Experimental study of the DLR F13/F13X models in TUM-AER wind tunnels

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# Contents

I. INTRODUCTION ................................................................................................................ 3

II. DLR F13 MODELS ............................................................................................................. 6

III. WIND TUNNELS.............................................................................................................. 7

IV. FORCE MEASUREMENTS ................................................................................................. 9

V. FLOW FIELD MEASUREMENTS ..................................................................................... 10
   V.1. SMOKE VISUALISATION................................................................................................. 12
   V.2. HOT-wIRE RESULTS FOR THE SMALL MODEL (F13) ................................................ 14
   V.3. HOT-wIRE RESULTS FOR THE LARGE MODEL (F13X) ............................................ 46
   V.4. PIV RESULTS FOR THE SMALL MODEL (F13) .......................................................... 74
   V.5. COMPARISON BETWEEN HOT-wIRE ANEMOMETRY AND PIV .............................. 84
   V.6. SPECTRAL ANALYSIS.................................................................................................. 87
   V.7. CORRELATION MEASUREMENTS ................................................................................ 93

VI. CONCLUSION ................................................................................................................. 101

VII. REFERENCES................................................................................................................ 102
I. Introduction

This report deals with the wake vortex formation and evolution of a four vortex system of a generic model in the near field and extended near field as well as the behaviour and decay in the far field region. The results were obtained during an experimental campaign as part of Work Package 1, Task 1.2.2, of the EC project FAR-Wake. Two different scaled models are used and also two different Reynolds numbers are investigated by means of hot-wire anemometry and particle image velocimetry.

Wake vortices emanating from large transport aircraft may endanger the flight safety of a following aircraft encountering the wake. It is well known that the trailing wake of a lifting body rolls up into a pair of strong counter-rotating longitudinal vortices that persists for many body dimensions downstream. The vortex strength is proportional to the bound circulation or body lift, and hence, for steady flight conditions this is approximately proportional to the weight of the generating aircraft. An aircraft encountering a vortex wake can experience sudden up wash, down wash or rolling along with increased structural dynamic loads, depending on its position and orientation with respect to the wake. Near the ground this can be especially dangerous, as the pilot has less time to recover from rapid changes in the aircraft's attitude.

Up to now flight safety has been ensured by maintaining a suitably large spacing between the aircraft during take-off and landing, as well as on flight routes. The Federal Aviation Administration in the U.S. and the Civil Aviation Authority in Europe regulate the separation distances. These distances are often considered as conservative to account for the varying behaviour of the vortices under different atmospheric conditions. In particular, all estimates on future air transport trends predict a severe increase in air traffic so that many major airports will experience their limitations leading to a critical assessment of aircraft spacing, especially for take-off and landing.

In the past numerous experimental and numerical investigations have been performed on the wake structure of generic wing configurations. Numerical studies comprise simple Betz methods as well as complex CFD simulations including Unsteady Reynolds Averaged Navier-Stokes (URANS) computations and Large Eddy Simulations (LES). As the wake vortex physical characteristics in space and time are still not completely understood comprehensive technology projects on wake vortex characterisation and control as well as on identification and safety issues have been conducted (EuroWake, C-Wake, AWIATOR).

Tests are conducted on both generic models and detailed Large Transport Aircraft (LTA) models. Wind tunnel, towing tank and catapult experiments give specific and complementary data resulting in a better description of the vortical structures of the different wake regions. Further, flight tests have been undertaken using triangular lidar measurements to observe and reveal the development of an aircraft generated wake under real meteorological conditions. Also, computational methods are used to provide reasonable estimates of the length of the hazardous wake vortex region. The related vortex models depend strongly on the description of the turbulent and unsteady quantities. The importance of unsteady effects on the wake vortex formation and evolution has been shown by experimental studies.
Precise tracking or prediction of wake vortex locations under all weather conditions is beyond the range of current technology. Therefore, many research activities concentrate on alleviating the wake vortex hazard by modifications of wing geometry and/or wing loading. Strategies to minimise the wake vortex hazard concentrate either on a Quickly Decaying Vortex (QDV) or on a Low Vorticity Vortex (LVV) design. An enhanced vortex decay (QDV) may be achieved by promoting three-dimensional instabilities by means of active or passive devices. An active system tested by Boeing uses periodically oscillating control surfaces to introduce the desired perturbations leading, after sufficient amplification, to the break-up of the vortices. The LVV design reduces the wake vortex hazard by enhancing the diffusion of the vorticity field. It is aimed on the generation of wake vortices with larger core size and smaller swirl velocities at the core radius after roll-up is completed. This may be achieved by injecting additional turbulence into the wake to increase the dispersion of vorticity and/or by altering the circulation distribution of the wake generating wing. The first type of mechanism is related to the use of spoilers or wing fins while the second type of mechanism is related e.g. to differential flap setting.

With respect to 3D perturbations vortex systems are generally unstable. The related mechanisms are summarized in the position paper [1]. This is caused by the amplification of asymmetric Kelvin waves under mutual straining of the vortices. If the separation between the vortices is large in comparison to their diameter, a system of stability equations can be derived by considering parallel vortex filaments with slight sinusoidal perturbations of their respective position. The equations of this linear system are given by Crow [2] for two counter-rotating vortices and by Crouch [3] and Fabre et al. [4] [5] for multiple vortex pairs. The system evolves due to the superposition of three effects: a) the straining experienced by each filament when displaced by a perturbation from its mean position in the velocity field induced by the other undisturbed filaments, b) the self induced rotation of the disturbed filament c) the velocity field induced on the filament by the other vortices when perturbed from their mean positions [2]. The mechanism which strains the vortex due to the displacement from its mean position in the velocity field by a perturbation induced by the other vortex filaments leads (mechanism a) to an amplification of the asymmetric Kelvin waves in case their polarization planes remain close to the extension planes of the straining field. This mechanism is balanced with the self induced rotation (mechanism b) which tends to shift the perturbation away from these planes. The frequency of this self induced oscillation is the frequency of the oscillation mode of the Kelvin displacement wave [4]. This mechanism introduces a dependence of the solution with respect to a measure of the diameter of the vortex core. Long-wave cooperative instabilities are of prime importance for applications to aircraft hazard alleviation as it could be possible that the dispersion of a vortex wake might be accelerated by means of this mechanism.

Especially the stability properties of a vortex configuration composed of two counter-rotating vortex pairs, Fig. 0a, have been considered. The vortex pairs can be co-rotating (\(\Gamma_1 > 0, \Gamma_2 < 0\)) or counter-rotating (\(\Gamma_1 > 0, \Gamma_2 < 0\)) as sketched in Fig. 0b [6]. In the wake of an aircraft, the outer vortex pair is produced at the wing tips or outer flap edges and the inner one by the inner flap edges or the horizontal tail plane. The linear method described above can be applied to Fig. 0a, if \(a_1, a_2 \ll b_1, b_2, (b_1 - b_2)/2\). The solution depends on \(R_c = R_2/R_1\) and \(R_b = b_2/b_1\). Without inner vortices the classical Crow instability develops on the outer vortex pair. Adding the second vortex pair leads to much higher amplifications [4] [5]. Fig. 0c shows a result of the linear theory for \(R_c = R_2/R_1 = -0.3\) and \(R_b = b_2/b_1 = 0.3\), which can be considered as a limit.
for a realistic aircraft. The most amplified perturbation has been plotted after one revolution of the inner vortices around the outer vortex pair. This initially introduced perturbation has been amplified by nearly a factor of 6000. This must be compared to the value obtained for the Crow instability (2.2) without the inner vortex pair. The towing tank result shown in Fig. 0d ($R_F = -0.37; R_B = 0.5$) confirms that this type of perturbation is effectively selected in a real four vortex wake [7] [8].

Figure 0. Long-wave perturbation in a four vortex system; a) definition of a four vortex system; b) classification of four vortex system, symbols mark numerical and theoretical results [6]; c) optimal perturbation obtained by linear theory after one revolution of the inner vortex pair around the outer pair; d) perturbation visible in a towing tank.

The results presented in the following sections include velocity and vorticity distributions complemented by turbulence quantities and spectral analysis.
II. DLR F13 Models

The DLR F13 models are full models consisting of a wing and a horizontal tail plane. Tab.1 shows the dimensions of the DLR F13 models and Fig. 1 and 2 the models installed in the wind tunnel test section (wind tunnel facility C).

<table>
<thead>
<tr>
<th></th>
<th>DLR F13</th>
<th>DLR F13X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span $b_W$</td>
<td>0.3 m</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Wing Chord Length $c_W$</td>
<td>0.05 m</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Wing Area $F_W$</td>
<td>0.015 m²</td>
<td>0.24 m²</td>
</tr>
<tr>
<td>Wing Aspect Ratio $AR_W$</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Horizontal Tail Plane Span $b_{HTP}$</td>
<td>0.09 m</td>
<td>0.36 m</td>
</tr>
<tr>
<td>Horizontal Tail Plane Chord Length $c_{HTP}$</td>
<td>0.035 m</td>
<td>0.14 m</td>
</tr>
<tr>
<td>Horizontal Tail Plane Area $F_{HTP}$</td>
<td>0.00315 m²</td>
<td>0.0504 m²</td>
</tr>
<tr>
<td>Horizontal Tail Plane Aspect Ratio $AR_{HTP}$</td>
<td>2.57</td>
<td>2.57</td>
</tr>
</tbody>
</table>

Table 1. Dimensions of the DLR F13 models.

Figure 1. The DLR F13 model

Figure 2. The DLR F13X model

The main wing has a fixed angle of attack of $\alpha=10.0^\circ$. The angle of attack of the horizontal tail plane is adjustable. The ratio of the spans is $R_b = \frac{b_{HTP}}{b_W} = 0.3$. The force and moment coefficients were determined by force measurements and therefrom the ratio of the circulations $R_{\Gamma} = \frac{\Gamma_{HTP}}{\Gamma_W} = -0.3$ was calculated. These ratios meet the requirement set by the consortium.

Although there is a laminar separation bubble on the top of the main wing no transition strips were used as there application on the small model is not possible.
III. Wind Tunnels

The wind tunnel A of the Institute of Aerodynamics of the TU München was used for the PIV and the force measurements. It has a test section that can be used open or closed and is 4.8 m x 2.4 m x 1.8 m (length x width x height) as shown in Fig. 3. It was used as an open test section for the PIV measurements and also partly for the force measurements and as a closed test section for the remaining force measurements in order to quantify wall influence. PIV measurements were possible up to 10 spans downstream of the small model. With the PIV measuring system only the mean velocities were obtained and then vorticity, cross flow velocity, etc. were calculated there from.

![Figure 3. The wind tunnel A.](image)

The wind tunnel C of the Institute of Aerodynamics of the TU München has a closed test section of 21 m x 2.7 m x 1.8 m (length x width x height) as shown in Fig. 4. The wake vortex system can therefore be observed up to 48 spans downstream of the small model and 12 spans downstream of the large model. The time dependent flow velocities are measured at specific measuring planes with a triple sensor hot wire probe for the small model and a double sensor hot wire probe for the large model. The double sensor can be used for higher cross flow velocities and therefore had to be used for the large model. The measuring planes are scanned twice with the double sensor hot wire probe, once in the xy-plane and once in the xz-plane. The measured velocities are then processed in order to obtain the mean velocities and vorticity. An analysis of the turbulent flow field and a spectral analysis are performed using the unsteady data.
Figure 4. The wind tunnel C.
IV. Force Measurements

The wind tunnel A was used for the force measurements based on a six component balance using the large model DLR F13X in the open and closed test section. Fig. 5 shows the curves for the ratio of the circulations $R_f = \frac{\Gamma_{HTP}}{\Gamma_W} = \frac{c_{L,HTP} F_{HTP}}{c_{L,W} F_W}$ over the angle of the horizontal tail plane $\eta_{HTP}$ for three Reynolds numbers, based on the wing chord length for a closed test section. The flow field measurements were performed only at the two lower Reynolds numbers. The required ratio of the circulations $R_f = -0.3$ is reached for $\eta_{HTP} = -4.0^\circ$. The corresponding lift coefficients for all Reynolds numbers are stated in Tab. 2.

![Figure 5. $R_f - \eta_{HTP}$ curve for different Reynolds numbers.](image)

### Table 2. Lift coefficient $c_L$ for different Reynolds numbers at $\eta_{HTP} = -4.0^\circ$.

<table>
<thead>
<tr>
<th>Reynolds number $Re$</th>
<th>Lift coefficient $c_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800000</td>
<td>1.04</td>
</tr>
<tr>
<td>320000</td>
<td>0.95</td>
</tr>
<tr>
<td>640000</td>
<td>0.99</td>
</tr>
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</table>
V. Flow Field Measurements

All hot-wire measurements were performed in the wind tunnel C. A hot wire probe was positioned downstream of the model and the velocities u, v and w were measured at a sampling rate of 3 kHz for 6.4 s. The voltages of the hot-wire anemometer were low-pass filtered at 1000 Hz and digitized with 16 bit precision. For the small model a hot-wire probe consisting of three wires was used, whereas for the large model a cross-wire probe was used, as the cross flow velocities were larger and therefore demanded a probe with larger flow cone angle. The free stream velocity $U_\infty$ was 25 m/s for the small model which corresponds to a Reynolds number of approx. 80000 based on the wing mean aerodynamic chord. For the large model two Reynolds numbers were investigated, one at $U_\infty=6.25$ m/s ($Re_\infty=80000$) and one at $U_\infty=25.0$ m/s ($Re_\infty=320000$).

The velocity data was then used to calculate the cross flow velocity $V_\theta$, the non-dimensional vorticity $\xi$ and the turbulence intensities using the equations stated below. In addition the in-phase Reynolds shear stress component $\overline{v'w'}/U_\infty^2$ is shown.

\[
V_\theta = \sqrt{v^2 + w^2}; \quad \xi = \frac{b/2}{U_\infty} \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right)
\]

\[
Tu_x = \frac{\sqrt{w'^2}}{U_\infty}; \quad Tu_y = \frac{\sqrt{v'^2}}{U_\infty}; \quad Tu_z = \frac{\sqrt{w'^2}}{U_\infty}
\]

The small model was also used for a PIV investigation in the wind tunnel A. The free stream velocity corresponds to that of the hot-wire anemometry tests ($U_\infty=25.0$ m/s; $Re_\infty=80000$). The PIV system used is a double pulsed 3D system and thus uses two CCD cameras. Each laser burst lasts 20 µs and the time between two bursts is 100 ms. The average is calculated over 30 double images.

Power spectral density distributions of the axial velocity fluctuations obtained by hot-wire anemometry are also evaluated. The spectral densities are calculated using a Fast Fourier Transformation (FFT) of the velocity fluctuation time series with a linear band averaging based on 1024 frequency bands. The evaluation is performed to detect characteristic spectral peaks indicating that turbulent kinetic energy is channelled into a narrow band due to quasi periodic fluctuations.

For the small model correlation measurements were performed using two hot-wire probes each consisting of three wires. Cross spectral density distributions of the spanwise velocity component are evaluated using the same parameters as for the evaluation of the power spectral density distributions.

The results of the different measuring planes for the hot-wire anemometry tests for the different Reynolds numbers and model scales are shown in the following chapters. Thereafter the PIV results are discussed and compared with the results obtained by hot-wire anemometry. The spectral analysis ends this chapter.
The coordinate system used is a system in reference to the model. It is a Cartesian system with x in free stream direction, y in spanwise direction and z upwards as shown in Fig. 6. The position $x = y = z = 0$ is the trailing edge of the wing in the symmetry plane of the model.

The data is presented in a dimensionless coordinate system in order to compare the vortex size and position for the different sized models. The non-dimensional coordinates used are $x^*$, $y^*$ and $z^*$, defined as

$$x^* = \frac{x}{b_w}; \quad y^* = \frac{y}{(b_w/2)}; \quad z^* = \frac{z}{(b_w/2)}.$$

Figure 6. The coordinate system for the DLR F13 models.
V.1. Smoke Visualisation

Smoke was used in order to visualise the Wing Tip Vortex (WTV) and the Horizontal Tail Plane Vortex (HTV). As the models are mounted inverted in the wind tunnel the vortices move upwards. The smoke visualisation was used in order to determine the positions and movements of the vortices in order to ensure that their position is within the area of movement of the hot-wire probe.

Fig. 7 is an overlay of two images taken from the WTV and HTV, respectively. The tail of the model with the horizontal tail plane can be seen on the right side of Fig. 7 and the smoke probe on the bottom part of the figure.

![Figure 7. Smoke visualising the path of the WTV and HTV for DLR F13X model.](image)

Fig. 7 clearly indicates that the HTV travels upwards faster than the WTV, which is due to induced velocities from the WTV. The rotation directions of the vortices are indicated in the figure. The figure approx. covers a distance from $x^*=0.5$ up to $x^*=12$.

Figs. 8 and 9 show the development of the WTV downstream of the DLR F13 model for two different velocities. The left edge of each figure is approx. $x^*=48$. On the right side of Fig. 8 the DLR F13 model is visible. Fig. 8 also clearly shows loops developing as the smoke travels downstream. This is also visible in Fig. 9, but the loops appear stretched. Such loops indicate the strong disturbance effect on the main vortex (WTV) observed in a four vortex system at appropriate combinations of distance and circulation of the counter-rotating vortices.
Figure 8. The WTV downstream development for the DLR F13 model (low speed).

Figure 9. The WTV downstream development for the DLR F13 model (high speed).
V.2. Hot-wire Results for the Small Model (F13)

This chapter deals with the hot-wire measurements performed on the DLR F13 model using a three-wire probe. Planes were measured at \( x^* = x/b = 1.0, 4.0, 8.0, 12.0, 16.0, 20.0, 24.0, 36.0 \) and 48.0 and the results are shown below. For each plane the cross flow velocity \( V_{\theta} \), the non-dimensional vorticity \( \xi \), the turbulence intensities (\( T_{ux}, T_{uy}, T_{uz} \)) and the Reynolds shear stress component \( \frac{\nu'^{2}}{U_{\infty}^{2}} \) are shown. The measurements were conducted at \( U_{\infty} = 25 \text{ m/s} \) which corresponds to a Reynolds number of approx. 80000 based on the wing mean aerodynamic chord.

Figs. 10-15 show the quantities for \( x^* = 1.0 \). Fig. 10 illustrates the cross flow velocity and the velocity vectors. The WTV is clearly visible at \( (y^*; z^*)_{WTV} = (0.977; -0.100) \) being the vortex with the highest cross flow velocities and rotating counter-clockwise.

At \( (y^*; z^*)_{HTV} = (0.270; -0.035) \) the HTV is visible rotating clockwise with significantly smaller cross flow velocities. At the left edge of Fig. 10 two weaker vortices are visible at \( (y^*; z^*) = (0.066; 0.200) \) and \( (y^*; z^*) = (0.014; 0.021) \) turning clockwise and counter-clockwise, respectively. These vortices are caused by the change in circulation through the fuselage interacting with the lifting surfaces, i.e. the wing and the Horizontal Tail Plane (HTP). Their rotation direction hints their source as a vortex caused by the drop in circulation in the fuselage area of a lifting surface is counter-rotating in comparison to the tip vortex of the lifting surface. The position of the lower of the two weak vortices in comparison to the remainder of the shear layer of the HTP and the direction of rotation indicate that this vortex is caused by the HTP, whereas the other one is then assigned to the wing-fuselage interaction.

Figs. 12-14 display the turbulence distribution in this measuring plane. High turbulence intensities in all direction can be found at the vortex core positions and the shear layer emanating from the wing can be seen at the lower edge of the measuring plane. The roll up of the shear layer into the WTV is almost complete as there is only little contact between the turbulence in the vortex and the shear layer. The Reynolds stresses \( \frac{\nu'^{2}}{U_{\infty}^{2}} \) are illustrated in Fig. 15 with values between -0.05 and 0.05 being blanked. The core areas of the dominant vortices exhibit a quadruple structure for the Reynolds shear stress component of the cross flow plane. The vortices are marked by a double pair of local shear stress maxima of opposite sign. These pairs are characterized by an angular shift of about 90° when considering a vortex of axial symmetry. The quadruple structure corresponds to the points of changes in the sign of the mean cross flow velocity. As the vortices are not yet fully developed at \( x^* = 1.0 \) these quadruple structures are not yet properly visible.
Continuing downstream to \(x^*=4.0\) Figs. 16-21 show the results obtained. In Fig. 16 the two weak vortices mentioned for \(x^*=1.0\) are not visible anymore. The WTV is still clearly visible at \((y^*; z^*)_{WTV} = (1.000; -0.296)\) being the most dominant vortex in the flow field. At \((y^*; z^*)_{HTV} = (0.232; -0.120)\) the HTV can be detected, but the cross flow velocities have decreased clearly. Both vortices have moved downwards, thereby the HTV moved inwards, whereas the WTV moved outwards. Fig. 17 displays the vorticity distribution. Again values between -1 and 1 are blanked in order to clarify the positions of the vortices. Only the WTV and the HTV remain at this downstream position. The peak vorticity value for the HTV has decreased in magnitude significantly to -1.5, which is only 7.1% of the peak vorticity value at \(x^*=1.0\). The WTV vorticity peak has decreased by 39.7% to 20.2. The large decrease for the HTV may be due to the vortex moving. As Figs. 16-21 are time averaged a movement of the vortex would result in a decrease in the vorticity peak. The turbulence intensities \(T_{ux}, T_{uy}, T_{uz}\) are illustrated in Figs. 18-20. A high peak can be seen for the WTV whereas the turbulence seems blurred for the HTV, which could also be an indication for the vortex moving. Fig. 21 shows the Reynolds stresses \(\overline{\nu'w'}/U_a^2\). Again values between -0.05 and 0.05 are blanked. For the WTV the quadruple structure mentioned above can now be seen better than at \(x^*=1.0\).

For \(x^*=8.0\) Fig. 22 shows the cross flow velocity distribution where the WTV is still clearly visible, but with significantly reduced velocities which corresponds to the reduced vorticity values in Fig. 23. Note, that vorticity levels between -0.5 and 0.5 are blanked in Fig. 23. The HTV can be found at \((y^*; z^*)_{HTV} = (0.268; -0.206)\) with a peak vorticity of -0.95 whereas the WTV is at \((y^*; z^*)_{WTV} = (1.030; -0.525)\) with the peak vorticity value being 12.6. Both vortices have moved downwards and outwards. The vorticity distribution also shows a speckled shape for the HTV and to some degree also for the WTV. Clearly the WTV is descending faster than the HTV which is not the case in the smoke visualisation using the large model. The turbulence intensities in Figs. 24-26 again indicate higher levels in the core of the WTV. Figs. 25 and 26 also show slightly increased values at the position of the HTV. Fig. 27 now clearly illustrates the quadruple structure of the WTV. Velocity fluctuation levels between -0.05 and 0.05 are blanked.

The next measuring plane downstream is at \(x^*=12.0\), the results of which are shown in Figs. 28-33. The HTV can hardly be seen in the vector and cross flow velocity plot in Fig. 28. In contrast the vectors indicating a counter-clockwise rotation of the WTV can still clearly be seen. Fig. 29 illustrates the vorticity distribution with values between -0.1 and 0.1 being blanked. A clear vorticity peak of 7.7 can be found at \((y^*; z^*)_{WTV} = (1.06; -0.747)\) for the WTV. The peak vorticity for the HTV is -0.5 at \((y^*; z^*)_{HTV} = (0.293; -0.520)\). These values again indicate a downward and outward movement of both vortices. The peak vorticity for the HTV is difficult to find as the area of vorticity of this magnitude is quite large. The WTV now also clearly shows speckles. Figs. 30-32 again show increased values for the position of the WTV and slightly increased values are still visible for the HTV in \(T_{uy}\). The quadruple structure of the WTV in Fig. 33 has not changed significantly in comparison to the image at position \(x^*=8.0\). Here values between -0.05 and 0.05 of the velocity fluctuations are blanked.

Continuing downstream to \(x^*=16.0\), Figs. 34-39 show the results obtained. Fig. 34 shows the again reduced cross flow velocities for the WTV. From this figure the HTV
can not be determined. Clearly visible is the induced downwash leading to the main flow direction being in negative z-direction, except for the vicinity of the WTV. The position of both vortices can still be determined by the vorticity distribution in Fig. 35. Here, the vorticity levels between -0.1 and 0.1 are blanked. The position of the WTV is at \((y^*; z^*)_{WTV} = (1.09; -0.912)\) and the HTV is at \((y^*; z^*)_{HTV} = (0.375; -0.627)\) again indicating a downward and outward movement. The vorticity peaks have dropped to 4.29 and -0.44 for the WTV and HTV, respectively. The turbulence intensities \(T_{ux}, T_{uy}, T_{uz}\) in Figs. 36-38 show no significant differences in comparison to the next upstream position. Also the Reynolds stresses \(\overline{v'w'}/U_\infty^2\) show no significant difference in Fig. 39.

At \(x^* = 20.0\), the flow has now also turned to an almost straight downward direction in the inboard part of the wing as shown in Fig. 40. The WTV is visible at \((y^*; z^*)_{WTV} = (1.12; -1.090)\). From Fig. 41 a vorticity peak of -0.24 can be determined with the position of the HTV being \((y^*; z^*)_{HTV} = (0.379; -0.974)\). The position of both vortices has again moved outwards and downwards. This downstream measuring position is the last one where the position of the HTV could be determined. Downstream of \(x^* = 20.0\) the vorticity drops so low, that a clear peak is not present. In contrast the peak vorticity of the WTV can still be recognized at a level of 3.28. Figs. 42-44 show the turbulence intensities in the three directions. Fig. 42 illustrates that the turbulence is confined within the WTV. The quadruple structure of the WTV in Fig. 45 has decreased slightly.

The next measuring plane downstream is at \(x^* = 24.0\), Figs. 46-51. The WTV can still be seen at \((y^*; z^*)_{WTV} = (1.17; -1.290)\) in Fig. 46 with a vorticity peak of 2.53, compare Fig. 47. This indicates a downward and outward motion of the WTV. The vortex now clearly shows speckles. Figs. 48-50 show that the higher turbulence levels are confined to the WTV. Fig. 51 displays slightly decreased levels of velocity fluctuations. However the quadruple structure is still visible.

Continuing downstream to \(x^* = 36.0\), Figs. 52-57, significant changes compared to the station at \(x^* = 24.0\) are visible. The WTV has moved to \((y^*; z^*)_{WTV} = (1.30; -1.670)\) and has significantly decreased in size, compare Fig. 52. Again the movement is downwards and outwards. The vorticity peak in Fig. 53 for the WTV has decreased to 1.09. In this figure vorticity levels between -0.05 and 0.05 are blanked. Therefore the vortex appears larger. Nevertheless the shape shows increased speckles. The turbulence intensities in all directions are now confined to the region of the WTV and have decreased significantly. The Reynolds stresses \(\overline{v'w'}/U_\infty^2\) still show the quadruple structure confined to the WTV. Note, that levels between -0.005 and 0.005 are blanked, which lets the structure appear significantly larger.

At \(x^* = 48.0\), the position and rotational direction of the WTV is difficult to extract from Fig. 58. Fig. 59 gives a clearer overview. The HTV is not visible in the vorticity distribution any more whereas the WTV is visible at \((y^*; z^*)_{WTV} = (1.35; -1.930)\) with a vorticity peak of 0.35. Values between -0.05 and 0.05 are blanked. The turbulence intensities have decreased further to a level of approx. 3% in the region of the vortex core, compare Figs. 60-62. The quadruple structure is also still visible in Fig. 63. Reynolds stress levels between -0.005 and 0.005 are also blanked here.
Fig. 64 illustrates the development of the peak vorticity value of the WTV over the downstream distance $x^*$. The WTV shows a gradual decrease in the peak of the axial vorticity value.

Fig. 65 shows the track of the vortex center in the $y^*-z^*$ plane. As stated above the WTV moves downwards and outwards continuously whereas the HTV moves inwards and then outwards while always travelling downwards. The data for the HTV is only available up to $x^*=20.0$. The downward velocity of the WTV decreases as it moves downstream. Note that the last two data points have a $\Delta x^*$ of 12, whereas the first seven data points have a $\Delta x^*$ of 4.
Figure 10. Cross flow velocity distribution and velocity vectors for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$.

Figure 11. Vorticity distribution for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$. 
Figure 12. Turbulence distribution $T_u_x$ for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$.

Figure 13. Turbulence distribution $T_u_y$ for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$. 
Figure 14. Turbulence distribution $T_{u_2}$ for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$.

Figure 15. Distribution of the Reynolds shear stress component $\overline{v'w'}/U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$. 
Figure 16. Cross flow velocity distribution and velocity vectors for the small model (F13) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$.

Figure 17. Vorticity distribution for the small model (F13) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$. 
Figure 18. Turbulence distribution $T_{u_x}$ for the small model (F13) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$.

Figure 19. Turbulence distribution $T_{u_y}$ for the small model (F13) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$. 
Figure 20. Turbulence distribution $T_u$ for the small model (F13) at $Re_e=80000$ and $x^*=4.0$, $\tau^*=0.1139$.

Figure 21. Distribution of the Reynolds shear stress component $\overline{v'w'}/U_{\infty}^2$ for the small model (F13) at $Re_e=80000$ and $x^*=4.0$, $\tau^*=0.1139$. 
Figure 22. Cross flow velocity distribution and velocity vectors for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$.

Figure 23. Vorticity distribution for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$. 
Figure 24. Turbulence distribution $Tu_x$ for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau*=0.2278$.

Figure 25. Turbulence distribution $Tu_y$ for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau*=0.2278$. 
Figure 26. Turbulence distribution $T_u_z$ for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$.

Figure 27. Distribution of the Reynolds shear stress component $\overline{v'w'}/U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$. 
Figure 28. Cross flow velocity distribution and velocity vectors for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$.

Figure 29. Vorticity distribution for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$. 

Figure 30. Turbulence distribution $T_{u_x}$ for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$.

Figure 31. Turbulence distribution $T_{u_y}$ for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$. 
Figure 32. Turbulence distribution $T_{u_2}$ for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$.

Figure 33. Distribution of the Reynolds shear stress component $\overline{\nu'' w''} / U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=12.0$, $\tau^*=0.3417$. 
Figure 34. Cross flow velocity distribution and velocity vectors for the small model (F13) at Re₉=80000 and x*=16.0, τ*=0.4555.

Figure 35. Vorticity distribution for the small model (F13) at Re₉=80000 and x*=16.0, τ*=0.4555.
Figure 36. Turbulence distribution $T_{ux}$ for the small model (F13) at $Re_c=80000$ and $x^*=16.0$, $\tau^*=0.4555$.

Figure 37. Turbulence distribution $T_{uy}$ for the small model (F13) at $Re_c=80000$ and $x^*=16.0$, $\tau^*=0.4555$. 
Figure 38. Turbulence distribution $T_{u_2}$ for the small model (F13) at $Re_c=80000$ and $x^*=16.0$, $\tau^*=0.4555$.

Figure 39. Distribution of the Reynolds shear stress component $\overline{v'w'}/U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=16.0$, $\tau^*=0.4555$. 
Figure 40. Cross flow velocity distribution and velocity vectors for the small model (F13) at Re=80000 and x*=20.0, τ*=0.5694.

Figure 41. Vorticity distribution for the small model (F13) at Re=80000 and x*=20.0, τ*=0.5694.
Figure 42. Turbulence distribution $T_u_x$ for the small model (F13) at $Re_c=80000$ and $x^*=20.0$, $\tau^*=0.5694$.

Figure 43. Turbulence distribution $T_u_y$ for the small model (F13) at $Re_c=80000$ and $x^*=20.0$, $\tau^*=0.5694$. 
Figure 44. Turbulence distribution $T_u_z$ for the small model (F13) at $Re_c=80000$ and $x^*=20.0$, $\tau^*=0.5694$.

Figure 45. Distribution of the Reynolds shear stress component $\bar{v}'\bar{w}' / U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=20.0$, $\tau^*=0.5694$. 
Figure 46. Cross flow velocity distribution and velocity vectors for the small model (F13) at \( Re_c = 80000 \) and \( x^* = 24.0, \tau^* = 0.6833 \).

Figure 47. Vorticity distribution for the small model (F13) at \( Re_c = 80000 \) and \( x^* = 24.0, \tau^* = 0.6833 \).
Figure 48. Turbulence distribution $T_{ux}$ for the small model (F13) at $Re_c=80000$ and $x^*=24.0$, $\tau^*=0.6833$.

Figure 49. Turbulence distribution $T_{uy}$ for the small model (F13) at $Re_c=80000$ and $x^*=24.0$, $\tau^*=0.6833$. 
Figure 50. Turbulence distribution $T_{u_2}$ for the small model (F13) at $Re_c=80000$ and $x^*=24.0$, $\tau^*=0.6833$.

Figure 51. Distribution of the Reynolds shear stress component $\overline{v'w'}/U^2_\infty$ for the small model (F13) at $Re_c=80000$ and $x^*=24.0$, $\tau^*=0.6833$. 
Figure 52. Cross flow velocity distribution and velocity vectors for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$.

Figure 53. Vorticity distribution for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$. 
Figure 54. Turbulence distribution $T_u_x$ for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$.

Figure 55. Turbulence distribution $T_u_y$ for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$. 
Figure 56. Turbulence distribution $T_{U_z}$ for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$.

Figure 57. Distribution of the Reynolds shear stress component $\overline{\nu'w'}/U_\infty^2$ for the small model (F13) at $Re_c=80000$ and $x^*=36.0$, $\tau^*=1.0250$. 
Figure 58. Cross flow velocity distribution and velocity vectors for the small model (F13) at \(Re_c=80000\) and \(x^*=48.0\), \(\tau^*=1.3666\).

Figure 59. Vorticity distribution for the small model (F13) at \(Re_c=80000\) and \(x^*=48.0\), \(\tau^*=1.3666\).
Figure 60. Turbulence distribution $T_{u_x}$ for the small model (F13) at $Re_c=80000$ and $x^*=48.0$, $\tau^*=1.3666$.

Figure 61. Turbulence distribution $T_{u_y}$ for the small model (F13) at $Re_c=80000$ and $x^*=48.0$, $\tau^*=1.3666$. 
Figure 62. Turbulence distribution $T_u_z$ for the small model (F13) at $Re_e=80000$ and $x^*=48.0$, $\tau^*=1.3666$.

Figure 63. Distribution of the Reynolds shear stress component $\overline{v'w'}/U_w^2$ for the small model (F13) at $Re_e=80000$ and $x^*=48.0$, $\tau^*=1.3666$. 
Figure 64. Decay in peak vorticity for the Wing Tip Vortex.

Figure 65. Trajectories of the vortices WTV and HTV in the y*-z*-plane.
V.3. Hot-wire Results for the Large Model (F13X)

This chapter deals with the hot-wire measurements performed on the DLR F13X model using a cross-wire probe. Each measuring plane was scanned twice, once to obtain data relevant to the xy-plane and a second time for the data relevant to the xz-plane. Planes were measured at $x^* = x/b = 1.0, 4.0, 8.0$ and $12.0$ and the results are discussed below. For each plane the cross flow velocity $V_{\theta}$, the non-dimensional vorticity $\xi$ and the turbulence intensities $(T_{ux}, T_{uy}, T_{uz})$ are shown. The product of velocity fluctuations $v'w'$, which were shown for the small model, is not available due to the use of a two wire probe. The measurements were conducted at $U_\infty = 6.25 \text{ m/s}$ and $U_\infty = 25 \text{ m/s}$ which corresponds to a Reynolds number based on the wing mean aerodynamic chord of approx. 80000 and 320000.

Figs. 66-85 refer to the case with $Re_c = 80000 \ (U_\infty = 6.25 \text{ m/s})$, which is the same Reynolds number as for the small model at $U_\infty = 25 \text{ m/s}$. A comparison of the results for the two models at the same Reynolds number will be conducted.

For $x^* = 1.0$ Figs. 66-70 are relevant. Fig. 66 illustrates the cross flow velocity and the velocity vectors. The position of the vortices is at $(y^*; z^*)_{\text{WTV}} = (0.930; 0.000)$ and $(y^*; z^*)_{\text{HTV}} = (0.267; -0.011)$. For the HTV this is only 2.4% of the wing span away from the position determined on the small model. The position of the WTV is further inward and downward than for the small model. The distance between the position of the WTV for the small and the large model is 11.0% $b_w$. The two weaker vortices are also visible at the top left of Fig. 66, both being slightly weaker as for the small model. The position of these two vortices is comparable with the position determined on the small model. Fig. 67 displays the vorticity distribution with values between -1 and 1 being blanked. All four vortices mentioned above are visible. The vorticity peak of the HTV is at -151, whereas the WTV has its vorticity peak at 91. The higher peak value for the HTV is again due to the measuring plane being significantly closer to the trailing edge of the horizontal tail plane than to the trailing edge of the wing. Both dominating vortices have a significantly higher peak vorticity than for the small model. This is due to the measuring grid resolution being slightly higher for the large model, which has a direct influence on the gradient. Figs. 68-70 illustrate the turbulence intensities $T_{ux}$, $T_{uy}$ and $T_{uz}$. Also for the large model, turbulence values below 2% are blanked for all cases. Clearly the shear layer emanating from the wing is visible at the lower edge of the measuring plane. The highest turbulence intensities can be found in the regions of the vortex cores.

Continuing downstream to $x^* = 4.0$ Figs. 71-75 show the results obtained. The two weak vortices mentioned for $x^* = 1.0$ have decayed, compare Fig. 71. The HTV is still clearly visible at $(y^*; z^*)_{\text{HTV}} = (0.269; -0.295)$, whereas the WTV is at $(y^*; z^*)_{\text{WTV}} = (0.930; -0.158)$. Both vortices have moved almost straight downwards, which is in contrast to the small model. Fig. 72 illustrates the vorticity distribution, clearly showing the WTV and HTV. Values between -1 and 1 are blanked in this figure. The HTV has reached a significantly lower position as the WTV in contrast to the results obtained for the small model. This effect was already visible during the smoke visualisation. The peak vorticity for the WTV is 58 and for the HTV -12. Similar to the small model there is a drastic decrease in the peak vorticity for the HTV to 7.9% of the value at $x^* = 1.0$. The turbulence intensities depicted in Figs. 73-75 show a similar picture as for the small model. The WTV has only a weak shear layer connecting it to
the remaining shear layer emanated by the wing. The turbulence peaks underline the statements made above, that there are only two remaining vortices.

At \( x^* = 8.0 \), Fig. 76 shows the cross flow velocity distribution where the HTV is still visible at \((y^*; z^*)_{HTV} = (0.375; -0.622)\) with significantly reduced velocities. They correspond to the reduced vorticity values in Fig. 77, where values between -0.5 and 0.5 are blanked. The position of the WTV is at \((y^*; z^*)_{WTV} = (0.991; -0.326)\) with a peak vorticity value of 43, whereas the peak value for the HTV is -5. Both vortices are moving downwards and outwards, but far faster than for the small model. The speckle shape of the HTV is similar to the one found for the small model. In contrast to the small model the HTV is descending faster than the WTV which confirms the results obtained by the smoke visualisation for the large model. Figs. 78-80 depict the turbulence intensity distributions showing two local peaks at the position of the two remaining vortices.

The next measuring plane downstream is at \( x^* = 12.0 \), Figs. 81-85. The HTV is difficult to determine in the vector and cross flow velocity plot of Fig. 81. The WTV can still be seen with significant cross flow velocities at \((y^*; z^*)_{WTV} = (1.085; -0.451)\). Fig. 82 depicts the axial vorticity distribution. Here levels between -0.1 and 0.1 are blanked. The WTV has a vorticity peak of 41 whereas the HTV has a peak of -3 at \((y^*; z^*)_{HTV} = (0.554; -0.872)\). The movement of the vortices is again downward and outward, but still at a higher velocity as for the small model. In Figs. 83-85 the turbulence intensity peaks indicating the position of the vortices can still be determined.

Continuing with the case at \( Re_c = 320000 \) \((U_\infty = 25 \text{ m/s})\) Figs. 86-105 depict the results obtained. The influence of the Reynolds number will be discussed for this case.

Figs. 86-90 illustrate the flow quantities in the first measuring plane at \( x^* = 1.0 \). Due to the higher free stream velocity higher cross flow velocities are observed in Fig. 86. The position of the WTV is at \((y^*; z^*)_{WTV} = (0.927; -0.006)\) and the HTV is at \((y^*; z^*)_{HTV} = (0.271; -0.011)\). For both vortices this is less than 1% difference with respect to the wing span in comparison to the case with the lower Reynolds number. The two weaker vortices are also visible, but the velocities in y- and z-direction are of the same magnitude as for the low Reynolds number case. Also the position of these two vortices is comparable. Fig. 87 shows the vorticity distribution with levels between -1 and 1 being blanked. The WTV is clearly visible and parts of the shear layer rolling up into the WTV are also observable just below the vortex. The shear layer emanated by the horizontal tail plane can also be detected rolling up into the HTV. The lower of the two weak vortices is depicted in Fig. 87, whereas the upper one is not visible. The peak value in non-dimensional axial vorticity for the WTV is 91 and for the HTV it is -176. Again the distance between the vortex source and the measuring plane is responsible for the high HTV value. For the WTV the peak vorticity value is identical to the one in the lower Reynolds number case, for the HTV it is of similar magnitude. The peaks in turbulence intensity as shown in Figs. 88-90 are much more confined to the core of the WTV as for the low Reynolds number case. The remaining wing shear layer appears much thinner and the turbulence intensity levels for the HTV is much lower whereas for the lower of the two weaker vortices a local turbulence maximum higher than for the HTV can be identified.
Figs. 91-95 refer to $x^*=4.0$ the next downstream measuring position. Fig. 91 depicts the two dominating vortices one being at $(y^*; z^*)_{WTV} = (0.898; -0.167)$, the other one at $(y^*; z^*)_{HTV} = (0.274; -0.288)$. The HTV has moved straight downward almost to the same position as for the low Reynolds number case. The WTV moves downward and slightly inward, which has not been observed for any of the other two cases. There is no evidence for the two weaker vortices still existing. Fig. 92 depicts the axial vorticity distribution showing the WTV and HTV with axial vorticity peaks of 58 and -64, respectively. The reduction in peak vorticity for the HTV is significantly smaller than in the previous cases. Just as for the low Reynolds number case the HTV has reached a significantly lower position in comparison to the WTV. The turbulence distributions in Figs. 93-95 show a completely different picture in comparison to the previous cases. The turbulence layer is fed into the HTV evident by the clockwise rotation of the layer attached to the HTV. A similar high turbulence level can be observed for the WTV as for the HTV, but here solely confined to the core region of the vortex.

At $x^*=8.0$, the two dominating vortices are visible in Fig. 96 at $(y^*; z^*)_{WTV} = (0.947; -0.367)$ and $(y^*; z^*)_{HTV} = (0.384; -0.675)$. The position of HTV is similar to the one reached for the low Reynolds number case whereas the WTV moved downward and outward reaching a position slightly below and inward in comparison to the low Reynolds number case. The peak vorticities in Fig. 97 is 46 for the WTV and -26 for the HTV with values between -0.5 and 0.5 being blanked. Both vortices show significant speckles. The turbulence intensities in Figs. 98-100 indicate that the roll up process of the shear layer into the HTV is almost complete. The area of turbulence around the WTV has increased in size.

The next measuring plane downstream is at $x^*=12.0$, Figs. 101-105. Here, the HTV can still be determined by the vector plot in Fig. 101 at $(y^*; z^*)_{HTV} = (0.617; -0.982)$. This puts the HTV further outward and further downward for the high Reynolds number case. The WTV is at $(y^*; z^*)_{WTV} = (1.045; -0.502)$. The peak values of axial vorticity are 42 for the WTV and -21 for the HTV. Figs. 103-105 show only confined areas of turbulence around the vortex cores. Note that the size of the area of turbulence around the WTV has again increased in size.

Fig. 106 illustrates the decay of the WTV for both Reynolds numbers. In comparison to the small model (Fig. 64) the overall level of peak axial vorticity is higher, but the decay rate is comparable. There is no significant difference for the large model between the two Reynolds numbers. Fig. 107 depicts the position of the WTV and HTV. For the HTV there is no difference for the first two measuring planes, but further downstream the vortex travels faster at high Reynolds numbers reaching a position lower and further outward at $x^*=12.0$. The WTV has a similar track for both Reynolds numbers, but for the higher velocity it is further inward descending slightly faster. However, the track of both vortices is different to the ones for the small model even though the Reynolds numbers are the same for two cases. This difference may then be attributed to some discrepancies in model geometry and/or HTP and incidence setting.
Figure 66. Cross flow velocity distribution and velocity vectors for the large model (F13X) at Re<sub>c</sub>=80000 and x*=1.0, τ*=0.0285.

Figure 67. Vorticity distribution for the large model (F13X) at Re<sub>c</sub>=80000 and x*=1.0, τ*=0.0285.
Figure 68. Turbulence distribution $T_u_x$ for the large model (F13X) at $Re_c=80000$ and $x^*=1.0, \tau^*=0.0285$.

Figure 69. Turbulence distribution $T_u_y$ for the large model (F13X) at $Re_c=80000$ and $x^*=1.0, \tau^*=0.0285$. 

Figure 70. Turbulence distribution $T_u$ for the large model (F13X) at $Re_c=80000$ and $x^*=1.0$, $\tau^*=0.0285$. 
Figure 71. Cross flow velocity distribution and velocity vectors for the large model (F13X) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$.

Figure 72. Vorticity distribution for the large model (F13X) at $Re_c=80000$ and $x^*=4.0$, $\tau^*=0.1139$. 

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Figure 73. Turbulence distribution $Tu_x$ for the large model (F13X) at $Re_c=80000$ at $x=4.0, \tau^*=0.1139$.

Figure 74. Turbulence distribution $Tu_y$ for the large model (F13X) at $Re_c=80000$ at $x=4.0, \tau^*=0.1139$. 
Figure 75. Turbulence distribution $T_u_z$ for the large model (F13X) at $Re_e=80000$ at $x=4.0$, $\tau^*=0.1139$. 
Figure 76. Cross flow velocity distribution and velocity vectors for the large model (F13X) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$.

Figure 77. Vorticity distribution for the large model (F13X) at $Re_c=80000$ and $x^*=8.0$, $\tau^*=0.2278$. 
Figure 78. Turbulence distribution $T_{u_x}$ for the large model (F13X) at $Re_{e}=80000$ at $x=8.0$, $\tau^*=0.2278$.

Figure 79. Turbulence distribution $T_{u_y}$ for the large model (F13X) at $Re_{e}=80000$ at $x=8.0$, $\tau^*=0.2278$. 
Figure 80. Turbulence distribution $T_u$ for the large model (F13X) at $Re_c=80000$ at $x=8.0$, $\tau^*=0.2278$. 
Figure 81. Cross flow velocity distribution and velocity vectors for the large model (F13X) at Reₐ=80000 and x*=12.0, τ*=0.3417.

Figure 82. Vorticity distribution for the large model (F13X) at Reₐ=80000 and x*=12.0, τ*=0.3417.
Figure 83. Turbulence distribution $T_{u_x}$ for the large model (F13X) at $Re_c=80000$ at $x=12.0$, $\tau^*=0.3417$.

Figure 84. Turbulence distribution $T_{u_y}$ for the large model (F13X) at $Re_c=80000$ at $x=12.0$, $\tau^*=0.3417$. 
Figure 85. Turbulence distribution $T_{uw}$ for the large model (F13X) at $Re_c=80000$ at $x=12.0$, $\tau^*=0.3417$. 
Figure 86. Cross flow velocity distribution and velocity vectors for the large model (F13X) at Re∞=320000 and x*=1.0, τ*=0.0260.

Figure 87. Vorticity distribution for the large model (F13X) at Re∞=320000 and x*=1.0, τ*=0.0260.
Figure 88. Turbulence distribution $T_u_x$ for the large model (F13X) at $Re_c=320000$ and $x^*=1.0, \tau^*=0.0260$.

Figure 89. Turbulence distribution $T_u_y$ for the large model (F13X) at $Re_c=320000$ and $x^*=1.0, \tau^*=0.0260$.
Figure 90. Turbulence distribution $T_u$ for the large model (F13X) at $Re_c=320000$ and $x^*=1.0$, $\tau^*=0.0260$. 
Figure 91. Cross flow velocity distribution and velocity vectors for the large model (F13X) at Re_c=320000 and x*=4.0, τ*=0.1040.

Figure 92. Vorticity distribution for the large model (F13X) at Re_c=320000 and x*=4.0, τ*=0.1040.
Figure 93. Turbulence distribution $T_{u_x}$ for the large model (F13X) at $Re_c=320000$ and $x^*=4.0, \tau^*=0.1040$.

Figure 94. Turbulence distribution $T_{u_y}$ for the large model (F13X) at $Re_c=320000$ and $x^*=4.0, \tau^*=0.1040$. 
Figure 95. Turbulence distribution $T_u_z$ for the large model (F13X) at $Re_c=320000$ and $x^*=4.0$, $\tau^*=0.1040$. 
Figure 96. Cross flow velocity distribution and velocity vectors for the large model (F13X) at $Re_c=320000$ and $x^*=8.0$, $\tau^*=0.2080$.

Figure 97. Vorticity distribution for the large model (F13X) at $Re_c=320000$ and $x^*=8.0$, $\tau^*=0.2080$. 
Figure 98. Turbulence distribution $T_{u_x}$ for the large model (F13X) at $Re_c=320000$ and $x^*=8.0$, $\tau^*=0.2080$.

Figure 99. Turbulence distribution $T_{u_y}$ for the large model (F13X) at $Re_c=320000$ and $x^*=8.0$, $\tau^*=0.2080$. 
Figure 100. Turbulence distribution $T_u$ for the large model (F13X) at $Re_e=320000$ and $x^*=8.0$, $\tau^*=0.2080$. 
Figure 101. Cross flow velocity distribution and velocity vectors for the large model (F13X) at $Re_c=320000$ and $x^*=12.0$, $\tau^*=0.3121$.

Figure 102. Vorticity distribution for the large model (F13X) at $Re_c=320000$ and $x^*=12.0$, $\tau^*=0.3121$. 

70 / 102
Figure 103. Turbulence distribution $T_{u_x}$ for the large model (F13X) at $Re_{c}=320000$ and $x^*=12.0$, $\tau^*=0.3121$.

Figure 104. Turbulence distribution $T_{u_y}$ for the large model (F13X) at $Re_{c}=320000$ and $x^*=12.0$, $\tau^*=0.3121$. 
Figure 105. Turbulence distribution $T_u_z$ for the large model (F13X) at $Re_z=320000$ and $x^*=12.0$, $\tau^*=0.3121$.

Figure 106. Decay in peak vorticity for the Wing Tip Vortex.
Figure 107. Trajectories of the vortices WTV and HTV in the y*-z*-plane.
V.4. PIV Results for the Small Model (F13)

This chapter deals with the PIV measurements performed on the DLR F13 model using a 3D PIV system. Planes were measured from $x^*=1.5$ up to 10.0 in steps of $\Delta x^*=0.5$ and the results are shown below. The measurements were conducted at $U_\infty=25$ m/s which corresponds to a Reynolds number of approx. 80000 based on the wing mean aerodynamic chord. For each plane the velocity component in x-direction $u$ is plotted as contour and the cross flow components $v$ and $w$ as vector plot. The velocities are made dimensionless with the free stream velocity $U_\infty$ and are therefore referred to as $u^*$, $v^*$ and $w^*$.

Figs. 108-125 illustrate the results for each plane. The HTV and WTV and their direction of rotation are depicted by the vector plots. The downward motion of the WTV is clearly visible and so is the shear layer, marked by a slightly reduced $u$-component, fed into the WTV up to approx. $x^*=8.5$. In the upper inner portion of the images an area of reduced axial velocity $u$ is visible which slowly disappears downstream. For the PIV the resolution of the image is one data point every 5 mm (approx. 1.7% $b_w$) whereas the hot-wire anemometry gathers data every 2 mm (approx. 0.7% $b_w$). This has a significant influence on the axial vorticity as the gradients of the cross flow velocity components are used. The peak values of the axial vorticity are therefore far lower for the PIV measurements and therefore not suitable for a comparison. Turbulence intensities can not be captured correctly with a PIV system as the sampling rate is too low. Therefore only the flow velocities in the three Cartesian directions are depicted here.

Figure 108. PIV result for the small model (F13) at $Re_c=80000$ and $x^*=1.5$, $\tau^*=0.0427$. 

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74 / 102
Figure 109. PIV result for the small model (F13) at Re_c=80000 and x^*=2.0, τ^*=0.0569.

Figure 110. PIV result for the small model (F13) at Re_c=80000 and x^*=2.5, τ^*=0.0712.
Figure 111. PIV result for the small model (F13) at Re=80000 and x*=3.0, \( \tau^*=0.0854 \).

Figure 112. PIV result for the small model (F13) at Re=80000 and x*=3.5, \( \tau^*=0.0996 \).
Figure 113. PIV result for the small model (F13) at Re_{c}=80000 and x^*=4.0, τ^*=0.1139.

Figure 114. PIV result for the small model (F13) at Re_{c}=80000 and x^*=4.5, τ^*=0.1281.
Figure 115. PIV result for the small model (F13) at $Re_c=80000$ and $x^*=5.0$, $\tau^*=0.1424$.

Figure 116. PIV result for the small model (F13) at $Re_c=80000$ and $x^*=5.5$, $\tau^*=0.1566$. 
Figure 117. PIV result for the small model (F13) at Re\(_c\)=80000 and x*\(^*\)=6.0, \(\tau^*\)=0.1708.

Figure 118. PIV result for the small model (F13) at Re\(_c\)=80000 and x*\(^*\)=6.5, \(\tau^*\)=0.1851.
Figure 119. PIV result for the small model (F13) at $Re_c=80000$ and $x^*=7.0$, $\tau^*=0.1993$.

Figure 120. PIV result for the small model (F13) at $Re_c=80000$ and $x^*=7.5$, $\tau^*=0.2135$. 
Figure 121. PIV result for the small model (F13) at Re<sub>c</sub>=80000 and x*=8.0, τ* = 0.2278.

Figure 122. PIV result for the small model (F13) at Re<sub>c</sub>=80000 and x*=8.5, τ* = 0.2420.
Figure 123. PIV result for the small model (F13) at Re<sub>c</sub>=80000 and x*=9.0, τ*=0.2562.

Figure 124. PIV result for the small model (F13) at Re<sub>c</sub>=80000 and x*=9.5, τ*=0.2705.
Figure 125. PIV result for the small model (F13) at $\text{Re}_c=80000$ and $x^*=10.0$, $\tau^*=0.2847$. 
V.5. Comparison between Hot-wire Anemometry and PIV

Here the entire span was scanned in order to have a comparison with the PIV on both sides of the model. The hot-wire results are interpolated on to a 1 mm x 1 mm grid. Then only every fifth vector of the interpolated field is displayed thus giving a vector every 5 mm thus matching the resolution of the PIV results. This guarantees a suitable comparison.

Fig. 126 shows the result obtained by hot-wire anemometry (HWA) for the small model with a triple wire probe at $x^*=4.0$. Fig. 127 illustrates the PIV result for the same measuring position. The position of the right WTV is similar for both measuring system, whereas the left WTV is further outboard for the PIV system. Clearly the PIV system over-predicts the velocity component $u$ in the vortex cores of the WTVs, whereas it is underestimated for the regions of the HTVs. The positions of the HTVs are almost identical for both measuring systems. The overall flow field is qualitatively identical, but in the regions of interest the cross flow velocities are also slightly smaller for the PIV result.

Fig. 128 illustrates the hot-wire result and Fig. 129 depicts the PIV result in the same measuring plane at $x^*=8.0$. The right WTV is predicted slightly upward and outboard with the PIV system and the left WTV is predicted even further outboard and upward as with the HWA system. The positions of the HTV are difficult to determine in both figures, but appear more upward for the PIV result. Again the velocity component $u$ is overestimated by the PIV system for the cores of the WTVs. And also this component is under predicted for the region of the HTVs again. The entire velocity field in all directions seems to have a lower value for the PIV system, at least in the area of interest.

Figs. 126-129 also indicate that the model is not fully symmetrical. Independent from the used measuring system the left WTV is always predicted more upward than the right one. The field of the velocity component $u$ is also not symmetrically to $y^*=0$, whereas it depends at $x^*=4.0$ on the used measuring system which side has a higher $u$ component. As exclusively the right hand side of the DLR F13 model was investigated, the left hand side shows a more upward and further inboard WTV and therefore might match the path of the WTV for the large model at the same Reynolds number better, compare Figs. 65 and 107.

Further knowledge on this topic is to be gained by the towing tank tests performed by DLR in mid 2007.
Figure 126. HWA result for the small model (F13) and $x^*=4.0$ over the entire span

Figure 127. PIV result for the small model (F13) and $x^*=4.0$ over the entire span
Figure 128. HWA result for the small model (F13) and $x^*=8.0$ over the entire span

Figure 129. PIV result for the small model (F13) and $x^*=8.0$ over the entire span
V.6. Spectral Analysis

In order to judge the instabilities developing in the vortex system, characteristic spectral peaks are searched for indicating that turbulent kinetic energy is channeled into a narrow band due to quasi periodic fluctuations.

A short overview is given below how the frequency content and related energy overshoots are evaluated with respect to the most dominant instability mechanisms: The presence of instability mechanisms propagating along the wake vortex in stream wise direction can lead to a relevant distortion of the vortex, accelerating its dispersion and decay. Usually, long, medium and short wave instabilities occur.

The most significant long wave instability for a counter-rotating vortex pair is the Crow instability. This instability is related to the strain effect induced by one vortex of a pair on the other one, and appears as a sinusoidal displacement of the vortex trajectories. The displacement amplitude grows exponentially in time but the amplification factor is low. This kind of instability is ultimately responsible for the wake vortex collapse in the far field.

Regarding two vortex pairs Crouch observed an instability mechanism with both symmetric and asymmetric modes, the wavelengths of which are shorter than those of the Crow instability, but large with respect to the effective vortex core size. A Crouch type instability may enhance wake vortex dispersion within \( x/b \approx 30 \).

Wavelengths of Crow and Crouch type instabilities are \( \lambda_{\text{Crow}} \approx 8 b_0 \) and \( \lambda_{\text{Crouch}} \approx 1.5 - 6.0 d \), respectively (here \( d \) denotes the distance between the two adjacent vortices of a four vortex system).

In this case two counter-rotating vortex pairs are investigated as explained in the introduction chapter. The lateral center of circulation is positioned at \( \tilde{b}_o = b_M \left[ \frac{1 + R_b R_F}{1 + R_F} \right] \), \( b_M \) being the distance between the two main vortices. \( R_b \) is the ratio of the spans \( R_b = \frac{b_{\text{HTP}}}{b_w} \) and \( R_F \) the ratio of the circulations \( R_F = \frac{\Gamma_{\text{HTP}}}{\Gamma_w} \). In this investigation these values are chosen to \( R_b = 0.3 \) and \( R_F = -0.3 \), see chapter II. This results to \( \tilde{b}_o = 1.3 b_M \) in the investigated case. The typical wavelength for the dominant instability in a counter-rotating vortex pair is \( \frac{\lambda_{\text{HTP}}}{b_o} \approx 2.5 \pi \). Calculating the reduced frequency this leads to \( k = \frac{f(b/2)}{U_\infty} = \frac{b}{2\lambda} = \frac{1}{5\pi} \frac{b}{b_o} \) and therefrom a frequency of \( f = \frac{2k U_\infty}{b} \approx 8.16 \text{Hz} \) results.

Figs. 130-138 illustrate typical power spectral density distributions for the HTV and WTV in each measuring position \( x^* = 1.0 \div 48.0 \). Clearly distinct peaks are visible around the calculated frequency \( f \) indicating the existence of periodic fluctuations.

In Fig. 131 a pronounced peak can be seen for the HTV at approx. \( f = 10 \text{ Hz} \) indicating strong periodic fluctuations for the HTV.
Figure 130. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=1.0; Re_c=80000$.

Figure 131. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=4.0; Re_c=80000$. 
Figure 132. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=8.0; \text{Re}_c=80000$.

Figure 133. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=12.0; \text{Re}_c=80000$. 
Figure 134. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=16.0; \ Re_c=80000$.

Figure 135. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=20.0; \ Re_c=80000$. 
Figure 136. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=24.0$; $Re_c=80000$.

Figure 137. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=36.0$; $Re_c=80000$. 
Figure 138. Power spectral density distributions taken in the areas of the wing tip vortex (WTV) and horizontal tailplane vortex (HTV) for the small model (F13) at $x^*=48.0$; $Re_c=80000$. 
V.7. Correlation Measurements

For the small model correlation measurements were performed using two hot-wire probes each consisting of three wires. The first probe is at a fixed position within the WTV or HTV, whereas the second probe is traversed within the same vortex at a position further downstream. The plots shown are cross spectral density distributions of the spanwise velocity component $v$ and were evaluated using the same parameters as for evaluation for the power spectral density distributions. Figs. 139-154 show the cross spectral density distributions for the first probe being at $x^*=1.0$. The second probe is positioned between $x^*=4.0$ and $x^*=48.0$. In Figs. 139-154 the odd figure numbers depict the cross spectral density distributions within the WTV whereas the even figure numbers depict the results for the HTV area at the same downstream location as the WTV. Note that the y-axis for the HTV is only half the magnitude of the WTV. Peaks are clearly visible for both vortices in the same frequency region as mentioned above for the power spectral density distributions. In some figures peaks are also visible at higher harmonics of this frequency.

Figure 139. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=4.0$.

Figure 140. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=4.0$. 
Figure 141. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=8.0$.

Figure 142. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=8.0$.

Figure 143. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=12.0$.

Figure 144. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=12.0$. 
Figure 145. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=16.0$.

Figure 146. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=16.0$.

Figure 147. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=20.0$.

Figure 148. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=20.0$. 
Figure 149. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=24.0$.

Figure 150. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=24.0$.

Figure 151. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=36.0$.

Figure 152. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=1.0$ and the other at $x^*=36.0$. 
Figs. 155-164 show the cross spectral density distribution for the first probe being at $x^*=12.0$. The second probe is positioned downstream between $x^*=16.0$ and $x^*=48.0$. Again the odd figure numbers depict the cross spectral density distributions within the WTV whereas the even figure numbers depict results for the HTV. Note that here the y-axis for the WTV is 20 times larger as for the HTV. Also here clear peaks are visible for both vortices for all measuring positions. This indicates that the frequency is contained downstream within the vortices.
Figure 157. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=12.0$ and the other at $x^*=20.0$.

Figure 158. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=12.0$ and the other at $x^*=20.0$.

Figure 159. Cross spectral density distributions for the WTV of the small model (F13) with one probe at $x^*=12.0$ and the other at $x^*=24.0$.

Figure 160. Cross spectral density distributions for the HTV of the small model (F13) with one probe at $x^*=12.0$ and the other at $x^*=24.0$. 
The following two figures depict the results obtained with one probe being within the HTV at $x^*=12.0$ and the other being traversed within the WTV at $x^*=12.0$ (Fig. 165) and vice versa (Fig. 166). At approx. $f=8\text{Hz}$ a clear peak is visible in both figures indicating that this frequency is dominant in both measuring positions.
Figure 165. Cross spectral density distributions for the small model (F13) with both probes at $x^*=12.0$, one in the HTV and the other in the WTV.

Figure 166. Cross spectral density distributions for the small model (F13) with both probes at $x^*=12.0$, one in the WTV and the other in the HTV.
VI. Conclusion

A comprehensive experimental investigation using the DLR F13 and DLR F13X models creating a four vortex system with counter-rotating/neighbored vortices has been conducted.

The determination of the circulation ratio by force measurements is shown. The results obtained by smoke visualisation give an overview of vortex trajectories and occurrence of instabilities. The flow fields observed by the means of hot-wire anemometry and particle image velocimetry are highlighted in detail. The vortices and their sources are explained and the development of the wake vortex system downstream is shown. The influence of the Reynolds number due to model scale and velocity is discussed. The differences in the results obtained by the use of the two different measuring systems are also pointed out.

The behaviour of the vortex pairs is slightly different for the two models with the large model (F13X) being four times larger than the small model (F13). For the small model a rapid decay in axial vorticity is observed for the horizontal tail plane vortex, whereas the wing tip vortex decays rather gradually. The movement of the two counter-rotating vortices during this decay is mainly downward and outward. For the large model at the low Reynolds number (Re_c=80000) the drastic decay in axial vorticity for the horizontal tail plane vortex can also be observed, whereas this is not evident for the high Reynolds number case. The decay rate of the wing tip vortex is similar to the small model for both Reynolds numbers (Re_c=320000). The path of the vortices differ significantly for the large model in comparison to the small model.

The results obtained by hot-wire anemometry and particle image velocimetry also differ slightly. Due to the fact that the hot-wire anemometry tests have a far denser data point distribution, the flow characteristics are captured in more detail. Especially in free stream direction the velocity is mapped far better by hot-wire anemometry.

Spectral analysis of the time dependent velocities obtained from the hot-wire tests has been carried out as well. The developing instabilities are attributed to characteristic spectral density peaks. These peaks were found at a frequency range matching the one predicted by stability analysis. The dominant reduced frequency is approx. \( k_{\text{dom}} = \frac{1}{5\pi} \frac{b}{\tilde{b}_0} \) with \( b \) as wing span and \( \tilde{b}_0 \) as the distance between the main vortices centroids. Similar findings can be seen in the cross spectral density results obtained by correlation measurements using two hot-wire probes.
VII. References


