reynolds numbers. The occurring cavitation structures are recorded with a highspeed-videocamera so that the development of the vortical structures can be investigated with high temporal resolution.
It can be observed that cavitation inception occurs not only in the spanwise vortices but also in the form of long, thin cavities oriented at approximately 45° to the mean flow (Fig. 2). These long cavities indicate the low-pressure cores of the streamwise vor-

tices that exist in the braid region between adjacent spanwise vortices and are aligned with the diverging separatrix. The observations correspond well with the topological model of the double structure in form of spanwise and streamwise vortices by Hussain and Hayakawa (1987).

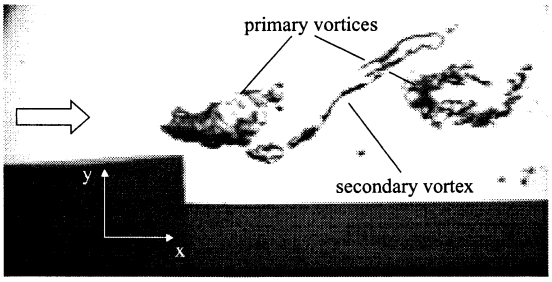

Figure 2: Cavitation in coherent vortical structures visualize the double structure of turbulence in the shear layer

MEASUREMENT OF INSTANTANEOUS VELOCITIES

Flow field measurements

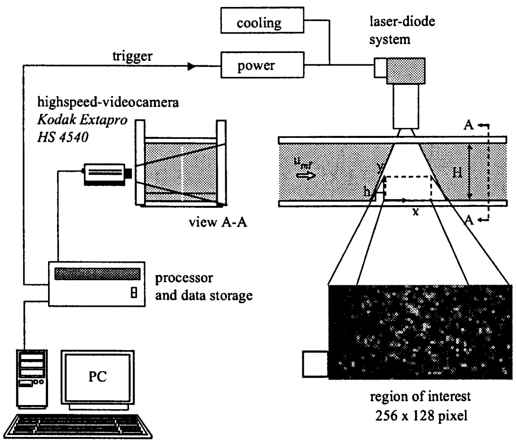

Figure 3: Experimental set-up for the TR-PIV with flow configuration

For the purpose of measuring the unsteady flow field, the video-based Particle Image Velocimetry (PIV) is used. With this optical measurement system, two components (2C) of the unsteady velocity vectors can be determined in a two-dimensional (2D) area of flow. For single frame, single pulsed, planar PIV with high temporal resolution (TR-PIV) a high-speed digital video-camera and a diode laser system is applied at a frame rate of 9,000 Hz. More about this experimental approach can be found in Baur and Köngeter (1999 and 2000). The results provide cinematography of time-dependant velocity fields (2D2C) in vertically oriented planes. The experimental set-up is shown in Figure 3.

Let u, v, w be the velocity components for the x, y, z direction. The Reynolds decomposition (e.g. Adrian et al. 1998) is applied for the u and v components to separate the small-scale coherent turbulent motion from the large-scale recirculation zone behind the obstacle. The method can be described by

$$u = \bar{u} + u' \qquad (1)$$

with time averaged velocities $\bar{u}$ and unsteady fluctuations u' for the x-direction. Time-averaging of the total velocity at each grid point over a sequence of 6500 realizations yields the large-scale motion. So the translation of vortices caused by the large-scale field is removed and the analysis of the turbulent characteristics easier.

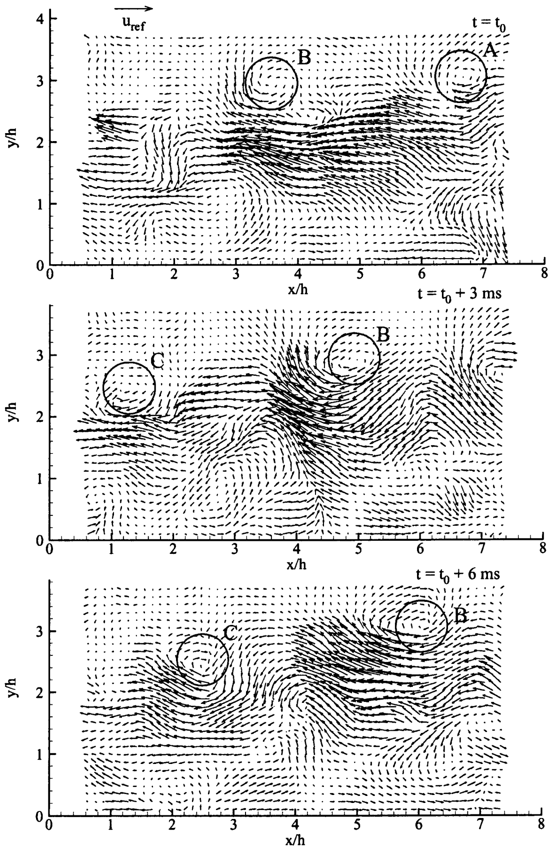

Figure 4: Fluctuating velocities of vortex shedding in a vertical (x/y)-plane behind the obstacle from time-resolved PIV

Figure 4 shows a typical time-series of instantaneous high-pass filtered velocity fluctuations in a vertical plane behind the obstacle at Re = 72,000. The cores of coherent vortical structures are indicated by the circles. The flow pattern shows a roughly circular clockwise-rotating vortical motion and a clear Q2 ejection underneath. Such a vortex pattern corresponds to the physical model of primary and secondary vortices. In the measurement plane a cross-section of the primary vortices and low-speed fluid below is realized. The zones of low-velocity fluid are associated with the formation of secondary, longitudinal vortices. In the wake of vortex A, a second vortex B is generated with same orientation.

Vortex C follows with reduced elongation. The spacing between successive vortices is determined to be S/h = 3.6 in the example.

The presented sequence of PIV realizations shows the efficiency of this measuring technique. Vortical structures are temporarily and spatially resolved. From the investigation of the whole sequence, the formation of spanwise and streamwise vortices turns out to be a quasi-cyclic process. It is not perfectly periodic due to the randomness of phase. Further quantification of the behavior is required.

Single-point measurements

The shedding frequency of the quasi-periodic formation of spanwise vortices is further investigated. In general, the streamwise velocity perturbations are employed for correlation analysis since the turbulence features are the strongest as compared to the transverse and spanwise perturbations, and thus contain the highest signal to noise ratio. In the present paper, the approach bases on the temporal correlation of the time-series of the two-dimensional velocity fluctuations u' and v' measured with a 2D-LDV-system in a single-point with the co-ordinates x_0 and y_0. The detected spatial behavior of the vortical structures (Figure 4) give evidence about the regions in the flow field where the vortex shedding is expected to be detectable from characteristic single-point measurements and the time-series analysis. It is expected that they yield quantitative results on the temporal generation of coherent vortical structures even at high Reynolds-numbers.

Conditional sampling. For conditional sampling of the fluctuating velocity components u' and v', the quadrant-technique using the following three conditions (Nakagawa and Nezu, 1981) is applied:

$$u' < 0 \qquad (2)$$

$$v' > 0 \qquad (3)$$

$$\left| u'v' \right| \geq \left| \overline{u'v'} \right| \qquad (4)$$

The here defined conditions are chosen to describe the characteristic motion of the secondary vortices indicated by an upward motion against the direction of the mean flow. The conditional sampling technique has been successfully used for the investigation of shear-flow phenomena (e.g. Zaman and Hussain, 1984). It provides a filtering of the velocity fluctuations during the post-processing. The filter function is I = 1, if the conditions of Equations 2 to 4 are true, and I = 0 else.

Auto-correlation. The second step in the post-processing is the analysis of the filtered velocity fluctuations by auto-correlation. The auto-correlation of the conditionally averaged velocities is used to determine the average time between the formation of two successive primary vortices but is not capable of detecting individual events. Kim et al. (1971) found that the first positive peak in the auto-correlation corresponded well with the period of the vortex shedding in their flow visualization. Here, the filter function I itself is used for the correlation procedure. The determination of the filter function and its auto-correlation are combined in the definition of the correlation function $\langle I \rangle$ according to Equation 5:

$$\langle I(x_0, y_0, \tau) \rangle = \frac{\int_T I(x_0, y_0, t+\tau) \cdot I(x_0, y_0, t)\,dt}{\int_T I(x_0, y_0, t)\,dt} \qquad (5)$$

For every temporal distance τ between two values I(t) the correlation coefficient is calculated. T is the total duration of the time-series. By this combination of post-processing methods, the temporal and spatial behavior of the vortex shedding is determined.

RESULTS

According to the quantification of the two-dimensional velocity fields with PIV, the plane y/h = 2.5 contains the characteristic flow phenomena. Thus, it was chosen for the LDV-measurements. The sampling rate of the 2D-measurements is 2.2 kHz. In Figure 5 the results of the auto-correlation are presented for different Reynolds-numbers. The computation of the auto-correlation function of conditionally sampled velocity data yields for every Reynolds number the indicated and clearly detectable local maximum at a time-period T_s. This period represents the mean shedding period of the primary vortices. It consequently also indicates the average wavelength of the spanwise vortical structures.

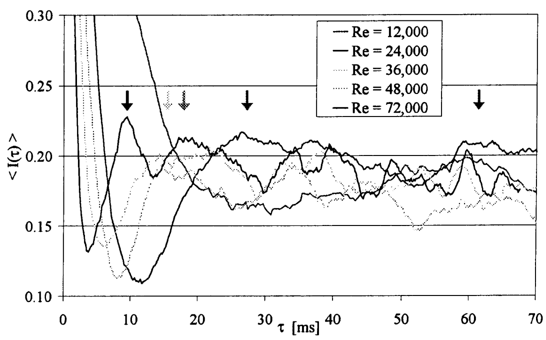

Figure 5: Auto-correlation coefficients of the filter function I in the measurement point x/h = 2.0 and y/h = 2.5

The shedding frequency of the vortices increase proportionally with the velocity. This leads to a value of the dimensionless Strouhal number Str = $h/(T_s \cdot u_{ref})$ practically independent of the Reynolds number (Figure 6). The shedding frequency $f = 1/T_s$ obviously is only dependent of the outer flow variables and is proportional to the inflow velocity u_{ref} and the Reynolds-number Re. A constant value of Str = 0.22 can be estimated.