Analysis of intermittent trailing edge vortex shedding using recurrence plots

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ABSTRACT

Time resolved particle image velocimetry is conducted in the wake of a trailing edge separated flow past a NACA4415 airfoil at a fixed angle of attack beyond the static stall angle to analyse the formation and temporal evolution of the wake coherent structures. Under the presented experimental circumstances, intermittent trailing edge vortex shedding occurs. A flow diagnostic analysis combining the proper orthogonal decomposition method with a recurrence plot and quantification analysis, reveals that the occurrence and duration of vortex shedding interruptions are random and that the duration of the interruptions are shorter than the intervals of regular shedding. Furthermore, a recurrence plot based conditional averaging strategy is used allowing for the spatiotemporal evolution of the wake centreline to be visualised and for the wake convection speed to be calculated. The latter was found to be distributed normally around 0.66 of the free stream velocity. Classic detection and tracking of the trailing edge vortices revealed a formation length of ≈ 20 % of the airfoil chord length downstream of the trailing edge before alternately shedding can occur through mutual interactions of the upper and lower shear layer.

1. Introduction

Flow separation on lifting surfaces is a commonly encountered, although mostly undesired, condition in aviation that occurs when a critical angle of attack is exceeded. Separated flows are inherently unsteady and comprise a series of complex fluid dynamical phenomena, including shear layer instability, coherent vortex formation and shedding, but also seemingly chaotic turbulent behaviour. As a consequence, accurately modelling and prediction of separated flows remains an ongoing challenge for fluid dynamicists and requires profound knowledge about the characteristic flow patterns and the associated time and length scales describing their development as well as their potential cyclicity. In particular, the reoccurrence of similar flow pattern is essential for the description of the flow as a non-linear dynamical systems. To improve and tailor flow control technologies, a profound understanding of the various cyclic flow events that occur regularly, frequently or infrequently, and at regular or irregular intervals is desirable.
The objective of the present investigation is to present a flow diagnostic strategy to analyse and characterise regular or quasi-regular vortex shedding using the example of a trailing edge separated flow past a NACA4415 airfoil section at large angle of attack. Time resolved particle image velocimetry (TR-PIV) is conducted in the wake region and the ensemble of PIV snapshots are analysed using a proper orthogonal decomposition (POD) method to identify the dominant large scale coherent wake structures. Special focus is directed towards quantifying vortex shedding intermittency which can be recognised by the abrupt, temporary interruptions of the periodic shedding behaviour. The tool of choice that will be explored here is the recurrence plot introduced by Eckmann et al. [1987] and successfully used a.o. by Lardeau et al. [2010] and Badrinath and Sarkar [2015] to study cyclic events in turbulent flows and intermittency behaviour in the flow past an oscillating airfoil, respectively.

2. Experimental set-up

2.1 Hardware
Measurements have been performed in the closed-circuit, continuous low-speed wind tunnel at DLR Göttingen. The wind tunnel had an open test section with a rectangular nozzle (0.7 m × 1.0 m). The airfoil model was a NACA4415 profile with a chord length $c$ of 200 mm and an aspect ratio of 4. The model was enclosed between two circular end plates with a diameter of 400 mm in order to reduce finite span effects. The angle of attack was fixed at $\alpha = 20^\circ$. Two component time-resolved particle image velocimetry (TR-PIV) was conducted in the cross sectional plane at model mid-span for a free stream velocities, $U_\infty = 25$ m/s corresponding to a Reynolds numbers $Re = 3.1 \times 10^5$. Two high repetition rate cameras were mounted side by side to obtain a combined camera field of view covering the airfoil’s trailing edge and wake (figure 1). Time series of 3000 PIV image pairs were recorded at 1.5 kHz (3000 fps), corresponding to a measurement time of 2 s. The PIV images were
processed using an interrogation window size of 20 px × 20 px and a 60% overlap yielding a grid spacing of 8 px or physical resolution of 1 mm or 0.005 c.

2.2 Flow diagnostics
The time resolved velocity field data was analysed by means of the $\Gamma_2$ method of Graftieaux et al. [2001] to locate the axis of individual vortices and to determine their sense of rotation. A proper orthogonal decomposition (POD) of the flow field was carried out to identify the dominant coherent flow structures and to study their spatiotemporal evolution. Additionally, recurrence plots are used to identify and characterise the recurrence of characteristic flow states and identify intermittency in the trailing edge vortex shedding.

The discretised implementation of the POD is based on the snapshot method introduced by Sirovich [1987]. For the present application of POD we consider the measurement time series of the vorticity field in the wake region of interest. The vorticity field was decomposed according to

$$\omega(x, y, t_n) = \sum_{i=1}^{N} a_i(t_n) \psi_i(x, y)$$  \hspace{1cm} (1)

with $N$ the number of instantaneous flow field realisations, $t_n$ the discrete time stamp, $\psi_i(x, y)$ the spatial POD modes, and $a_i(t)$ the corresponding mode time development coefficients. The eigenvalues associated with the eigenmodes, denoted by $\lambda$, indicate the relative contributions of the eigenmodes to the total kinetic energy [Lumley, 1970]. As the POD modes are sorted by their eigenvalues in decreasing order, the first modes are considered dominant and represent the most prominent flow structures in terms of energy content and statistical prevalence.

2.3 Recurrence plots
Recurrence plots are a diagnostic tool for visualisation and analysis of cyclic behaviour of dynamical systems. It was introduced by Eckmann et al. [1987] and an extensive review was published recently by Marwan et al. [2007]. Recurrence plots indicate the time instances at which the phase space trajectory of a dynamical system passes through the same small area. More specifically, a recurrence plot can be seen as a two dimensional square binary map with both axes being time where the value of at the location $(i, j)$ is defined as

$$R_{ij} = \Theta (\epsilon - \| \vec{x}_i - \vec{x}_j \|), \hspace{1cm} i, j = 1, ..., N \hspace{1cm} (2)$$

where $N$ is the number of the measured states $\vec{x}_i$ in the phase space, $\Theta$ is the Heavyside step function,
\|\cdot\| \text{ is a norm, in the present case the } l_\infty \text{ norm is chosen, and } \epsilon \text{ is a threshold distance. Following this definition, } R_{ij} = 1 \text{ if the locations } \vec{x}_i \text{ and } \vec{x}_j \text{ are closer together than the threshold distance } \epsilon \text{ and } R_{ij} = 0 \text{ otherwise. By definition } R \text{ is symmetric with respect to the main diagonal line, } R_{ij} = R_{ji}, \text{ and the latter is referred to as the line of identity with } R_{ii} = 1. 

For the present calculation of recurrence plots, the phase space is defined with reference to the time development coefficients of the dominant mode pair of the proper orthogonal decomposition of the vorticity field, assuming that they characterise the properties of the flow as a dynamical system.

The original purpose of recurrence plots is to give a visual impression and perceptual analysis of the dynamic behaviour of trajectories in phase spaces, but additional quantitative information can be extracted through a recurrence quantification analysis [Marwan, 2011, Charles L. Webber and Marwan, 2015]. The simplest measure of the RQA is the recurrence rate (RR) which is defined as

\[
RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{ij},
\]

for the entire recurrence plot. The recurrence rate is a measure for the density of recurring events. For some applications, it can be useful to determine a piece-wise recurrence rate along the line of identity to obtain a time varying measure for the probability of recurrence. To calculate the piece-wise recurrence rate, equation 3 is adapted to

\[
RR(t_k) = \frac{1}{(2m+1)^2} \sum_{i,j=k-m}^{k+m} R_{ij},
\]

with \( t_k \) the discrete time stamp corresponding to the \( k^{th} \) state in the phase space \( \vec{x}_k \) and \( m \) a measure for the size of the window for the piece-wise evaluation of the recurrence rate. In the present study we calculate the recurrence rate according to equation 4 with \( m = 5 \).

3. Results

In this study we consider the flow past a NACA4415 at a fixed angle of attack beyond the static stall angle experiencing trailing edge separation. The time averaged flow field is rather unspectacular (figure 2). The boundary layer on the suction side of the airfoil remains attached up to about 70% of the chord length. Thereafter, the boundary layer separates giving rise to a recirculation region that covers the last 30% of the airfoil chord and extents into the wake (figure 2a). The mean wake centreline is extracted by least square fitting the points of local velocity deficit in the wake and is indicated by the dotted lines. It lies exactly between the upper and lower shear layer associated
Figure 2: Time averaged velocity (a.) and vorticity fields (b.) in the wake of a trailing edge separated NACA4415. The dotted lines mark the wake centreline extracted by connecting and fitting the points of lowest velocity deficit in the wake.

here with positive and negative vorticity, respectively (figure 2b).

The instantaneous flow fields are much more interesting and reveal some peculiar behaviour.

The left column in figure 3 depicts a series of 4 consecutive snapshots of the vorticity field, each $\Delta t U_\infty / c = 0.083$ apart, starting at time $t_a$ during the PIV time series. This sequence clearly reveals the characteristics of periodic trailing edge Karman-like vortex shedding. As a result of the interaction between the upper shear layer due to the trailing edge separated boundary layer and the lower pressure side trailing edge shear layer, individual vortical structures are formed that alternate shed and convect downstream yielding an undulating wake pattern. The high temporal resolution of the measurements allows for individuals structures to be tracked across the consecutive images.

In the right column, another series of 4 consecutive snapshots of the vorticity field are presented, now starting at a later time $t_b$ during the same PIV time series. Here, the upper and lower shear layer lie neatly on top of each other. No signs of mutual interaction and subsequent alternate vortex shedding are observed. Within the duration of one measurement series of 3000 images or 2 s, the flow is predominantly governed by periodic vortex shedding interrupted by intermittent no shedding phases.

In the remainder of this paper, we present a flow diagnostic methodology to analyse the phenomenon of intermittent vortex shedding by example of the presented observations on the NACA4415. In particular, we will focus on identifying and visualising the occurrence of intermittency and on quantifying vortex shedding properties such as convection speed and shedding frequencies.
**Figure 3**: Sequences of 4 consecutive instantaneous snapshots of the vorticity field in the wake of a trailing edge separated NACA4415 starting at a specific time $t_a$ (left) and $t_b$ (right) within the entire PIV sequence. The time between consecutive images is $\Delta t U_\infty / c = 0.083$. 
Figure 4: First 2 eigenmodes of the POD of the vorticity field (a.-b.), their corresponding mode coefficients (c.-d.), the eigenvalue distribution (e.), and the frequency spectrum of the first mode coefficient (f.).
3.1 POD analysis

To extract the dominant flow patterns from the PIV time series and analyse their temporal evolution, the vorticity field was subjected to a POD after subtraction of the time average vorticity field. The results of the POD analysis are summarised in figure 4 including the first two dominant POD modes (figure 4a-b), the phase space diagram constructed based on the time development coefficients of the first mode pair (figure 4c), a short sequence showing the time history of these time development coefficients (figure 4d), the POD eigenvalue distribution (figure 4e), and the frequency spectrum of the first mode coefficient (figure 4f). The first two eigenmodes represent a similar pattern and have approximately the same eigenvalue $\lambda$ indicating that these modes are coupled and form a mode pair. The pattern, consisting of a succession of large-scale spatial structures with alternating sign, is spatially shifted by a quarter wavelength in the second mode with respect to the first and represents the periodic vortex shedding in the wake. The corresponding mode coefficients are temporally shifted by a quarter wavelength, indicating that energy is shifted from one mode to the other such that the linear combination of both modes creates the downstream convective motion of the large scale wake structures. For the ideal case of perfect, uninterrupted, single frequency harmonic vortex shedding, the instantaneous flow field realisations in the phase space diagram spanned by the normalised POD coefficient $a_1/\sqrt{2\lambda_1}$ and $a_2/\sqrt{2\lambda_2}$ lie on the unit circle where the angular position on the circle indicates the vortex shedding phase angle [van Oudheusden et al., 2005]. For the situation of intermittent vortex shedding, the points in the phase diagram in figure 4c, representing individual flow field realisations, do not describe a clean circle but cover an entire disk area. In addition to the vortex shedding phase angle, denoted by $\beta$, the radial distance from the origin $R_a$ is determined to describe the instantaneous state of the vortex shedding. Since the mode coefficients are a measure of the relative energy contribution of the corresponding mode, the radial distance $R_a$ is a measure for the presence of large-scale trailing edge vortices. This is demonstrated exemplarily for the selected time instants $t_a$ and $t_b$, representing shedding and no-shedding phases respectively. In accordance with the above, the point in phase space representing $t_a$ lies outside of the unit circle and the point representing $t_b$ inside. The vortex shedding frequency is estimated from a Fourier analysis of the time series of the first mode coefficient. The temporal development of the first and second mode coefficient are very similar and are basically only shifted by a quarter period with respect to each other and contain the same frequency information. The frequency spectrum indicates frequency content within a rather broad frequency band between 300 Hz to 400 Hz (figure 4f). A least square fit of the spectrum by a Gaussian distribution is centred around 340 Hz. Calculating the Strouhal number using this estimate of the frequency and an estimate of the wake height at $x/c = 0$ of 0.028 m as the relevant length scale, yields $Str = c f / U_{\infty} = 0.38$, which is of the expected order of magnitude.
Figure 5: Recurrence plot (RP) for a selected time interval between $tU_\infty/c = 15 - 24$ after the start of the measurement (a.). The phase space for the calculation of the RP is defined by the time development coefficients of the dominant POD mode pair. The normalised threshold distance is set at $\epsilon = 0.2$. Black refers to recurrence or $R_{ij} = 1$, white to $R_{ij} = 0$. Subsets of the recurrence plot surrounding the time instants $t_a$ (b.) and $t_b$ (c.), representing phases associated with vortex shedding and intermittent behaviour respectively, are highlighted.

3.2 Recurrence plots
To further characterise the intermittency in the vortex shedding, the diagnostic tool of recurrence plots is adopted. The recurrence plot for a selected time sequence between $tU_\infty/c = 15 - 24$ after the start of the measurement series is presented in figure 5. For every pairwise combination of time instants $t_i$ and $t_j$, the recurrence plot indicates whether or not the flow fields at these instants are considered similar. If the corresponding location on the recurrence plot is black, the flow fields are considered similar, if it is white, they are not. Similar in this context means that the vectors in phase space are closer to each other than a certain threshold. For the present application, the phase space vector is constructed using the time development coefficients of the dominant POD modes pair, $\ddot{x}(t) = (a_1/\sqrt{2\lambda_1}, a_2/\sqrt{2\lambda_2})$, as they seem to adequately described the dominant shedding dynamics. The threshold distance is normalised by the maximum distance in the phase space and set at $\epsilon = 0.2$.

In general, the recurrence plot patterns can be classified according to their typology and textures [Marwan et al., 2007]. The most prevalent patterns that can also be observed here include the
line of identity, periodic structures of diagonal lines parallel to the line of identity, vertical and horizontal lines or areas, and white areas or bands. As every flow field is similar or recurrent to itself, the diagonal going from the bottom left to the top right is black and referred to as the line of identity. A clear example of a structure of diagonal lines parallel to the line of identity is observed around \((t_a, t_a)\) and enlarged in figure 5b. These diagonal lines occurs when a segment of the trajectory runs almost in parallel to another segment and are indicative of periodic behaviour with a frequency given by the distance between the parallel lines. This is in accordance with the flow field development observed in figure 3(a-d). The length of these parallel lines are relatively short indicating the intermittency of the periodic shedding. Vertical and horizontal lines or areas in the recurrence plot are indicative of very slow changes of the phase state and the flow field dynamics it describes. An example of such an area is observed around \((t_b, t_b)\) (figure 5c). Looking back at the flow fields in figure 3(e-h), the similarity between successive flow fields in absence of vortex shedding is readily observable and well captured in the recurrence plot. Finally, white areas, like for example around \((t_a, t_b)\), indicate non stationarity and abrupt and significant changes in the dynamics.

The recurrence plot provides an accurate visualisation of the occurrence of different dynamic regimes within a time series and the transition between them. From this visualisation we can now extract further quantitative information such as the recurrence rate, which provides a measure for the time varying probability of recurrence. According to the definition (equation 4) the recurrence rate for a certain discrete time stamp \(t_k\) is close to one when the region around \(t_k\) in the recurrence plot is predominantly black and decreases the more white spots occur. It can never drop to zero as a portion of the line of identity is always taken into account. With regard to our example of intermittent trailing edge vortex shedding, high values of the recurrence rate indicate intervals characterised by the absence of vortex shedding and low values can be associated with periodic vortex shedding. The time series of the recurrence rate for the entire measurement series is presented in figure 6a. A perceptual analysis of the evolution of the fluctuations of the recurrence rate does not indicate a systematic alternation of vortex shedding and intermittent interruptions which is confirmed by a frequency analysis. The occurrence of intermittency seems to be arbitrary based on the observation window considered here. To statistically analyse and compare the duration of shedding cycles and interruptions, an critical recurrence rate is determined, below which the flow is considered to be in trailing edge shedding mode. The height of the critical recurrence rate is chosen by carefully examining individual images and comparing the recurrence rate with the radial distance of \(R_a\) in the POD coefficient phase space (figure 6b,c). For the present application the critical recurrence rate is set at \(RR_c = 0.4\). The resulting cumulative probability distribution of the
Figure 6: Recurrence rate (RR) for a larger (a.) and shorter (b.) sequence and the radius ($R_a$) in the phase diagram spanned by the time development coefficients of the two dominant POD modes (c.).

Figure 7: Cumulative probability density ($P$) of intermittent phases (■) and regular shedding phases (◆) expressed in terms of convective times.

duration of intervals of regular vortex shedding and in absence of vortex shedding are presented in figure 7. The duration of the intervals is expressed in terms of convective times. In general, the
Figure 8: Instantaneous (a.) and RP-based conditionally averaged (b.) vorticity field for $t_c = t_r$. The mean wake centreline is indicated by the dashed black line and the subsequently extracted wake region of interest by the dotted grey line. The extracted wake region of interest vorticity field from the instantaneous (c.) and RP-based conditionally averaged (d.) fields. The instantaneous wake centreline is highlighted in (d.) by the black line. The evolution of the amplitude of the centreline in downstream direction (e.) for $t_r$ and two successive snapshots.

Phases of continuous vortex shedding are longer than the interruptions. The maximum duration of uninterrupted vortex shedding is about 10 convective times, whereas the maximum duration of interruption is less than 2 convective times. The durations of both the shedding and the intermittent phases are scattered. Hence, not only the occurrence of intermittent interruption of regular trailing edge vortex shedding appears to occur random but also their duration.

3.3 Wake undulation

A characteristic feature of the regular trailing edge vortex shedding is the undulation of the wake.
In a first step towards quantifying the spatiotemporal development of the wake, the wake centreline is extracted for instantaneous snapshots. Although we seem to able to detect the wake line by eye in the vorticity field at $t_a$ in figure 8a, turbulent fluctuations and noise make it virtually impossible to unambiguously and automatically determine the instantaneous wake centreline based on the raw vorticity field. A smoothing or averaging strategy is required that preserves the dynamics of the system. Mulleners and Rütten [2016] recently proposed a versatile conditional averaging approach based on recurrence plots that is adopted here. For every time instant $t_k$, a conditional average is calculated by averaging over all instants $t_i$ that are considered similar based on the recurrence plot, i.e. for which $R_{ki} = 1$. The resulting RP-based conditionally averaged vorticity field at $t_a$ in figure 8b now reveals the wake pattern even clearer and allows for the automated detection of the wake centreline as the boundary between positive and negative sign vorticity. To allow for the wake amplitude variations to be examined, a wake region of interest is first isolated centred around the mean wake centreline figure 8(c-d). The wake region of interest is indicated in figure 8(a-b) by the grey dotted area. From the conditionally averaged data in the wake region of interest figure 8(d) the instantaneous wake centreline is identified and the amplitude along the downstream location is defined with respect to the mean wake centreline.

The spatiotemporal evolution of the amplitude of the wake centreline is visualised in figure 9c for the time interval $t_c = 15 - 24$. In a similar way, the vorticity along the mean wake centreline is represented (figure 9a). In both representations, the downstream convection of the wake can be identified by the upwardly oriented ridges of positive and negative vorticity or amplitude. The convection speed can be directly determined from the slopes of these ridges yielding a near gaussian distribution around a mean value of $u_{conv}/U_\infty = 0.66$ (figure ??). Regions where the recurrence rate goes past the critical rate are indicated by the grey shading and mark no shedding regions (figure 9). They coincide well with the areas in the vorticity and amplitude representations where the ridges have faded out as a result of the absence of vortex shedding.

3.4 Wake vortex detection
Figure 9: Vorticity along the mean wake (a.), recurrence rate (b.), and amplitude of the instantaneous wake line (c.) in function of convective time. The grey shading indicates regions of interrupted vortex shedding based on the critical recurrence rate.

Figure 10: Probability density $Q$ of the wake convection speed calculated from the slopes of the high and low vorticity ridges in figure 9a including gaussian fit.

Finally, the wake vortices in the RP-based conditionally averaged snapshots are identified and tracked in time to reveal their trajectories. The trailing edge vortices emerging from the pressure
side shear layer follow a common trajectory that initially evolves almost horizontally until $x/c \approx 0.2$, where the trajectory bends and continues linearly but with a steeper angle (figure 11a). By discretising the wake trajectory and averaging over all vortices found at those discrete locations, the downstream evolution of the negative sign wake vortices is obtained (figure 11b) as well as their circulation history by integrating the vorticity within the indicated squared region (figure 11c). For vortex locations up to $x_0/c = 0.15$, circulation increases as the vortex is still part of the shear layer that feeds it. Once the vortex separates from the shear layer, its shape evolves from an elongated ellipse into a more circular shape while increasing in size. The vorticity spreads out radially and the circulation decreases. The vorticity redistribution within the vortex can be seen more clearly by observing the vertical cross sectional profiles at different downstream locations (figure 12a). The absolute vorticity value level in the vortex core gradually decreases while the width of the vortex increases (figure 12b-c). The latter was determined by least square fitting the vertical vorticity distribution with a gaussian distribution. The growth of the vortex core appears to be a two phase linear process. Before $x/c = 0.20$ the width increases linearly at a higher rate than thereafter. This change in growth occurs shortly after the maximum circulation is reached and the individual vortex has separated from the shear layer. The near wake region can thus be divided into a vortex formation region, for $x/c < 0.20$ followed by an interaction region. This can also be recognised in figure 9c, where the amplitude of the wake centreline starts increasing near $x/c = 0.20$.

4. Conclusion

The rapid improvement of experimental techniques and equipment tempt scientists to collect more and more data. For the analysis of these vast amounts of scientific data, smart, efficient, and effective algorithms are desirable to extract, combine and reduce the available information at hand to answer specific questions about the subject under investigation.

In this paper we have presented a flow diagnostic strategy combining POD, a recurrence plot analysis, and a classic vortex detection scheme to analyse and characterise intermittent vortex shedding in the wake of a trailing edge separated flow past a NACA4415 airfoil. The flow field in the wake of the airfoil at a fixed angle of attack beyond the static stall angle was measured by means of time resolved particle image velocimetry. A proper orthogonal decomposition of the time series of vorticity fields revealed intermittent behaviour of the periodic vortex shedding which was further analysed by means of the recurrence plot for the phase space constructed by the POD coefficients of the dominant mode pair.

Characteristic patterns in the recurrence plot indicated the different flow dynamics alternately
Figure 11: Common trajectory of the counter clock wisely rotating trailing edge vortices (a.). At specific locations along the trace, indicated by the circular markers, averaged vorticity fields are calculated over all vortices with axis detected at that same location \( x_0/c \), providing a picture of the downstream vortex development (b.). The negative sign averaged vorticity within the square subregions surrounding the vortex was integrated to obtain the associated circulation development along the wake trace (c.).

observed within the time series, associated with the presence and absence of regular trailing edge vortex shedding.

Further quantification of the recurrence plot in terms of the recurrence rate allowed for the analysis
of the duration of shedding and interruption intervals. A critical recurrence rate was determined to distinguish between shedding and no shedding intervals. In general, the duration of the interruptions was shorter than the duration of the regular shedding cycles. The interruptions were found to occur randomly and also their duration did not seem to be predictable.

Based on the similarity information provided by the recurrence plot, the flow fields were conditionally averaged. This approach led to a reduction of noise in the individual flow fields while preserving the flow dynamics and allowed for further analysis of the wake and vortex dynamics. The wake centreline and the vorticity along the mean wake centreline were extracted for all snapshots and represented in function of time. This representation was used to calculate the wake convection speed distribution and visually revealed the intermittent intervals of vortex shedding.

Finally, vortex locations and trajectories were determined. For discrete locations along the trajectory of the negative sign trailing edge vortices, the vortex size and strength, in terms of circulation and core vorticity magnitude, were extracted. Within the first 0.2 c downstream of the trailing edge, the vortex remained part of the shear layer that feeds it, taking up circulation and growing linearly in size. Beyond this formation length, the vortex separated from the shear layer, vorticity spread radially within the growing vortex, and interactions with the upper shear layer led to increasing fluctuations of the amplitude of the wake centreline within shedding intervals.

**Figure 12:** Vorticity profiles extracted from vertical cuts through the averaged vorticity fields of the counter clockwise rotating trailing edge vortices at different downstream locations (a.). Downstream evolution of the minimum vorticity in the vortex centre (b.) and the size of the vortex based on the width $\Delta$ of the vertical vorticity profile (c.).
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References


