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Coherent structure eduction from PIV data of an electromagnetically forced separated flow

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Abstract

Periodic addition of momentum by wall parallel electromagnetic forces has a strong influence on the separated region of a stalled airfoil. As in the case of periodic blowing and suction, actuation frequency and momentum input are the main factors of influence. However, the control authority depends as well on the actuation wave form. This latter aspect is investigated in the present paper by means of time resolved particle image velocimetry data from the suction side of an inclined flat plate. The control effect is rated by the size of the remaining recirculation region in the time averaged flow fields. Typically, the controlled flow possesses a small number of relatively large vortices, which are assumed to be related to the control mechanism. Consequently, the time resolved flow fields have been analysed by proper orthogonal decomposition and continuous wavelet transform to extract dominant features of the flow.

Keywords: Flow control; Coherent structures; Proper orthogonal decomposition; Continuous wavelet transform

1. Introduction

Flow separation control is a long standing topic in fluid mechanics research, since it has significant technological consequences. An overview of flow control including a comprehensive discussion of separation control is given by Gad-el-Hak (2000). Among the various methods available to control flow separation, the periodic addition of momentum is a relatively new one. Since it is often successful and requires for the same control goal, i.e. lift increase, typically much less momentum input than static actuation, periodic excitation has been intensively investigated during the last two decades. "Active flow control", a term now commonly used for periodic excitation, has been extensively reviewed by Greenblatt and Wygnanski (2000), additional aspects can be found in the more recent overview by Seifert et al. (2004). The canonical case of the flow around a circular cylinder controlled by internal acoustic excitation has been investigated, e.g., by Huang (1995), Fujisawa and Takeda (2003) and Fujisawa et al. (2004). Commonly, the excitation frequency and the time averaged momentum input are regarded as the key control parameters.

Seifert (2007) characterizes actuation as the "primary enabling technology" for active flow control. Widely used actuation systems are, among others, loudspeakers, rotating valves connected to pressure sources and/or sinks, surface mounted piezo benders, and piezo fluidic actuators. In electrically conducting fluids, momentum input can be realized as well by electromagnetic, i.e. Lorentz forces. Lorentz force actuators do offer a number of attractive features:

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momentum is generated directly in the fluid without associated mass flux, the frequency response of the actuation is practically unlimited, no moving parts are involved. In the case of low conducting fluids and weak magnetic inductions, to which the present paper is limited, the force is independent of the flow and can be easily computed from first principles. These advantages are, however, bought dearly by a low energetic efficiency, which is intrinsically coupled to the generation of Lorentz forces with strong electric and weak magnetic fields (Shatrov and Gerbeth, 2007). In spite of this, Lorentz force actuators are a valuable tool for basic research, and a considerable amount of experimental and numerical data on electromagnetic flow control in poorly conducting fluids has been collected. For a recent review we refer to Weier et al. (2007).

The successful application of time periodic Lorentz forces to control separation at stalled airfoils has been shown experimentally by Weier and Gerbeth (2004) and Cierpka et al. (2007) and numerically by Mutschke et al. (2006). In the present paper, specifically the rôle of the actuation wave form for otherwise fixed parameters is discussed based on time resolved particle image velocimetry (TR-PIV) data. While actuation wave form effects have previously been observed in conventionally, see, e.g., Margalit et al. (2002), as well as in electromagnetically excited (Weier and Gerbeth, 2004; Cierpka et al., 2007) separated flows, the underlying mechanism is not yet fully understood.

2. Experimental set-up and parameters

Fig. 1 shows the arrangement of flush mounted electrodes and permanent magnets which has been used to generate a wall parallel Lorentz force. This assembly was proposed by Gailitis and Lielausis (1961). The Lorentz force density

$$\mathbf{F} = \mathbf{j} \times \mathbf{B} \tag{1}$$

is the cross product of a current density $\mathbf{j}$ and a magnetic induction $\mathbf{B}$. As mentioned above and described in detail, e.g., by Weier and Gerbeth (2004), the current density distribution is independent of the flow in the case considered here. The electric as well as the magnetic fields have, apart from end effects, only components in wall normal and spanwise direction. Owing to Eq. (1) the Lorentz force distribution possesses a wall parallel component F_x only. The magnitude of the Lorentz force density is largest directly at the wall and decays exponentially with the wall distance. For further details and explanation, we refer to Weier and Gerbeth (2004).

The forcing level is characterized by an effective momentum coefficient as

$$c'_\mu = \frac{1}{2}\frac{aB_0}{\rho u_\infty^2}\frac{l}{c}\sqrt{\frac{1}{T}\int_0^T j(t)^2\,\mathrm{d}t} \tag{2}$$

relating the rms value of the total Lorentz force to a characteristic free stream momentum. In Eq. (2), a is the width of a single electrode or magnet and l its length. B_0 denotes the magnetic induction in wall normal direction measured at the magnets surface, $j(t)$ the current density depending on time t and T the period of oscillation, respectively. As common practice (see, e.g., Greenblatt and Wygnanski, 2000), momentum coefficients are quoted in percentage terms for convenience.

In the current paper, excitation with a triangular wave form and a rectangular wave form with a $\frac{1}{3}$ duty cycle (DC) has been investigated. The $DC = \frac{1}{3}$ rectangular signal is referred to as "pulsed" in the following. In Fig. 2 the wave form of the two signals is given graphically. The excitation frequency $f_e = 1/T$ is normalized using the chord length c and the

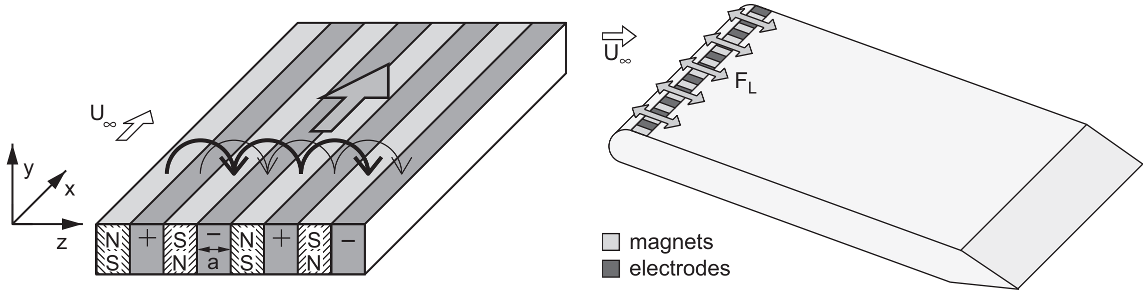

Fig. 1. Electrode/magnet-array generating a wall parallel Lorentz force in streamwise direction (left) and short electrode/magnet-array for time periodic forcing at the leading edge of the inclined plate.

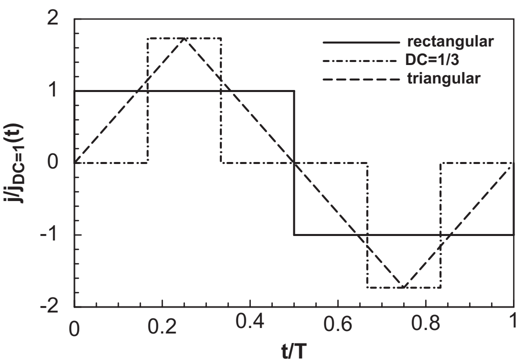

Fig. 2. Wave form of the triangular and pulsed excitation signal, a rectangular waveform ($DC = 1$) is given for reference.

'free stream velocity u_∞ as

$$F^+ = \frac{f_e c}{u_\infty}. \tag{3}$$

The plate used in the experiments was made of PVC and had a circular leading edge, a span width of 140 mm, a chord length of 130 mm and a thickness of 10 mm. Electrodes and magnets had a width and length of $a = l = 5$ mm each. Plate shape and material were chosen as to allow for ease of manufacturing and durability in the electrolyte solution (0.25 M NaOH). The PIV measurements reported in the following were performed in a small electrolyte channel, driven by a centrifugal pump. A settling chamber with a free surface and equipped with a filter pad, two honeycombs and a set of four screens result nevertheless in a relatively small turbulence level in the test section. The latter, featuring a free surface as well, is 1 m long and has a $0.2 \times 0.2\,\mathrm{m}^2$ cross section. To reduce end effects the plate has been mounted between rectangular plates with rounded edges made from PMMA extending from the bottom of the test section to the free surface in vertical and from 30 mm in front of the leading edge to 30 mm behind the trailing edge in horizontal direction. At the surface of the magnets, a mean magnetic induction of $B_0 = 0.35$ T has been measured. A high power amplifier FM 1295 from FM Elektronik Berlin was used to feed the electrodes. It was driven by a frequency generator Agilent 33220A.

The PIV set-up consisted of a Spectra-Physics continuous wave Ar^+-laser type 2020-5 as light source and a Photron Fastcam 1024PCI 100 K to record the images. A thin ($\Delta z \approx 1$ mm) light sheet, formed by two cylindrical lenses, was spread at mid-span of the plate extending in the direction of the flow (x) and normal to the test section bottom (y). Since the laser delivered light continuously, the camera was operated in shuttered mode at 60 Hz frame rate with a single image exposure time of 2 ms. For each parameter configuration a total of 6400 single images of $1024 \times 512\,\mathrm{pixel}^2$ has been recorded synchronized to the excitation signal. For the seeding, polyamide particles (Vestosint) of 25 μm mean diameter were chosen. In the plane of the light sheet, x- and y-velocity components have been calculated from the images using PIVview-2C 2.4 from PivTec. Each image was correlated with its successor using multigrid interrogation with a final window size of $16 \times 16\,\mathrm{pixel}^2$ and 50% overlap, image deformation and sub pixel shifting was applied as well.

3. Data postprocessing

While still not fully understood, the physical mechanism of periodic excitation is surely connected to unsteady vortex formation and interaction phenomena. Therefore, the time averaged velocity fields can give information on the overall effect of excitation on the flow but will of course hide the details of vortex interactions. In former studies, e.g., Cierpka et al. (2007), phase averaging was applied to overcome these limitations to a certain extent. However, using rectangular excitation wave forms, peaks of comparable height may occur in the power spectra for several frequencies connected to the Fourier coefficients of the excitation signal and a proper choice of a dominant frequency becomes difficult. Nevertheless, it is necessary to condense the vast amount of information provided by the TR-PIV measurements in order to interpret the data. To extract the coherent structures from the velocity fields several methods have been proposed and were discussed, e.g., by Bonnet et al. (1998).

In the present paper, coherent structures have been educed from the time resolved velocity fields based on continuous wavelet transform (CWT) as well as on proper orthogonal decomposition (POD). It is neither intended nor possible to give a complete treatment of both approaches in the following. Instead, only brief explanations are provided to facilitate understanding of the results.

3.1. Proper orthogonal decomposition

For reduced order modelling and flow structure eduction POD is nowadays almost a standard technique to analyse flow fields. An overview and tutorial has been given, e.g., by Cordier and Bergmann (2003). The basic idea is to find an approximation of the function

$$f(x,y,t) \approx \sum_{k=1}^{K} a_k(t)\Phi_k(x,y), \tag{4}$$

which tends to be exact for $K = \infty$. The POD basis functions $\Phi_k(x,y)$ are chosen to be orthonormal and as good as possible for each K in a least square sense (Cordier and Bergmann, 2003). Considering $f(x,y,t)$ as a flow variable, measured at N_t instants of time, Eq. (4) results in finding basis functions that fulfill

$$\min \sum_{i=1}^{N_t} \left\| f(x,y,t_i) - \sum_{k=1}^{K} (f(x,y,t_i), \Phi_k(x,y))\Phi_k(x,y) \right\|_2^2, \tag{5}$$

where $\|\cdot\|_2$ is the L_2 norm and $(.,.)$ the inner product of two quantities. Using velocity distributions as input, the resulting POD-modes $\Phi_k(x,y)$ are an optimal decomposition in terms of energy. The POD-modes used in the following are based on the vorticity ω (Eq. (9)) and are therefore optimal in terms of enstrophy instead. The choice of vorticity distributions as input follows Kostas et al. (2005) who showed that the convergence of vorticity based POD-modes is superior to that of velocity based modes. Incidentally the computational effort is reduced by a factor of two since only one variable per measurement point has to be analysed. By adequate ordering the measurements into a matrix $\mathbf{A}$,

$$\mathbf{A} = \mathbf{U}\boldsymbol{\sigma}\mathbf{V}^{\mathrm{T}}, \tag{6}$$

the problem can be solved by standard singular value decomposition (SVD) routines. $\mathbf{A}(N_t, N_{x,y})$ denotes the matrix of the measurements. $\boldsymbol{\sigma}$ is the diagonal matrix of singular values in decreasing order $(\sigma_1 \leqslant \sigma_2 \cdots \sigma_{r-1} \leqslant \sigma_r \leqslant 0)$ with $r = \min(N_t, N_{x,y})$. The first r columns of $\mathbf{U} = (U_1, U_2, \ldots, U_{N_t})$ are the left singular vectors and the first r columns of $\mathbf{V} = (V_1, V_2, \ldots, V_{N_{x,y}})$ are the right singular vectors of $\mathbf{A}$ and correspond to the POD-modes $\mathbf{\Phi}_k$.

The data volume generated by the TR-PIV is of the order of $N_t = 6400$ time instants with $N_{x,y} \approx 8000$ vectors each. Performing the corresponding decomposition directly by SVD routines needs a considerable amount of computing power.

To decrease the numerical effort, we followed the snap shot method as proposed by Sirovich (1987). By premultiplying $\mathbf{A}$ with its transpose, one ends up with the eigenvalue problem

$$\mathbf{A}^{\mathrm{T}}\mathbf{A}\boldsymbol{v} = \lambda\boldsymbol{v}, \tag{7}$$

where λ_i are the eigenvalues and $\boldsymbol{v}_i$ the eigenvectors of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$. The singular values are $\sigma_i = \sqrt{\lambda_i}$ and the POD-modes can be calculated using

$$\mathbf{\Phi}_k = \frac{1}{\sqrt{\lambda_k}}\mathbf{A}\boldsymbol{v}_k. \tag{8}$$

The problem size is thereby reduced by a factor of three. Eigenvalue routines from the GNU scientific library (GSL) (Galassi et al., 2006) have been used to perform the computations.

3.2. Continuous wavelet transform

For the CWT, we followed the method proposed by Schram et al. (2004). A two-dimensional Mexican hat wavelet has been used to analyse time resolved vorticity fields calculated from the TR-PIV data. This approach allows the statistical evaluation of different vortex characteristics such as vortex size and circulation, trajectories and mean convection velocities. A comprehensive review of wavelet techniques for fluid mechanics is provided by Farge (1992).

In the following, some practical aspects of the implementation are given. As mentioned above, the procedure follows closely that proposed by Schram (2002), although the vortex detection here is based on the vorticity field

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \tag{9}$$

instead of the enstrophy field. u and v denote the velocity components in x- and y-direction, respectively. The vorticity field is in principle a well-suited basis to detect vortices, since it is Galilean invariant. In order to discriminate between coherent structures and shear layers the λ_2-criterion as proposed by Jeong and Hussain (1995) was used. Assuming two-dimensional, incompressible flow, the criterion reduces to

$$\lambda_2 = \left(\frac{\partial u}{\partial x}\right)^2 + \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}. \tag{10}$$

Vortices are characterized by a negative λ_2. For regions of positive λ_2 the vorticity field has been artificially set to zero. The wavelet analysis was later performed on this thresholded vorticity field.

The two-dimensional Mexican hat wavelet is defined in polar coordinates as

$$\Psi(r, l) = \frac{1}{l}\left(2 - \frac{r^2}{l^2}\right)\exp\left(-\frac{r^2}{2l^2}\right), \tag{11}$$

with the wavelet scale l and the radius r. Again following Schram (2002), the Lamb–Oseen vortex is assumed to be a representative model of the coherent structures. The distribution of tangential velocity u_ϕ and vorticity ω

$$u_\phi(r) = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(\frac{r^2}{2\delta^2}\right)\right], \tag{12}$$

$$\omega(r) = \frac{\Gamma}{2\pi\delta^2}\exp\left(\frac{-r^2}{2\delta^2}\right) \tag{13}$$

describing the Lamb–Oseen vortex is an exact solution of the Navier–Stokes equations. Γ denotes the circulation, and δ the size of the vortex, respectively.

The size of the vortex core D_K is usually defined by the location of maximum tangential velocity and hence is $D_K = 3.17\delta$ for the Lamb–Oseen vortex. Evaluating the wavelet coefficient for a Lamb–Oseen vortex

$$\langle \Psi_l | \omega \rangle = 2\pi \int_0^\infty \underbrace{\frac{\Gamma}{2\pi\delta^2}\exp\left(\frac{-r^2}{2\delta^2}\right)}_{\omega} \underbrace{\frac{1}{l}\left(2 - \frac{r^2}{l^2}\right)\exp\left(-\frac{r^2}{2l^2}\right)}_{\Psi_l} r\, \mathrm{d}r, \tag{14}$$

gives for the derivative of the scale

$$\frac{\partial\langle \Psi_l | \omega \rangle}{\partial l} = -\frac{2\Gamma l^2(l^2 - 3\delta^2)}{(l^2 + \delta^2)^3}. \tag{15}$$

That way it is possible to relate the wavelet scale to the size of a corresponding Lamb–Oseen vortex as $l/\delta = \sqrt{3}$.

Another criterion rates the similarity of the detected structure to a Lamb–Oseen vortex. The absolute value of the wavelet coefficient depends on the size of a vortex and its strength. From Eq. (13) the circulation Γ at the vortex centre reads

$$\Gamma_0 = 2\pi\delta^2\omega_0 \quad \text{for} \ (r = 0). \tag{16}$$

Using the relation $l/\delta = \sqrt{3}$ and Γ_0 in Eq. (14), the maximum wavelet coefficient depends only on the wavelet scale l and centre vorticity ω_0,

$$\langle \Psi_l | \omega \rangle_{\mathrm{th}} = \frac{3}{4}\pi\omega_0 l. \tag{17}$$

The ratio between the detected wavelet coefficient and the theoretical one, β, can be calculated with the vorticity at the centre of the structure as

$$\beta = \frac{\langle \Psi_l | \omega \rangle}{\langle \Psi_l | \omega \rangle_{\mathrm{th}}}. \tag{18}$$

In the following, the β-criterion was set to show at least an 85% agreement between the Lamb–Oseen vortex model and the detected structure.

In order to determine the best possible choice for the wavelet scales, the structure eduction algorithm computes the size of potential structures in advance and adjusts the range of scales which are used in the transformation. Applying this procedure allows for a more precise scale detection and saves computational time.

Since the separated flow over the inclined plate is relatively complex, both algorithms have been tested and verified to give reliable results for the well-documented case of the flow around a circular cylinder.

4. Results

4.1. POD-modes

While the flow field has been measured at several angles of attack, momentum coefficients and excitation frequencies, the following discussion will be limited to $c'_\mu = 2.6\%$, $F^+ = 1$ and an inclination angle of $\alpha = 13^\circ$. In the upper row of Fig. 3 the time averaged streamwise component of the velocity for the baseline flow as well as for the flow excited with two different wave forms are shown.

Regions of negative u, i.e. backflow, are drawn with dashed contour lines in Fig. 3 and indicate separation. It is clearly to be seen that separation is suppressed by excitation with both wave forms. However, some small

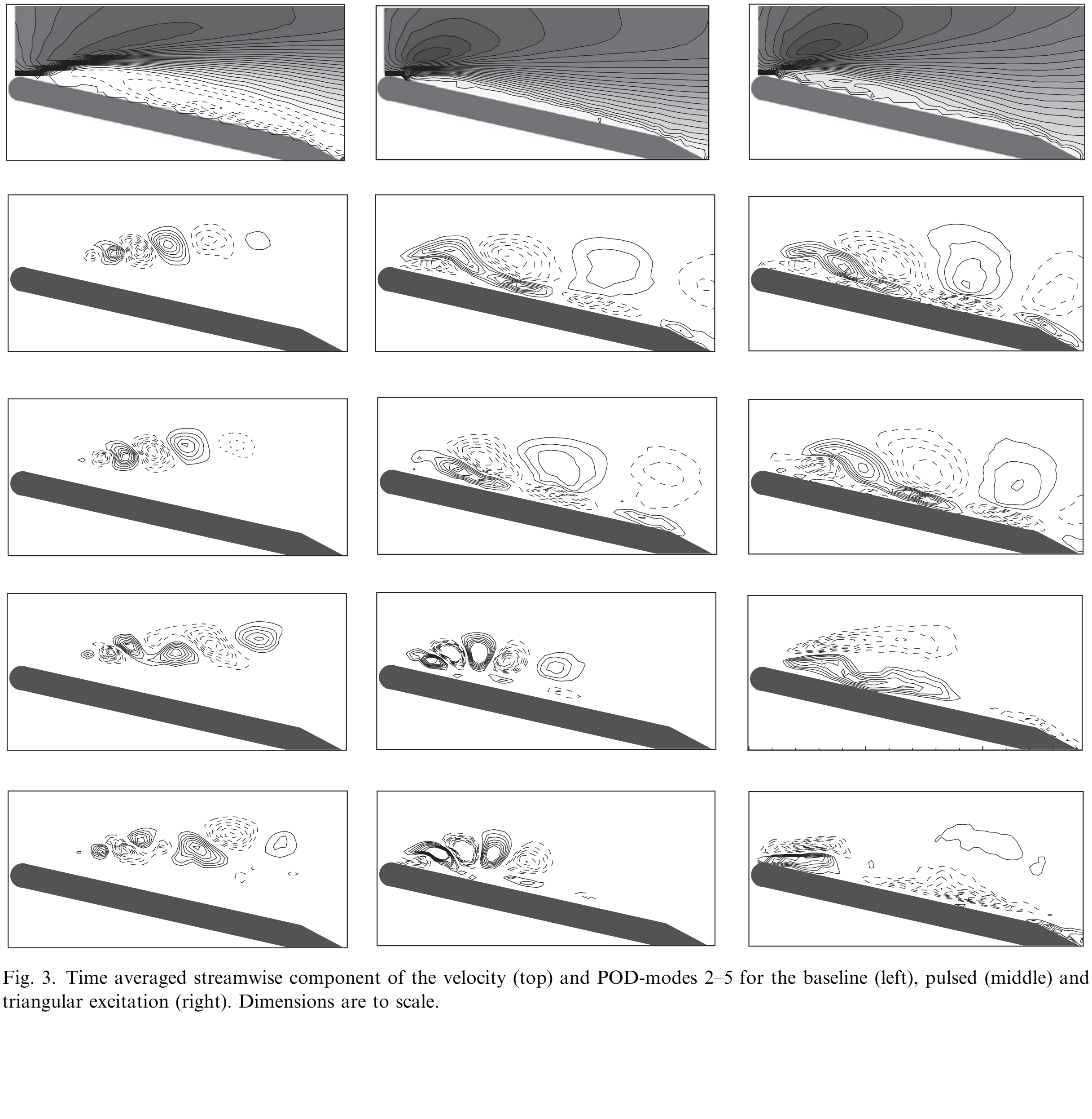

Fig. 3. Time averaged streamwise component of the velocity (top) and POD-modes 2–5 for the baseline (left), pulsed (middle) and triangular excitation (right). Dimensions are to scale.

differences in the flow near the surface of the plate are also visible. In the lower part of Fig. 3 the POD-modes 2–4 of ω are plotted, dashed contour lines identify negative values. The first mode of the POD belongs to the mean flow, since the total vorticity has been decomposed (Siegel et al., 2007). It is therefore not of interest for the eduction of the periodic characteristics of the flow. For the unforced case (left side) the vortex shedding modes 2 and 3 and the higher order vortex shedding modes are clearly visible. In the excited case the picture looks quite different. The mechanism for the reattachment of the mean flow is supposed to be the intensified momentum exchange between the outer flow and the separation region driven by the large scale vortex structures. Phase averaging shows generation of such structures in the actuator region and a following downstream motion (Cierpka et al., 2007). These features can also be deduced from the vorticity modes. Modes 2 and 3 are relatively similar for the different wave forms. However, modes 4 and 5 show smaller, but clearly distinguishable structures for the pulsed excitation. Due to the short duration of excitation, an additional natural shedding cycle occurs between the positive and negative parts of the excitation signal in the case of pulsed excitation. In the average, smaller structures are generated which disappear much faster than the vortex structures produced by the relatively gentle change of momentum input due to the triangular wave form. Note that the POD-modes do not indicate vortex structures, but are regions where significant features in terms of enstrophy content occur, meaning they correspond to regions of significant enstrophy and energy transfer.

Notable differences can also be seen in the enstrophy fraction that each mode contributes to the overall dataset. For the flow around a circular cylinder with vortex shedding, the POD-modes occur, except of the mean mode, pairwise (Cordier and Bergmann, 2003). A similar behavior is clearly visible in Fig. 4 for the first modes of the baseline flow and the pulsed excitation. In the case of triangular excitation, only modes 2 and 3 are paired. Since the Reynolds number is relatively high, $\mathrm{Re} = 10^4$, giving rise to a broad bandwidth of flow scales, and probably caused as well by PIV resolution limits, the enstrophy content of the modes does not decrease as steep as for lower Reynold numbers and numerically determined data (Kostas et al., 2005). However, a shift of enstrophy to higher modes which is originated by the excitation is clearly visible.

4.2. Vortex statistics using CWT

Using the CWT, vortices similar in shape to the Lamb–Oseen vortex are searched for in the PIV data of each time step. This approach leads to a large amount of data for each run containing position and characteristics of the detected vortices. In order to plot these data, the vortex parameters, including y-position, have been averaged for each streamwise location. The underlying discretization in streamwise direction is that of the PIV mesh.

In Fig. 5 the positions of the vortex centres are plotted versus the streamwise coordinate, yielding vortex trajectories in an averaged sense. For the baseline case, the vortices separate from the shear layer and move downstream, where they get deformed and eventually disappear.

Under excitation with the pulsed wave form, small vortices are produced in the actuator region. During the phase of no forcing, referred here as ‘‘off time’’, these vortices separate and are convected downstream near the surface of the plate. The trajectory induced by the triangle wave excitation is not as close to the plate as for the pulsed excitation. The likely cause for this observation is the comparatively slow change in momentum input. It allows for a shear layer to develop in the upstream forcing phase and pushes it away from the plate at the same time.

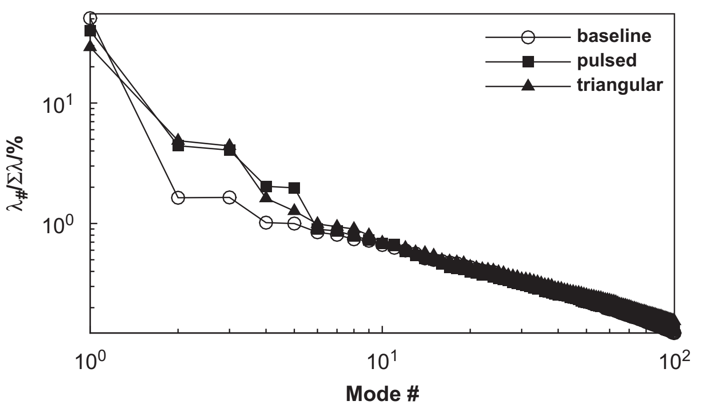

Fig. 4. Enstrophy fraction for the first 100 POD-modes for baseline (circles), pulsed (squares) and triangular excitation (deltas).

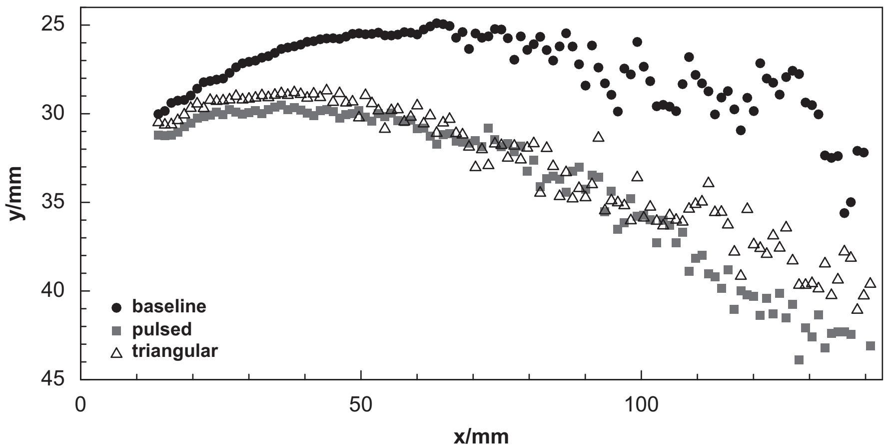

Fig. 5. Vortex trajectories determined by the CWT analysis, *y*-direction stretched.

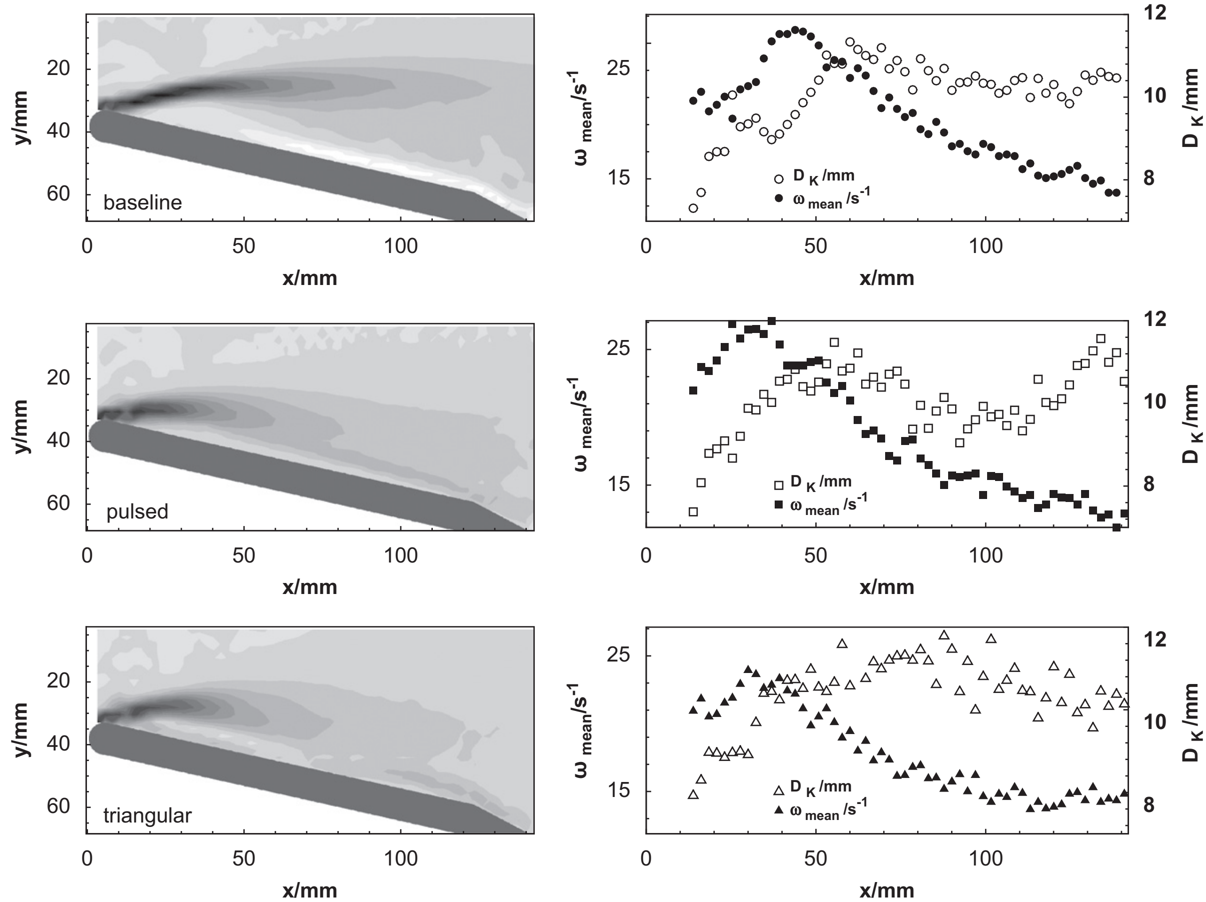

Fig. 6. Time averaged vorticity (left), mean core diameter D_K and mean vorticity in the centre of the detected vortices for the baseline (top), pulsed, and triangular excitation (bottom).

All trajectories show a considerable scattering of the vortex locations further downstream which is due to the fact that a smaller number of vortices is detected. Concurrently, the similarity of the deformed vortices to a Lamb–Oseen vortex wanes. More information about the effects of the excitation wave form can be extracted looking at, e.g., the size and core vorticity of the vortex structures. Fig. 6 shows the time averaged vorticity fields (left) and statistical averages of the vorticity in the centre of a vortex (right, filled symbols) and of the vortex core size D_K (right, open symbols). The vorticity at the vortex centre can be used as a measure for the energy content or intensity of a vortex structure. For the baseline flow, the vortices begin to grow in the shear layer. When they separate, the vorticity in the centre diminishes while the size decreases slowly. The decay of the vorticity means that the energy of the structures dissipates and is transferred to the flow. The point for the maximum vorticity of the vortices is shifted upstream due to the momentum input in the excited cases. Since the decay rate is of the same order as in the baseline flow, the momentum transfer takes place further upstream, suppressing the evolution of the separation bubble. For the pulsed wave form, smaller and compacter vortices are produced as compared to the triangular excitation. This is visible in the higher vorticity content. As mentioned above in the off time vortices are shed as well and are then convected downstream. In the phase with downstream directed Lorentz force, fast moving vortices are produced, while an upstream pointing force generates slower ones. This is a reason for the observed increase in vortex size, starting at $x \approx 100$ mm distance from the leading edge. The faster vortices catch the slower ones and they merge to a single large vortex. For the triangular excitation, large deformed structures are produced, reflected by the higher spread of the core diameter.

5. Conclusion

An apparent influence of the excitation wave form on coherent structures of the separated flow could be shown using POD as well as CWT of TR-PIV data. The tools applied seem to be able to detect the flow characteristics and to highlight important features. Simultaneous TR-PIV and force balance measurements are scheduled for the near future with the aim to provide the necessary link of the educed flow structures to the resulting lift increase.

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