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Towing tank PIV measurements on 2- and 4-vortex systems IGE

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TOWING TANK PIV MEASUREMENTS ON 2- AND 4-VORTEX SYSTEMS IGE

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Abstract

The present report is part of the WP 3 “Wake evolution near the ground” of the FarWake project. Experimental investigations were performed in the tow tank at Göttingen to describe spatial-temporal flow evolution of 2- and 4-vortex systems in ground effect (IGE). The F13 model consisting of one or two rectangular wings is used as vortex generator and is towed along a ground plate at specific heights h/b = 0.5, 0.25, 0.125. In case of the 4-vortex system a span width ratio of b_2/b_1 = 0.3 and circulation ratios of \( \Gamma_2/\Gamma_1 = \pm 0.3 \) are considered; i.e. co- and counter-rotating vortex pairs. A Stereo Particle Image Velocimetry setup is employed to determine the flow velocity fields in a cross plane. The flow fields are analysed with respect to flow separation at the ground, the generation of secondary vortices, the spatial-temporal development of the vortex trajectories and vortex circulation.

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1 Introduction

When a longitudinal vortex system consisting of two counter-rotating vortices produced by a positive lift generating device approaches the ground their lateral spacing begin to spread. Neglecting viscous effects and assuming a flat ground, the same flow field is produced when the ground surface is notionally replaced by a plane of symmetry. Now, the lateral movement of the vortices can be explained by the influence of the virtual counter-rotating vortices on the opposite side of the symmetry plane. Considering viscous effects, a boundary layer at the ground establishes of opposite signed vorticity. The induced flow on the ground passes an adverse pressure gradient beneath the vortices which leads to a flow separation. From this flow separation, secondary vortices with opposite sense of rotation are produced which rebound from the ground. Their interactions with the primary vortex result in a complex three-dimensional flow field. The behaviour of wake vortices in ground proximity is of particular interest for the optimization of the staggering of landing or starting aircraft at airports. An overview about the previous work and present knowledge on wake vortices near the ground is given by L. Dufresne and G. Winckelmans, 2005.

The present experimental investigations focus on the development of the spatial-temporal flow evolution of 2- and 4-vortex systems in ground proximity. The experiments were carried out in a tow tank within which an adjustable ground plate is installed. The F13 model is used as vortex generator and is towed along the horizontal aligned ground plate applying heights of $h = \frac{1}{2} b$, $\frac{1}{4} b$ and $\frac{1}{8} b$ with respect to the trailing edge of the main wing ($b$ represents the geometric span width of the main wing). Three different vortex configurations were investigated; i.e. one 2-vortex-system and two 4-vortex systems consisting of two co- and counter rotating vortex pairs. The 4-vortex systems are generated using two wings with a span width ratio of $b_2 / b_1 = 0.3$. The circulation of the inner vortex pairs are set to $\Gamma_2 / \Gamma_1 = \pm 0.3$ by adjusting the inclination of the horizontal tip wing. The flow fields obtained by PIV are further analysed with respect to the development of the vortex trajectories and circulation strengths.

2 Experimental setup

2.1 Generic model

For generation of well-defined 2- and 4-vortex systems the DLR’s F13 model (for details see Carmer and Konrath, 2006) was used. It consists of a horizontal rectangular main wing with fixed incidence producing a pair of symmetric counter-rotating vortices. The wing is attached to the carriage of the tow tank via a profiled strut which ends in the centre of the wing (Fig. 1). To produce another inner co- or counter-rotating vortex pair an additional rectangular wing (horizontal tail wing) can be mounted using a thin fuselage. Several horizontal tail wings with different span widths and chord lengths are available. Together with an adjustable inclination angle of the horizontal tail wing the circulation and span width ratio between inner and outer vortex pair can be varied within in a wide range. Table 1 summarizes some dimensions and parameters of the different available wings.

A Wortmann profile modified by Princeton University FX63-137B-PT especially designed for low Reynolds numbers was used for the main wing as well as for the horizontal tail wings.

<table>
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<tr>
<th>F13 model</th>
<th>Wing span, mm</th>
<th>Chord length, mm</th>
<th>Incidence</th>
<th>A.R.</th>
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<tr>
<td>Main wing</td>
<td>$b = b_1 = 300$</td>
<td>50</td>
<td>$\alpha = 10^\circ$</td>
<td>6</td>
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<tr>
<td>Horz. tip wings</td>
<td>$b_2 = 60; 90; 120; 150$</td>
<td>25; 35; 50; 75</td>
<td>$\varepsilon = -16^\circ - +4^\circ$</td>
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Table 1: Dimensions and parameters of generic wing model F13.
2.2 Tow tank with adjustable ground plate

The experiments were carried out in the water tow tank at Göttingen (WSG), which has a total length of 18 m and a cross section size of 1.1 m x 1.1 m. The tank is equipped with several glass windows in the side and the bottom walls providing good optical access. At the top of the tank a carriage to which models can be attached is moving along two tracks. The maximum tow speed is 5 m/s. For triggering purposes several magnetic sensors are arranged nearby the tracks. To ensure quiescent ambiance conditions through which the model is moved a waiting period of 20 minutes between each run was applied allowing the water to settle down.

**Fig. 2** shows the arrangement of the adjustable plate within the tow tank to simulate a ground above which the model can move at different heights. The ground plate is carried out of Plexi glass and is attached to several vertical threaded rods, which allow for a precise adjustment. The total length of the ground plate is 14.5 spans (4.35 m). The measurement plane is located 5.7 spans (1.71 m) downstream the sharpened leading edge of the ground plate.

![Figure 2: Dimensions of water tow tank (WSG) with installed plate for ground simulation in dependency of the model’s span width of b = 300 mm.](image)

2.3 Stereo-PIV setup

A Stereo-PIV measurement system was employed in order to obtain time dependent cross-sectional flow velocity fields of the descending wake vortex system. The tank was seeded with hollow glass spheres with a mean diameter of 11 microns and a density of 1.1 g/cm³.

![Figure 3: PIV arrangement at WSG.](image)
The laser light sheet, powered by a dual cavity Nd:YAG laser each of 190 mJ pulse energy with a repetition rate of 10 Hz, illuminates a cross plane through a side window of the water tank above the ground plate. The two PIV cameras were positioned at the opposite side of the tank with viewing angles of about ±45° with respect to the light sheet (Fig. 3). The high-resolution cameras (PCO-1600, 1600 x 1200 px) are able to acquire double-frame images with a maximum recording rate of 15 Hz. Two glass prisms filled with water were arranged in front of the cameras (Fig. 3) such that the air/water interface is aligned perpendicular to the lens’ (focal length 21 mm) axis in order to avoid image aberrations. A programmable sequencer synchronizes the cameras with the pulsed laser light sheet and the moving model.

The reference time \( t = 0 \) of the measurements corresponds the moment when the trailing edge of the model passes the light sheet. The PIV measurement is started at \( t = 0.1 \) (model without fuselage) or \( 0.2 \) s (model with fuselage and horizontal tip wing) recording double-frame images with a rate of 10 Hz.

### 2.4 PIV image calibration and image processing

For the camera calibration a transparent calibration grid was aligned with the light sheet. The calibration images are used to de-warp and map the stereo image recordings onto a Cartesian grid (Willert, 1997). As to compensate for possible slight misalignments between the plane of the calibration grid and the plane of the light sheet, a disparity correction has been performed on a set of particle images obtained from illumination with an especially thinned light sheet. A correlation analysis is applied between two images from each camera, which were recorded at exactly the same time. Therefore, both correlated images contain the same particle ensembles acting as markers within the light sheet seen by both cameras. Resulting non-zero shifts of the de-warped images indicate a misalignment between the cameras. For a correction the shifts are introduced into the mapping function after a fitting.

The state-of-the-art PIV displacement algorithms employed a multi-pass multi-grid interrogation method with window shifting and deformation (Scarano, 2002). The idea is to start the evaluation with large interrogation windows on a coarse interrogation grid. After each evaluation step the interrogation window sizes are reduced and the grid is refined. The intermediate results are applied to re-evaluate the particle images by shifting and deforming the interrogation windows according to the local velocities and velocity gradients respectively. Therewith, the particle displacements inside an interrogation window become constant and the final correlation peak moves towards the centre of the correlation function. This technique enhances the dynamic range, accuracy, reliability and spatial resolution of the measurement significantly, particularly, in the case of high flow velocity gradients, which in the current case occur in the vortex cores.

Whittaker’s reconstruction was applied for sub-pixel peak interpolation. The size of the final correlation window was 32px x 32px and 50% overlap resulting in time-resolved flow fields with more than 10,000 vectors. For outlier detection, normalized median filtering (Westerweel and Scarano, 2005) and replacement by lower-order peaks was employed.

### 3 Results

#### 3.1 Test configurations and parameters

Three different model configurations are used in the experiments. The first one is a 2-vortex system generated by the F13-model without fuselage (Fig. 1). For the second and third one the F13-model is used with fuselage and attached horizontal wing \( (b_2 = 90 \text{ mm}, c_2 = 35 \text{ mm}) \) with suction side upward and downward to generate two co- and counter rotating vortex pairs respectively (4-vortex systems). The parameters of the different configurations are listed in Table 2.

For all configurations the same test conditions are used which are summarized in Table 3. Mainly a model velocity of 1.5 m/s is used for all configurations. In only one case (2-vortex system, \( h/b \approx 0.2 \)) a lower velocity of 0.65 m/s is applied, however, this case is not considered in this report.
## Configuration Parameters

<table>
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<tr>
<th>Configuration</th>
<th>Circulation ratio $\Gamma_2/\Gamma_1$</th>
<th>Span width ratio $b_2/b_1$</th>
<th>Incidence of htlz tail wing $\varepsilon$</th>
<th>Remarks</th>
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<tr>
<td>1</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>2-vortex system</td>
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<td>2</td>
<td>0.3</td>
<td>0.3</td>
<td>+9.6°</td>
<td>4-vortex system: Co-rotating vortex pairs</td>
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<tr>
<td>3</td>
<td>-0.3</td>
<td>0.3</td>
<td>-3°</td>
<td>4-vortex system: Counter-rotating vortex pairs</td>
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### Table 2: Parameters of tested model configurations.

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<th>Parameter</th>
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<th>Value</th>
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<tr>
<td>$U$</td>
<td>1 / 2 / 3</td>
<td>1.5 m/s</td>
</tr>
<tr>
<td>$U$</td>
<td>See table 2</td>
<td>0.65 m/s</td>
</tr>
<tr>
<td>$Re$</td>
<td></td>
<td>74 250</td>
</tr>
<tr>
<td>$Re_\Gamma$</td>
<td></td>
<td>52 000</td>
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<tr>
<td>$t_0$</td>
<td></td>
<td>6.64 s</td>
</tr>
<tr>
<td>$\Delta t^*$</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>$\nu$</td>
<td></td>
<td>$1.0 \times 10^{-6}$ m²/s</td>
</tr>
<tr>
<td>$c_L$</td>
<td></td>
<td>1.1</td>
</tr>
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<td>$\Gamma_0$</td>
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<td>0.05252 m²/s</td>
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<tr>
<td>$h / b$</td>
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<td>0.196</td>
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### Table 3: Measurement conditions and parameters. The dimensionless parameter $h/b$ relates the height of the wing trailing edge above the ground over the wing span width.

### 3.2 Spatial-temporal evolution of 2-vortex system in ground proximity

#### 3.2.1 Velocity and vorticity distributions

The observed flow developments are very similar for all investigated cases, although the resulting vortex parameters and the vortex trajectories differ. Therefore, the flow evolution is exemplarily discussed for the case of the 2-vortex system (configuration 1) and $U = 1.5$ m/s, $h/b = 0.25$ (s. Table 3 for further parameters). The corresponding cross-flow velocity fields from the port side of the model are shown in the Figures 4 – 6. Plotted are the in-plane velocity vectors and the out-of-plane vorticity. The ground plate is located at $z = 75$ mm. The movement of the passing model is directed into the plane of paper.
Figure 4: Cross-flow velocity field of configuration 1, $U = 1.5$ m/s and $h / b = 0.25$ from $t^* = 1$ to 6 ($t^* = t \cdot U / b$).
Figure 5: Cross-flow velocity field of configuration 1, $U = 1.5 \text{ m/s}$ and $h / b = 0.25$ from $t^* = 7$ to $9$ ($t^* = t \cdot U / b$).
At \( t^* = 1 \) (Fig. 4) the main clockwise rotating vortex is located close to the wing tip position \((y = 150 \text{ mm}, z = 0 \text{ mm})\). At the boundary layer the vortex induces an outboard directed flow. The plot at \( t^* = 4.5 \) shows that the vortex is moving in the outboard direction caused by its interaction with the ground. Its vertical position is only slightly lower than the wing tip position which remains approximately constant up to \( t^* = 11.5 \). In the velocity field of \( t^* = 5 \) slightly inclined vectors at \( y = 210 \text{ mm} \) close to the ground can be observed indicating the beginning of a flow separation at the ground. The flow field at \( t^* = 6 \) now shows clearly a region of closed flow separation of positive vorticity.

At first the region of closed flow separation is growing as it can be seen in the plots of Fig. 5 for \( t^* = 7 \) and \( t^* = 7.5 \). The separation is shifted outboard according to the movement of the vortex. The lateral distance \( s \) of the beginning of flow separation on the ground to the vortex position slightly reduces from \( s/h \approx 0.4 \) at \( t^* = 6 \) to \( s/h \approx 0.24 \) at \( t^* = 8 \).

At \( t^* = 9 \) the flow field in the separation region changes. Portions of positive vorticity separate from this region and are starting to move with the bulk flow induced by the vortex. This process continues as it can be seen in the velocity fields of Fig. 6 for \( t^* = 9.5 \). In the plot of \( t^* = 11.5 \) (Fig. 6) an enlarged separation region can be observed. A series of small scale vortices, i.e. a vortex sheet, of positive vorticity are arranged along an arc around the tip vortex which will be entrained by the vortex. Now, again the lateral distance between vortex and flow separation at the ground is \( s/h \approx 0.4 \).

The vortex now has reached a distance of about one span width towards the side wall of the tow tank which is the limit assumed in the present investigations up to which side wall effects can be neglected. Within this time frame \((t^* = 0 - 11.5)\) the vortex core remains circular and does not undergo strong changes in its size. The velocity distributions show a stable vortex without any indication of a collapse or vortex breakdown.
3.2.2 Vortex trajectories and circulation strength

The Q-criterion is applied to the PIV data to identify the vortex core regions within the instantaneous velocity fields (Carmer et al. 2007, 2008). The positions of the vorticity centroids

$$\bar{x}_C = \frac{1}{\Gamma} \iint \omega \bar{x} \, dA$$

are evaluated from the vortex core areas and are used as definition for the vortex center. The trajectories of the vortices are obtained by tracing the vortex centers in the wake vortex system evolving in time.

The vortex circulation is evaluated by integrating the out-of-plane vorticity component $\omega_z$ in a circular area with radius $r$ centered at the core position as

$$\Gamma(r) = \iint \omega_z \, dA.$$  

Adapting a common method to evaluate the circulation of wake vortices from field data (e.g., Gerz et al. 2002), a mean value of the vortex circulation is then obtained from radially averaging $\Gamma(r)$ values over $1/12 \leq r/b \leq 1/4$:

$$\Gamma_{5-15}(r) = \frac{6^{1/4b}}{b^{1/12b}} \int \Gamma(r) \, dr.$$  

In each of the following plots in Fig. 7 – 9 the data of every valid run of the same test case is plotted to prove the repeatability of the results. In Fig. 7 the trajectories are plotted for $U = 1.5 \text{ m/s}$ and $h/b = 0.5$. In the first diagram the dimensionless time $t^*$ is plotted against the spanwise core position. In a second diagram the vertical vortex center position as well as the vortex circulation is plotted also against the spanwise position of the vortex core. From the first diagram it can be seen that the lateral velocity of the outboard directed movement of the vortex at the beginning is small and increases with decreasing altitude. At a spanwise position of $y/b = 0.54 - 0.58$, i.e. at about $t^* = 8$, a kink can be observed in the trajectories of both diagrams. After performing a slight rebounding, the vortex continues to move outboard with approximately constant altitude and lateral velocity.

Figure 8 show the results for the case $h/b = 0.25$. Now, the lateral velocity of the vortex is approximately constant accordingly to the small changes in the vortex altitude. The lateral velocity of the vortex is much higher in comparison to the case $h/b = 0.5$ according to the lower altitude. The vortex circulation plotted in the second diagram tends to decrease slightly caused by the viscous effects at the ground.

The results for the last case of $h/b = 0.125$ are shown in Figure 9. According to the lower height $h$ the lateral velocity of the vortex again is much higher in comparison to the cases former discussed. This means that the time frame within which the vortex can be assumed to be not affected by the side walls of the tank is limited to $t^* = 8$. Now, the small altitude just at the beginning of the vortex formation results in an upward movement of the vortex after passing the spanwise position of about $y/b = 0.65$ ($t^* = 3$). Again the circulation slightly decreases in time.
Figure 7: Vortex trajectories (red) and circulation (blue) development for 2-vortex system with \( U = 1.5 \) m/s and \( h/b = 0.5 \) (\( t^* = t \cdot U / b \)).
Figure 8: Vortex trajectories (red, yellow) and circulation (blue) development for 2-vortex system with $U = 1.5$ m/s and $h/b = 0.25$ ($t^* = t \cdot U / b$).
3.3 Spatial-temporal evolution of 4-vortex systems in ground proximity

3.3.1 Velocity and vorticity distributions

The effects of an additional co- or counter-rotating vortex pair in ground proximity are investigated by adding a thin fuselage to the model to which a horizontal tip wing is attached with the suction side upward and downward, respectively.

Figure 10 shows the velocity and vorticity distributions in the wake of the port and starboard side of the wings for configuration 2 (see Table 2) and \( U = 1.5 \, \text{m/s} \), \( h/b = 0.5 \). The vortices of the co-rotating vortex pairs can be clearly identified by the vorticity distribution at \( t^* = 1 \). Also, visible are flow disturbances between the inner vortices which are mainly produced at the junction of the strut and the main wing. The inner vortices are moving quickly downward with increasing lateral distance. A quick decay of the inner vortices can be observed vanishing completely at \( t^* > 12 \).
In **Figure 11** the velocity and vorticity distributions for the corresponding case of the counter-rotating vortex pair (configuration 3) is plotted. Earlier obtained results from the same configuration without ground plate show that the inner vortices start to orbit around the tip vortex. In the current case the development of the inner vortices is quite different. They move downward keeping their vertical position with respect to the tip vortices. At the same time their lateral distance reduces which lead to a cancelation of opposite signed vorticity. The circulation of both inner vortices has cancelled out each other at $t^* = 15$. The inboard directed movement of the inner vortices is caused by the ground proximity analogous to the outboard movement of the opposite signed tip vortices.

**Figure 10:** Velocity and vorticity distribution for 4-vortex system of co-rotating vortex pairs (configuration 2) with $U = 1.5$ m/s and $h/b = 0.5$ ($t^* = t \cdot U / b$).
Figure 11: Velocity and vorticity distribution for 4-vortex system of counter-rotating vortex pairs (configuration 3) with $U = 1.5 \text{ m/s}$ and $h/b = 0.5$ ($t^* = t \cdot U / b$).
Figure 12: Vortex trajectories (red) and circulation (blue) development for 4-vortex system of co-rotating vortex pairs (configuration 2) with $U = 1.5$ m/s and $h/b = 0.5$ ($t^* = t \cdot U / b$).
3.3.2 Vortex trajectories and circulation strength

In the following Figures from 12 – 14 and 15 – 17 the results of the vortex analysis as described in Section 3.2.2 are shown for the vortex systems consisting of co-rotating (configuration 2, see Table 2) and counter-rotating (configuration 3) vortex pairs, respectively. In this analysis only the tip vortices at the port side is considered.

Comparing the trajectories of the 4-vortex system (configuration 2) consisting of two co-rotating vortex pairs (Fig. 13) with that of the 2-vortex-system (Fig. 7) the tip vortex occurs at approximately the same spanwise position of $y/b \approx 0.83$ at $t^* = 29$. However, in the case of the 4-vortex system the tip vortex starts with a lower lateral velocity until $t^* \approx 15$.

![Figure 13: Vortex trajectories (red) and circulation (blue) development for 4-vortex system of co-rotating vortex pairs (configuration 2) with $U = 1.5$ m/s and $h/b = 0.25$ ($t^* = t \cdot U / b$).](image-url)
At this time the tip vortex also reduces its decent velocity. The altitude is slightly lower in comparison that of the 2-vortex system. Accordingly the tip vortex of the 4-vortex system continues to move outboard with a slightly higher lateral velocity. The decrease of circulation is lower for the 4-vortex system. It seems that the tip vortex gains the circulation of the entrained inner vortex (see Section 3.2.1). This applies also to the case of h/b = 0.25 and 0.125 (Fig. 8 and 9 in cp. with Fig.13 and 14). Differences in the trajectories between the 2- and 4-vortex systems can be observed for h/b = 0.25. For h/b = 0.125 the development of the trajectories are similar.

The 4-vortex system consisting two counter-rotating vortex pairs (configuration 3) show differences in the trajectories and the circulation plots. For h/b = 0.5 (Fig. 15) the inner vortices induces obviously a higher decent velocity of the tip vortices which end up at a lower altitude of about z/b = 0.2 in comparison to z/b = 0.12 at y/b = 0.62 for the 2-vortex system. Also the plots of the circulation are quite different. The lower position of the tip vortex for the 4-vortex system leads to a higher decrease of the circulation.

However, the results for h/b = 0.25 and 0.125 of the 4-vortex system are similar to that of the 2-vortex system (Fig. 8 and 9 in cp. with Fig.16 and 17).

Figure 14: Vortex trajectories (red) and circulation (blue) development for 4-vortex system of co-rotating vortex pairs (configuration 2) with U = 1.5 m/s and h/b = 0.125 (t* = t · U / b).
Figure 15: Vortex trajectories (red) and circulation (blue) development for 4-vortex system of counter-rotating vortex pairs (configuration 3) with $U = 1.5$ m/s and $h/b = 0.5$ ($t^* = t \cdot U / b$).
Figure 16: Vortex trajectories (red) and circulation (blue) development for 4-vortex system of counter-rotating vortex pairs (configuration 3) with $U = 1.5 \text{ m/s}$ and $h/b = 0.25$ ($t^* = t \cdot U / b$).
4 Conclusions

The present experimental study focuses on the spatial-temporal evolution of 2- and 4-vortex systems created at constant altitude above a horizontal ground. The results of Stereo-PIV measurements in a tow tank are used to describe the flow topology and to determine the vortex trajectories and their circulation. In dependency of the heights of \( h/b = 0.5, 0.25 \) and 0.125 the maximum time frame up to which wall effects in the tow tank can be assumed to be negligible ranges from \( t^* = 5 \) to \( t^* = 29 \).

The interaction of the flow induced by the port vortex was described for the case of the 2-vortex system and \( h/b = 0.25 \). A flow separation beneath the vortex could be observed. However, instead of generating a single large scale secondary vortex, several smaller vortices of opposite vorticity are generated by the separation region.

From an analysis of the vortex trajectories the outboard directed lateral movement of the port vortices is determined, which depends on the vortex circulation and core distance to the ground. The observed velocities of the lateral vortex movement agree to the relation

\[
\nu = \frac{\Gamma}{4\pi \cdot h}
\]
within which $\Gamma$ represents the current vortex circulation and $h$ the current height of the vortex core above the ground. The relation expresses Biot-Savart’s law analogue to the equation of the descent speed of a pair of counter-rotating vortices (see de Bruin, 2005) using a separation distance of $2h$. An explanation for the relation can be given as follows: The non-viscous flow of a vortex in ground proximity can be generated also by replacing the ground surface with a plane of symmetry. Then, the vortex and the virtual counter-rotating vortex on the opposite side of the symmetry plane represent a vertically oriented 2-vortex system moving laterally.

Also the inner vortices of the 4-vortex systems are strongly influenced by the ground already at distances of $\frac{1}{2}b$. Without ground proximity the inner vortices starts to orbit around the tip vortices for the investigated case of $b_2/b_1 = 0.3$ and $\Gamma_2/\Gamma_1 = -0.3$ (Carmer and Konrath, 2006). This is no longer the case when the vortices come into ground proximity. The results for $h/b = 0.5$ show that the inner vortices are forced to reduce their separation distance according to their opposite sense of rotation. After some time both inners vortices cancel out each other. Nevertheless, the inner vortices induce a higher decent speed of the tip vortices, so that differences between the 2-vortex and 4-vortex system can be seen also in the trajectories of the outer tip vortices. These differences vanish for lower values of $h/b$, also in the case of the 4-vortex system consisting of two co-rotating vortex pairs.

References


L. Dufresne and G. Winckelmans. Previous work and present knowledge on wake vortices near the ground. FAR-Wake research project Report D 3.0, Univ. cath. Louvain (UCL), 2005.

