Analysis of fluid - structure interaction with PIV and LV:  
the case of a splitter plate in a converging channel

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ABSTRACT

The three-dimensional structure of the wake generated by a splitter plate (flat plate with tapered trailing edge) separating two accelerating turbulent streams of equal velocity is studied experimentally with Stereoscopic Particle Image Velocimetry (SPIV) at a moderate Reynolds number. The wake is characterized by cellular shedding resulting from a complicated flow – structure interaction, in which three-dimensional modes of the plate vibration result in a standing wave along the plate trailing edge. Vortex shedding at the trailing edge occurs in cells separated by nodes of the standing wave. The vibration modes are not discussed in this paper, but the emphasis is on the flow phenomena. This paper also focuses on the presentation of data analysis techniques for SPIV measurements to assess complicated, highly three-dimensional fluid dynamics of the wake. Many fundamental features of the shedding process controlling the wake can be derived from the time-mean statistics. Velocity and turbulence data presented in a plane normal to the main flow direction visualize clearly the cellular structure and related secondary flows. Cellular structure is established by spanwise periodic appearance high-speed fluid inside the wake. The spanwise location of high-speed fluid coincide with the nodes the standing wave at the plate tip. Highest turbulence energy is concentrated to the regions between the nodes, referred as anti-nodes. Much of the potential of the PIV-technique lies beyond the determination of the mean-flow pattern and turbulence levels. To estimate the energy and spatial distribution of vortex shedding, spectral and correlation methods are adapted to the PIV data. By presenting the spanwise variation of the streamwise spectra along the trailing edge, the nature of vortex shedding is confirmed. High turbulence energy at the anti-nodes is related to a very narrow band of wavelengths resulting from the vortex shedding. 2D space correlation function reveals that the shedding in two neighbouring cells takes place in 180deg phase-shift. This is observed also in instantaneous velocity fields. Laser Vibrometer (LV) is used to measure the vibration of the plate tip. The spectra of the plate vibration are compared to those measured from the fluid. In addition to LV, image analysis techniques are applied to the PIV-images to determine the properties of the plate vibration. Cellular structure, i.e. a standing wave, is observed in the vibration of the plate tip. Lower vibration energy is related to the node locations, where as the energy is clearly higher around the anti-node locations. Finally the information of the plate vibration and velocity field are combined by establishing conditionally averaged flow fields as a function of the plate vibration phase. These results show that the vortex shedding is synchronized to the phase of the plate tip vibration.
1. INTRODUCTION

Cellular shedding of spanwise vorticity is observed at the trailing edge of a splitter plate. The build up of the cellular structure is a result of a complicated flow – structure interaction (FSI), in which three-dimensional modes of the plate vibration establish a standing wave along the plate trailing edge. Vortex shedding occurs in cells separated by nodes of the standing wave. This paper aims at explaining the three-dimensional flow structure of the near wake due to the cellular shedding and to present some properties of the plate vibration including the presence of the standing wave. The source of the plate vibration and the feedback mechanisms between the vortex shedding and plate vibration are not discussed here.

The experiments are conducted in a 2D convergent channel, where the splitter plate, which is actually a flat plate with tapered trailing edge, is mounted. The motivation to this study arises from a nozzle design in which the splitter plate is used to divide two streams and three-dimensional secondary flows arising at the trailing edge should be avoided to ensure controlled mixing.

The structure of the wake in the present setup has much in common with the observations made from the wakes of flexible cables for which the vortex induced vibration can establish a standing wave along the cable (see for example Newman & Karniadakis 1996). Other typical cases to produce cellular shedding are those of rigid cylinders placed in spanwise shear flow and spanwise tapered bodies placed in homogeneous flow (see for example Lucor et al. 2001 and Castro & Rogers 2002). In these cases the spanwise variation of preferred shedding frequency forces static cells with different shedding frequencies to form along the span of a cylinder.

This paper starts by presenting the experimental setup and short description of the measurement techniques, including Stereoscopic-PIV (SPIV) and Laser Vibrometer (LV). Then, the analysis techniques for the SPIV data are introduced. Description of the spectral analysis and 2D-autocorrelation estimation adapted to PIV-data are explained. Also the image analysis technique to extract the plate tip movement from the PIV-images is presented. The results section presents the mean-flow pattern of the wake with secondary flows, the characteristics of vortex shedding and some properties of the plate vibration. Finally the connection between the plate vibration and vortex shedding is established based on the results presented.

2. EXPERIMENTAL SET-UP AND DATA ACQUISITION

The measurements are carried out in a 2D convergent channel. Important dimensions, normalized by the trailing-edge thickness (h = 1mm), are presented in Fig. 1. Width of the channel is 120h. The length of the splitter plate is 600h with last 50h of the plate tapered from the body thickness of 3h to 1h in the trailing edge. The plate is hinged from the upstream end, while the other end is free to move according to flow. The material of the plate is polycarbonate (\(\rho=1200\text{kg/m}^3\)). The convergent channel is installed into a water loop fed by a centrifugal pump. The Reynolds number based on the trailing-edge thickness (h = 1mm) and the free-stream velocity at the tip (\(U_e = 11\text{ m/s}\)) is 11,000. This free-stream velocity is used to normalize the velocities. The coordinate system is also presented in the Fig. 1.

Fig. 1. Dimensions of the convergent channel and the splitter plate.

SPIV (2D-3C) measurements are performed just after the trailing edge in the x-z-plane. A measurement window with dimensions of 50x40h^2 is used and vectors are computed to a grid with the size of 86x62 nodes. This results in a spatial resolution of 0.6h, which is the spacing between vectors. A traversing system can be used to scan the wake in several x-z-planes with 1h spacing in y-direction. This is only slightly more than the spacing between vectors in the measurement.
plane. The calibration of the SPIV-system is performed separately on each level to minimize registration errors. All together seven planes are measured (+/-3h in relation to the wake symmetry plane). The location of the SPIV measurement planes is presented in Fig. 2. In the $xy$ –plane normal PIV (2D-2C) measurements are conducted. In this plane the measurement window is smaller with dimensions of 30x12h$^2$. This window size yields a spatial resolution of 0.4h. Again several planes are scanned in z-direction by the traversing system, which is also illustrated in the Fig. 2. Vector fields are computed with standard two-pass FFT-algorithm utilizing decreasing interrogation area size (64pix/32pix) and 50% over-lapping between adjacent interrogation areas.

![Fig. 2. PIV measurement positions in the x-y –plane and x-z –plane and LV measurement positions in the plate tip.](image)

Laser Vibrometer (LV) measurements are conducted close to the plate trailing edge. LV is used to investigate the amplitude and spectrum of plate vibration. The measurement points are aligned in z-direction according to the PIV measurements to a node and anti-node position of the standing wave. The measurement positions are located only 2h upstream from the trailing edge, as illustrated in Fig. 2. The sampling rate is 10kHz and the number of samples is roughly 64000. The LV-system provides a voltage output proportional to the velocity of the surface. Thus by using appropriate calibration procedure one can record the time-trace of the surface velocity. The system used in these experiments is a commercial one; Dantec DISA 55X. The analysis of the LV-data is explained below.

3. DATA ANALYSIS

Next the analysis techniques for the SPIV data to elucidate complicated and highly three-dimensional fluid dynamics of the wake are presented. Many fundamental features of the shedding process controlling the wake can be derived from the time-mean statistics. The SPIV-data is used to compose the time-mean turbulence quantities in a 3D-volume by combining several individual measurement planes. This is done to visualize better the mean-flow pattern and especially the secondary flows. However, much of the potential of the PIV-technique lies beyond the determination of the mean-flow pattern and turbulence levels. To estimate the energy and spatial distribution of vortex shedding, spectral and correlation methods are adapted to the PIV data. These techniques further describe the nature of cellular shedding. In addition to LV, image processing techniques are applied to the PIV-images to determine the properties of the plate vibration. Also the data analysis procedure to treat the LV data is explained briefly. More detailed description of the data analysis procedure is presented in Eloranta et al. (2004). In the following instantaneous velocity is denoted by $u$, fluctuation component by $u'$ and mean-value by $U$.

3.1 The construction of the 3D mean-flow field

Several $xz$ –planes are measured across the wake with the spacing of 1h. This data can be used to create a 3D-volume for the time-mean turbulence quantities. As the first step, the data on each level is processed individually to yield the time-mean statistics, such as mean and RMS velocities. After this the computed statistics on each layers is combined into a 3D-volume simply by placing successive layers into a form of 3D-matrix. In this case, the resolution in y-direction is slightly lower than in the measurement plane. This 3D data volume can be cut in any plane, also in the $yz$ –plane, which cannot be directly measured in the present set-up. This plane is particularly interesting since the secondary
flows related to the cellular structure are hard to discern in the other planes. The statistics on each plane is based on a set of 500 velocity fields. The contours presented in the y-z plane utilize some averaging in the streamwise direction. The averaging is typically performed over three vectors in x-direction to smooth the data.

3.2 Periodic and coherent structures

Already a visual examination of 2D-PIV data allows certain deductions of spatial scales and nature of coherent flow structures to be made. However, a careful analysis of these features is needed. A natural extension to the statistical analysis of the wake described above is the estimation of frequency and amplitude of the vortex shedding and its spatial distribution. Two-dimensional velocity fields allow – with some limitations – the estimation of space-correlation functions and spectra. Poor time resolution inherent in the standard PIV technique is compensated by working in the spatial domain. High-speed PIV can naturally be utilized to estimate these properties in the time-domain. First limitation in the spectral and space-correlation estimations from the PIV-data is the very limited range of scales available. Typically the range of length scales covers only one order of magnitude. Thus, for example the estimation of the full turbulence spectra cannot be a realistic target. However, by choosing appropriate measurement resolution, the spectral analysis and space-correlation functions prove to be effective tools to estimate certain periodic phenomena, such as vortex shedding. Now the data to be analysed is a set of 2D-3C or 2D-2C velocity fields. The analysis can be performed for any velocity component and in any direction. The requirement of stationary data is now not strictly fulfilled, since the flow is accelerating and the wake is developing in the downstream direction. This may broaden the spectral peaks slightly and add some bias to the correlation function, but does not invalidate the methods, because these trends are not too severe.

Estimation of the Power Spectral Density

First the analysis procedure to estimate the spatial distribution of the vortex shedding frequency (or actually the wavelength) and amplitude along the trailing edge is presented. This procedure is based on the computation of 1D Power Spectral Density (PSD). The application of 2D spectral estimation for PIV data is also possible as demonstrated in Piirto et al. (2000). However, now the spatial information is also of interest and 2D-techniques are utilized only in the estimation of the space-correlation function. The starting point of the analysis is an instantaneous velocity field. The PSD can be computed for each column (or row) in the data. Depending on the vector computation parameters, one column contains typically 40-100 vectors. Fig. 3 shows an example of about 90 samples long u_y signal extracted from one streamwise column of the PIV velocity field (processed as explained below) and the resulting PSD. Periodic shedding and the related peak in the spectrum are easily identified from the instantaneous velocity sample. The PSD is computed using zero-padded FFT with a length of 1024. The length of the FFT is large compared to the length of the sample, but since the computational time is not too long, smooth PSD function is preferred.

Fig. 3. An example of a velocity signal measured by PIV and corresponding PSD as a function of the wavelength.

The steps in the pre-processing of the velocity data include trend removal and windowing. The acceleration needs to be removed and there are two options to choose from. The subtraction of the local time-mean value results in the classical Reynolds decomposition. Even though this technique is appropriate in many cases, it does not necessarily provide a signal with zero mean-value, which would be ideal for the estimation of PSD. Thus, another technique using local trend removal is adopted. Sliding mean with user-defined window length is computed for the column to be analysed and subtracted from the data. Now the window length is chosen to be 4λ_x. This actually means high-pass filtering the data, but if the scales of interest are known in advance, this procedure does not limit the useful information. The aim is to estimate the energy related to a certain range of the length scales. The data is windowed using half of a Hanning-
window for both ends of the data. The window covers only 10 samples in both ends and thus does not influence most of
the values. This is done just to suppress the discontinuities in the ends of the data.

The actions described above are performed for each column in the velocity field and as a result, a map portraying
instantaneous streamwise PSD’s as a function of the spanwise location is accomplished. If the spanwise variation is not
of interest, these PSD’s can be averaged in the z-direction. However, in this case the cellular structure is studied and
variation in the z-direction is an important issue. The instantaneous PSD map is computed for each velocity field after
which all the PSD maps are averaged. This averaging procedure corresponds to that carried out in the classical Welch-
method, in which the signal is divided in several overlapping sections, the PSD is computed for each section and these
PSD’s are averaged. Now the instantaneous velocity fields correspond to sections in the Welch-method. The averaging
is carried out for a set 500 measurements resulting a map for the time-mean spectrum as a function of the spanwise
location. Examples of such maps are presented in Fig. 9.

The analysis procedure is described for the data measured in the x-z –plane, but in the results section also spectra
estimated from the x-y -plane are presented. The procedure is exactly the same as in the x-z –plane, but the variation of
the shedding energy is naturally estimated as a function of the y-coordinate.

**Estimation of the 2D auto-correlation function**

In the estimation of the 2D space auto-correlation function (2D-SACF) the information of the spanwise location is
discarded and spanwise homogeneous mean-velocity field is assumed. The estimation of the 2D-SACF starts from an
instantaneous velocity field. The auto-correlation function $r$ for positive correlation lags can be computed as follows:

$$
\hat{r}(\Delta i, \Delta j) = \frac{1}{(p - \Delta i)(q - \Delta j)} \sum_{i=1}^{p-\Delta i} \sum_{j=1}^{q-\Delta j} u'(i, j) \cdot u'(i + \Delta i, j + \Delta j)
$$

The equation for the negative lags is very similar. Variables $\Delta i$ and $\Delta j$ correspond to the correlation lags in x- and z-
direction, respectively. The symbols $p$ and $q$ correspond to the dimensions of the data matrix. Now only the auto-
correlation functions are computed, but the procedure can also be used to estimate the cross-correlation functions.

The average 2D-SACF map is computed simply by taking the mean of all the 500 instantaneous correlation maps.
Examples of mean correlation maps are presented in Fig. 11. Auto-correlation at zero lag is normalised to the value of
1.0, which is also obvious from the equation 1. The correlation map is symmetrical so that the 1st and 3rd quadrants
share the same information. The same is true for the 2nd and 4th quadrants. However, for the sake of visualization the
entire correlation map is always presented.

Combining the results from the spectral estimation as a function of the spanwise location and 2D-SACF map gives very
circumstantial insight into the process of vortex shedding as will be presented in the results section.

**3.3 Detection of the plate movement**

The analysis of the image data acquired in the PIV-experiments is not limited to the determination of the fluid velocity
field. In this case, an image processing algorithm is used for the data acquired in the x-y-plane to detect the position
and velocity of the splitter plate tip in the direction normal to the main flow. This is naturally done simultaneously with
the fluid velocity measurement. This is of interest since the plate vibration has an essential role in the fluid mechanics of
the wake. Another example of application combining image analysis with the evaluation of fluid velocity field is the
analysis of the dispersed phase in multi-phase flows (see for example Honkanen et al. 2004 and Eloranta et al. 2004b).

The PIV laser sheet illuminates the lower surface of the plate tip, as can be seen in Fig. 4. This image is cropped from
the original PIV-data and thus some particles are also visible. The y-position of the plate tip is determined by locating
the lower surface. To this end, the image is first median filtered to reduce the effect of particle images. The size of the
median filter kernel is 5x5 pixels. Then a convolution of the image is taken with a mask representing a vertical line.
This operation further unifies the surface line. The image after these steps is presented also in the Fig. 4. To find the
location of the surface in y-direction, vertical intensity profile is extracted over a region indicated by a rectangle. The
maximum of the profile is located with an accuracy of one pixel. Then three points of the profile around the maximum
are used to achieve sub-pixel accuracy with a polynomial fit on these values. The fitting procedure corresponds to that
used in PIV-algorithms for sub-pixel displacement.
The velocity of the plate tip is determined from this data by a cross-correlation algorithm. An interrogation area is placed to cover a small section of the plate lower surface. This is done based on the information of the plate position. From the computed cross-correlation map only the shift in the y-direction is determined. The cross-correlation is computed from the original image without image enhancement. Now the sub-pixel accuracy is obtained with 1D Gaussian peak-fitting algorithm, similar to a typical PIV-algorithm.

The accuracy related to the determination of the plate position, which is usually better than one pixel, is good compared to the amplitude of the plate vibration, which is in the order of 20pix. A visual inspection of one data set, i.e. 500 frames, showed that only in two frames the tip position was determined incorrectly due to a large cluster of particles passing the surface and introducing strong intensity compared to the reflection from the plate surface. The determination of the plate velocity is more susceptible to errors since the y-displacement of the tip is typically less than one pixel between the two frames. The error analysis is not trivial and should follow the guidelines formulated for PIV-algorithms, for example those presented in Fincham & Spedding (1997) and McKenna & McGillis (2002). Considering the thickness of the flare and reflection at the surface as an estimate for the particle size, it is reasonable to expect accuracy in the order of typical PIV-experiment, say 0.2pix. However, the velocity of the plate tip is used in the following only to provide the direction of motion and the energy of vibration. For these purposes the accuracy is seen adequate.

After repeating the above-explained process for the entire data set, one has the information of the plate tip location and velocity measured simultaneously with the fluid velocity field. It is shown by LV measurements that the tip vibrates sinusoidally at a distinct frequency. To study the coupling between the plate vibration and vortex shedding, the fluid velocity data is conditionally averaged according to the phase of the vane tip. Since sinusoidal vibration mode is expected, the plate tip location and speed can be used to determine the phase of the tip in the vibration cycle. The entire cycle is divided in 8 phases. Conditional average, or actually a phase average, of the velocity field is established by sorting the velocity fields according to the tip phase and averaging the velocity fields related to a certain phase. For a set of 500 images, the number of fields used for the computation of the phase average is thus about 30.

### 3.4 Analysis of the LV signal

The signal from the LV system is first multiplied by a calibration coefficient to yield the velocity signal in the dimension of m/s. Then the signal is band-pass filtered between 1kHz and 3kHz. This band is centred on the vortex shedding frequency. Low frequencies are removed since they are related to the vibration of the entire test bench and low-pass filtering is utilized to remove noise. Spectrum of the vibration signal is computed using Welch-method and 2048 samples long FFT, with 50% overlapping and Hanning window. Examples of the spectra of the plate tip vibration are presented in Fig. 12.

## 4. RESULTS

First the mean-velocity field of the streamwise component ($U_x$) in the $xz$-plane is presented in Fig. 5. The data is measured in the wake symmetry plane ($y=0$) just after the trailing edge. The main flow direction is from bottom to top. Organized secondary structure is clearly observed in a form of a periodic spanwise variation of the mean velocity. A trace of this pattern can also be observed in the instantaneous velocity fields as a discontinuity in the vortex shedding as will be shown later. In Fig. 5, also the RMS velocity field for the same data set is presented. The spanwise inhomogeneity of the wake is evident also in terms of turbulence intensity. To visualize the 3D-structure of the wake, the mean-flow field in the $xy$-plane at 10h down-stream of the trailing edge is presented in Fig. 6. Contours on the background represent the streamwise velocity component $U_x$, and vectors the in-plane components, i.e. $U_y$ and $U_z$. This figure clearly shows that a cellular 3D-structure is formed. The high velocity streaks appearing in the Fig. 5 divide the
wake in cells with distinct secondary flow pattern. At the locations of high streamwise velocity, referred as ‘nodes’ in the following, the $U_y$ component is strong and free-stream fluid is entrained inside the wake. On the other hand, this entrained fluid is partly conveyed to the cells by the action of $U_z$-component. Below the mean-velocity field, the turbulence intensity field at the same position is presented. The cellular structure is again evident. Highest turbulence energy is related to the regions between the nodes, which are referred as ‘anti-nodes’.

Fig. 5. Contours of the streamwise mean velocity and turbulence intensity in the x-z-plane at the centre of the wake.

Fig. 6. Mean-velocity and turbulence intensity fields in the y-z-plane at 10h downstream from the trailing edge.

Next examples of instantaneous velocity fields in the x-z-plane are presented in Fig. 7. The measurement position is the same as for the mean-velocity data presented above. Contours on the background correspond to the $u_y''$-component and the vectors to the $u_x''$- and $u_z''$-components. The double prime in the velocity component signifies that a spanwise constant mean-velocity field is subtracted from the original velocity field. This procedure removes the streamwise mean-acceleration from the instantaneous fields. This approach is chosen to better visualize the high-speed regions in the fluctuation fields. Periodic shedding patterns are striking in most images, especially in the contours of $u_y''$. In many cases the vortex tubes show high spanwise coherence over the entire cell, i.e. between the high-speed streaks in the mean-velocity field. The vortex tubes in the adjacent cells are connected through a dislocation or a kink crossing over the high-speed streaks. At least in some cases it is evident that the vortex tube is bent to the downstream direction close to the high-speed streaks. This is expected, if the higher convection velocity pulls the ends of the vortex tube in the streamwise direction. In some frames, such as the example in the middle, the shedding is unorganized with more or less chaotic pattern. However, most of the frames show very clearly organized patterns as in the first and last example.
Examples of instantaneous velocity fields in the \( xy \)-plane in the node and anti-node locations are presented in Fig. 8. Contours on the background represent spanwise vorticity \((\omega_z)\). In the node position shedding is intermittent and weak. In the anti-node clear shedding structure is always visible.

**Fig. 7. Examples of instantaneous velocity fields in the \( x-z \)-plane.**

**Fig. 8. Examples of instantaneous velocity fluctuation fields in the \( x-y \)-plane. Data from the node on the left and from the anti-node on the right.**

Periodic structures in the instantaneous fields are further analyzed by the computation of the streamwise PSD estimate as a function of the spanwise position. The data used for this analysis is the same as used for the computation of mean-flow field in Fig. 5. The results are presented in Fig. 9. Spectra for all three velocity components are presented. The spanwise location (\( z \)-direction) in on the abscissa and the wavelength on the ordinate-axis. Spanwise variation of the turbulence energy was already observed in the velocity RMS-field. Now the spectra show that the turbulent fluctuations are related to a very narrow wavelength band. The dominant shedding wavelength is clearly visible and fairly constant across the span of the measurement window. Especially the fluctuations of the \( u_z \) component are concentrated on the edges of the high-speed regions.

**Fig. 9. Streamwise spectra computed from the PIV-data in the \( x-z \)-plane.**
To further scrutiny the differences of vortex shedding in the node and anti-node positions, instantaneous peaks of the spectra (i.e. peak energy and the wavelength related to the peak) are analyzed for the data measured in the the $xy$-plane. Instantaneous spectrum means now a spectrum computed from one vector field. Scatter plots of instantaneous shedding energies and wavelengths are presented in Fig. 10. Although the resolution of the FFT-estimate is not sufficient to produce smooth distribution for the wavelengths, the differences between the node and the anti-node are clearly seen. The scatter plots show that in the anti-node, the energy and frequency of the vortex shedding do not vary much from one realization to another. This is not the case in the node, where instantaneous energies and wavelengths have higher deviation. The shedding is not totally absent in the node, but the energy is approximately half of that related to the shedding in the anti-node position. The shedding wavelength is approximately the same. This confirms the conclusions made from the Fig. 8. Another conclusion from these plots is that there is some variation in the instantaneous shedding frequency, but it does not show for example intermittent switching between two separate frequencies, which is sometimes observed in forced vibration.

![Fig. 10. Distribution of energy vs. wave-length of instantaneous streamwise spectra for $u_y$ in the node (left) and anti-node (right) positions.](image)

The organization of the periodic shedding pattern is further analyzed by the computation of 2D space auto-correlation maps, which are presented in Fig. 11 for all the velocity components. Again only the data in the wake symmetry plane is presented. The pattern found in the correlation maps confirms the observations made from the instantaneous fluctuation fields in Fig. 7. Maximum correlation in the streamwise direction is achieved at the distance of about $5h$. This is naturally the wavelength produced also by the spectral estimation. In $z$-direction the maximum correlation is found at the distance of $38h$ corresponding to the distance over two cells. There is actually a negative correlation at the distance of $19h$, which indicates that two adjacent cells shed vortices with 180 deg phase shift. This phenomenon can be identified already from the examples of the instantaneous velocity fields. The fact that the correlation map shows such a clear pattern, indicates strongly that this is a very well organized periodic structure and not just an incident captured in some example fields.

![Fig. 11. 2D-SACF computed from the PIV-data in the $x-z$-plane.](image)

The results presented above imply that the shedding process locks into particular positions along the span of the trailing edge. The reason for this behavior is the vibration mode of the plate resulting in a standing wave along the trailing edge. The vibration of the splitter plate is examined both with the LV-data and PIV-images. Spectra of the plate tip vibration measured by the LV-system in two $z$-locations are presented in Fig. 12. Only the range between 1-3kHz is shown, since it is known to be the range of the vortex shedding at the plate tip. The dominant frequency peak in this range is
distinctly visible. The energy of the plate vibration is considerably higher in the anti-node position compared to the node position. Similar analysis can be performed by determining the plate tip location and velocity from the PIV-images measured in the x-y-plane. In this plane several z-locations along the span of one cell are measured. Fig. 13 shows the z-profile of the RMS of the plate tip velocity between two nodes. Cellular structure is also observed in the vibration of the plate tip. Lower vibration energy is related to the node locations, whereas the energy is clearly higher around the anti-node locations. This is in accordance with the LV-results.

The frequency obtained by the LV-system is the same both in the node and anti-node positions. This frequency can be compared to the frequency of vortex shedding determined from the PIV-data by the estimation of PSD. Fig. 14 presents a 1D spectrum in the space-domain computed from the PIV-data in the x-y-plane (anti-node location) for the u_y-component. Maximum energy is located at the wavelength $\lambda_{PIV} = 5.34h$. This value can be converted into frequency domain by choosing a convective velocity from the mean-velocity field of the corresponding data set. The mean-velocity field in the xy-plane computed from the data used for the PSD estimation is presented in Fig. 15. Let us assume that the convection velocity of the vortices is the mean velocity along the streamline where the vortex centers are typically convected. Since the flow is accelerating, this convection velocity is not constant in the x-direction. Thus, also the actual wavelength varies in x-direction, since the wake is developing. The vortex streets are typically located at $y = \pm 1.25h$, which can be estimated from the RMS-fields in the x-y-plane (not shown here). The velocity at this y-location is approximately 10.5m/s, which yields a frequency of 1966Hz. This value can be compared to the flat plate vibration frequency from the LV-measurement, which is 1965Hz. The agreement is excellent.

Fig. 12. Spectra of the plate tip vibration from LV-data measured in the node and anti-node positions.

Fig. 13. Z-profile of the plate tip vibration intensity over one cell, i.e. the span between two nodes.
Fig. 14. Streamwise PSD computed for $u_y$ in the wake symmetry plane. The data is measured in the x-y plane in the anti-node position.

Fig. 15. Mean-velocity field in the x-y plane in the anti-node position.

Finally the relation between the phase of the vortex shedding and the tip movement is studied. In the analysis of plate vibration from the PIV-data, the location and the velocity of the plate tip are determined for each individual frame in the set of 500 images. This information can be tied to the flow field by constructing a set of conditional mean-velocity fields according to the movement (phase in the periodic cycle) of the plate tip. Naturally the assumption behind this operation is that the plate vibration is related to the vortex shedding and the plate vibrates in a characteristic (sinusoidal) periodic mode. The latter is confirmed by the LV-measurements. The path of the plate tip is decomposed into eight phases, which are illustrated by red dots in Fig. 16. For example, the location of the tip is the same in 1st and 5th phase but in the 1st phase the plate tip is moving up and in the 5th down. Red line extending over all the averaged velocity fields can be used as an aid to follow the phase of individual vortices. One can notice that the yellow vortex under the line in the first image starts moving to the right as the phase of the tip proceeds (figure by figure). In the last frame the situation is almost the same as in the first frame and the cycle starts again from 1st phase. This sequence of frames simply proves that the vibration of the plate is synchronized to the vortex shedding.

5. CONCLUSIONS

The combination of PIV to study the flow and LV to measure the mechanical vibration of a structure separating two streams proves to be successful in showing the origin of three-dimensionality of the mean-flow field. In this paper, we have shown that the wake behind a two-dimensional body under negative pressure gradient develops a distinct three-dimensional structure. The fundamental reason for this phenomenon is a complicated fluid-structure interaction between the flat-plate and the fluid. It is shown that a standing wave pattern is established on tip of the flat plate, which enhances the vortex shedding in the anti-node positions. Future work is focused to understand the actual mechanism of receptivity and the energy transfer between fluid and the plate.
Fig. 16. Phase-averaged velocity fields after the plate tip as a function of the tip phase (presented as a red dot).

REFERENCES


