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Fundamental Research on Aircraft Wake Phenomena

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*Towing-tank visualizations of two-vortex systems in ground effect*

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Towing-tank visualizations of two-vortex systems in ground effect
Technical Report TR-3.1.2-3

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Abstract

The case of a longitudinally developing wake vortex pair generated by a generic wing model is investigated at a moderate, yet significant, Reynolds number ($c U_\infty / \nu \simeq 40,000$ and $\Gamma_0 / \nu \simeq 32,000$) through towing tank visualizations. Laser Induced Fluorescence (LIF) visualizations are performed in order to study qualitatively the dynamics of both the primary vortices and the separating boundary layer at the ground. The configuration is a wake vortex pair generated by a wing model following a constant altitude track, at a constant velocity above a fixed ground. Three different altitudes of wake generation In Ground Effect (IGE) are investigated: $0.5 b_0$; $0.25 b_0$ and $0.125 b_0$. The reference length scale, $b_0$, is the vortex spacing as measured experimentally Out of Ground Effect (OGE).

Volume and two-dimensional visualizations are presented, as well as primary vortex trajectories. The mechanism of boundary layer separation with opposite sign vorticity, subsequently orbiting around the primary vortices and leading to vortex rebound and transition of the whole vortex system to turbulence, is clearly observed. The vortex trajectories show the effect of the initial altitude on the vortex dynamics. For $h_0 \approx 0.5 b_0$, a phase of vortex roll-up occurs, during which the primary vortex circulation increases and the observable vortex separation distance decreases. For $h_0 \approx 0.25 b_0$ and $0.125 b_0$, no clear roll-up phase is observed showing that the process is affected by the ground. In that case, the primary vortices are transported away from each other as soon as they are generated, and rebound higher than their altitude of generation. A notable observation is the rapidity of the dynamics, leading to transition to turbulence (boundary layer separation, interaction of secondary vorticity with the primary vortices) and also vortex bursting when the initial altitude is decreased. A propagating perturbation occurring much earlier than OGE generates end-effects and leading to vortex bursting is also observed: its origin is discussed and remains an open issue.

These qualitative observations are in good general agreement with some recent numerical work, also that carried within FAR-Wake. The space developing dynamics IGE are very similar to the longitudinally uniform one during the initial (essentially two-dimensional) phase, and then becomes rapidly quite different as three-dimensionality is developing and transition to turbulence occurs. This work will be completed by quantitative measurements carried out at DLR in the framework of the FAR-Wake project.
Introduction

The present work is a contribution to the subtask 3.1.2 of the FAR-Wake project. It is dedicated to investigating spatially-developing wakes In Ground Effect (IGE) under idealized conditions. The ground interactions of a 2-vortex system generated by an aircraft wing model have been investigated by means of visualizations in a towing tank. The wing model follows a constant altitude track with a constant velocity above a fixed ground. Three different altitudes of vortex generation IGE are investigated: \( h_0 \approx 0.5 b_0 \); \( 0.25 b_0 \) and \( 0.125 b_0 \). Due to the low initial altitudes (i.e. vortices generated IGE), ground effects occur before any Out of Ground Effect (OGE) instability affects the two primary vortices (e.g. the long-wavelength Crow instability does not develop).

Laser Induced Fluorescence (LIF) visualizations are carried out in order to obtain qualitative information on the dynamics of both the primary vortices and the ground separating boundary layer. Two-dimensional visualizations in cross-sections allow the investigation of the two-dimensional dynamics, while volume visualizations are performed to gain qualitative insight about the strong three-dimensional interactions between the primary vortices and the secondary vorticity emanating from the separating boundary layer. The instabilities induced by these interactions and the resulting transition of the whole vortex system to turbulence are of particular interest. Due to the limited effort initially planned for this task, the results of this work are limited to qualitative visualizations and vortex trajectories. It has to be completed by the work performed at DLR (visualizations and Particle Image Velocimetry, PIV, measurements of similar configurations).

This Technical Report is organized as follows. Section 1 briefly relates the present investigation to the work accomplished in the framework of the FAR-Wake Work Package 3 on wake vortices IGE. The experimental set-up and methods used in this study are detailed in Section 2. Section 3 presents the results and is followed by the conclusions.
1 Context

A complete review of past studies and present knowledge concerning the dynamics of wake vortices near the ground has been produced as a starting point of the FAR-Wake Work Package 3 [5]. This information is not repeated here and the interested reader is referred to this document and to the references therein.

Extensive investigations have been recently carried out in the framework of the FAR-Wake project; mainly concerning Subtask 3.1.1, dedicated to wake vortices with longitudinal uniformity. Longitudinally uniform vortices IGE have been investigated experimentally [1] and numerically [8, 6] at low Reynolds number ($\Gamma_0/\nu = 5000$), showing the strong three-dimensional interactions between the primary and secondary vortices. Three-dimensionality is first introduced by the development of an elliptic-like instability in the secondary vortices, the primary ones becoming unstable subsequently. This mechanism leads to a “turbulent” decay of the whole vortex system that occurs much faster than in two-dimensional cases. Recently these results have been extended to a higher Reynolds number ($\Gamma_0/\nu = 20000$) using Large Eddy Simulation (LES) [7]. The dynamics appear to be very similar in terms of general dynamics and instability mechanisms. However, the strong interactions between the primary and secondary vortices rapidly generates more complex three-dimensional vortical structures leading to more turbulence and to a faster vortex decay at high Reynolds number. As a contribution to the FAR-Wake project, the influence of ground effect on wake roll-up has also been investigated numerically for different altitudes of vortex generation and at different Reynolds numbers [3]. The main conclusion being that the ground effect on the wake vortex sheet and its roll-up are not significant for altitudes down to $h/b \approx 0.25$. Finally, in a very recent work, the first LES of a space developing wake vortex pair IGE has been carried out and compared to longitudinally uniform three-dimensional and two-dimensional simulations [2]. The essential feature related to the space developing case is the fact that the vortex sheet rolls up in a spiralling manner. This roll-up results in the presence of a significant axial flow in the primary wake vortices, and in the earlier three-dimensionality of the flow and transition to turbulence. Moreover, wake vortices are not exactly parallel to the ground (slight inclination of an angle of about $\beta = V_0/V_\infty$, with $V_0$ the descent velocity of the vortex pair and $V_\infty$ the velocity of the wing). It is stressed however that, for computational cost issues, the space-developing configuration was not really relevant: a very large lift coefficient, $C_L = 6$, was used in order to artificially increase the inclination angle and thus use a shorter computational domain. It was more a “proof of concept” of what can be achieved by state-of-the-art numerical simulations.

The objective of the present work is to characterize experimentally (qualitatively, through visualizations) the dynamics of space developing wake vortex pairs in ground effect and the effect of the initial altitude.
2 Experimental Details

2.1 Experimental set-up

The present experimental work has been carried out in the towing tank facility of the Division of Thermodynamics, Fluid Dynamics and Turbomachinery (TERM) of the Mechanical Engineering Department at UCL. The facility is 14 [m] long, 1 [m] large and about 0.5 [m] high (water height used in this work). A computer controlled linear module allows towing any model into the tank over a distance of 11 m with a maximal speed of 3 [m/s]. The starting and final positions, as well as the velocity and acceleration can be varied to decompose a single run into different phases. In our case, the configuration is simply composed of an acceleration phase, a constant velocity phase and a final deceleration phase. The focus is to investigate the IGE dynamics of wake vortex pairs generated at constant velocity.

![Figure 1: Model (wing + profiled arm) fixed on the translating module into the towing tank. The injection system is also shown.](image)

In order to generate aircraft wake vortex pairs, a generic wing model has been built. It is composed of an airfoil and of a profiled arm that is fixed on the translating module (Figure 1). The Wortmann FX63-137B-PT (F13) profile has been used, which is a low Reynolds number airfoil. In the present work, the wing is characterized by a wingspan of $b = 24.8$ [cm] and a chord of $c = 4$ [cm]. The resulting aspect ratio is $AR = 6.2$.

Thin plastic tubes are integrated inside the wing model in order to inject fluorescein dye at the wing tips into the two trailing vortices. These tubes connect the dye container (fixed on the translating module) to the wing tips where dye is injected into the flow through needles of diameter $d = 0.8$ [mm]. The injection system has been optimized to minimize the perturbations induced on the trailing vortices. The configuration retained for the visualizations is the following: towing velocity $V_\infty = 1$ [m/s], angle of attack $\alpha \simeq 14$ [$^\circ$]. Thus, with a kinematic viscosity of $\nu \simeq 10^{-6}$ [m$^2$/s] for water (water temperature...
\( \simeq 20 [\degree C] \), the Reynolds number based on the wing chord is \( Re_c \simeq 40000 \). Finally, three different altitudes of vortex generation have been investigated: \( \frac{h_0}{b_0} \simeq 0.5, 0.25 \) and 0.125 (Figure 2), with \( b_0 (\simeq 20 \text{cm}) \) the initial vortex spacing as measured experimentally OGE (after roll-up) and equal to \( \frac{\pi}{4} b \) for an elliptic wing OGE.

\[ \text{Figure 2: Schematic view of the different configurations in cross-sections: (a) } h_0 \simeq 1.45 b_0 \text{ (OGE)}, \text{ (b) } h_0 \simeq 0.5 b_0, \text{ (c) } h_0 \simeq 0.25 b_0, \text{ (d) } h_0 \simeq 0.125 b_0. \]

\[ \text{2.2 Experimental methods} \]

As mentioned previously, LIF visualizations are performed. For this purpose a 5W Argon Laser is used to illuminate the flow. Fluorescein dye is injected at the wing tips to visualize the two primary vortices. Rhodamine dye, mixed with a bodying agent, is laid down on the ground, in order to also visualize the separating boundary layer and thus the ground generated secondary vorticity.

Different kind of visualizations, recorded with a digital camera, are carried out. Two-dimensional visualizations are used to obtain information on the two-dimensional dynamics. In that case, the cross-section is illuminated with a laser sheet. The cross-cut visualizations can be recorded from the back of the towing tank, perpendicularly to the laser sheet, in the direction of the vortex axis. This method is used to obtain the vortex trajectories and the OGE wake parameters through image analysis: descent velocity \( V_0 \) and vortex spacing \( b_0 \) from which vortex circulation can be computed using \( \Gamma_0 = 2 \pi b_0 V_0 \). In order to obtain good quality visualizations, the cross-section is also visualized from the
side of the towing tank: these visualizations are used to get qualitative information on the dynamics (Figures 5, 7 and 9). Finally, volume visualizations are obtained by illuminating the flow using a light cone from the side of the towing tank (Figures 4, 6 and 8).

2.3 Flow conditions and experimental constraints

As in any experimental investigation, several constraints are inherent to the experimental setup used. It is worth discussing them in order to determine their effect and, if possible, apply some corrections to the experimental results.

In this work, the objective is to investigate experimentally a semi-open flow (bounded by the horizontal ground on one side and unbounded in all other directions). The finite extend of the towing tank implies two different effects on the resulting flow field. Due to the longitudinal limited extend (in the direction of the model displacement), the constant velocity phase is preceded by an acceleration phase and is followed by a deceleration phase. These acceleration and deceleration phases are known to induce wave perturbations propagating along the vortices: the so-called ”end-effects” leading to an increase of the vortex core and a subsequent vortex bursting (see [10, 9] and references therein). As pointed out in [10], end-effects involve one vortex only: in the case of a vortex pair, it can occur on one or both of the primary vortices and it occurs rarely exactly simultaneously on the two. The case of smoke visualizations in which only one of the two primary vortices was affected by vortex bursting leading to its subsequent vanishing, showed the continuous motion of the remaining vortex. It suggests that the former was not destroyed but merely vanished from the visualization due to the dispersion of the marker from the vortex core. This is confirmed by the fact that vortex circulation remains constant in the numerical simulations of wave propagations in vortex cores [9]. However, if the global circulation remains constant, it is clear that vortex bursting due to end-effects modifies dramatically the vorticity distribution and the structure of the vortex core. This effect could be beneficial for air transport safety when considering the persistence of wake vortices during take-off and landing, when end-effects could occurs due to the brutal change in the aircraft lift. From an experimental point of view however, this effect must be avoided when investigating vortices generated during constant lift phases (which is the case investigated here). In order to minimize end-effects and to obtain a significant vortex life-time before bursting, the parameters (acceleration, velocity, deceleration) of the different phases have been optimized as much as possible.

The observations concerning end-effects also remind us that dye is a passive tracer and not a marker of vorticity level. It is very efficient to visualize the vortex dynamics and the changes in the vortex structure, but, concerning the strength and the life-time of the vortices (in terms of circulation), one has to take much care before drawing any conclusions. Thus, the qualitative results obtained here have to be completed with quantitative measurements.

The second effect is related to the limited extend of the towing tank in the transversal directions. The presence of the lateral and lower boundaries (solid walls) affects the dynamics of the vortex pair. The effect of the bottom wall is, of course, desired for the actual investigation of wake vortices IGE, but is also a limiting factor when characterizing the dynamics OGE. When determining the parameters OGE (to obtain the reference parameters and characterize the flow field obtained with the wing model) the descent velocity of the vortex pair is affected by the lateral and bottom boundaries. In order to
reduce this effect, a compromise has been made between the wingspan and the relative distance from the walls. For OGE experiments, the model has been towed at a high enough altitude above the ground (Figure 2).

Figure 3 shows the trajectory of the vortex pair generated OGE. After a phase of vortex roll-up (the vortex separation decreases), a phase of constant vortex spacing (constant descent velocity $V = V_0 = \frac{\Gamma_0}{2\pi b_0}$, see also Figure 13a) allows to determine the OGE parameters before ground effects occurs (vortex spacing increases and descent velocity decreases). After correcting these parameters by taking into account the influence of vortex images due to the towing tank boundaries, the parameters found are the following:

$$\Gamma_0 \approx 0.032 \text{ [m}^2/\text{s]}$$
$$b_0 \approx 0.20 \text{ [m]}$$
$$Re_c \approx 4.0 \times 10^4$$
$$Re_{\Gamma} \approx 3.2 \times 10^4$$
$$C_L \approx 1.26$$

The lift coefficient, $C_L$, is obtained from the following expressions for the lift, $L$:

$$L = \frac{1}{2} \rho V_\infty^2 S C_L = \rho V_\infty b_0 \Gamma_0$$

with $\rho$, the water density, $V_\infty$, the towing velocity, and $S$, the wing surface, leading to:

$$C_L = 2 \frac{b_0 \Gamma_0}{V_\infty S}$$

The results obtained for the three altitudes of vortex generation IGE are presented in the next section.
3 Results

In this section, LIF visualizations and vortex trajectories are presented. The dimensionless lateral position, \( y^* \), and altitude, \( z^* \), are obtained using the initial vortex spacing OGE \( b_0(\simeq 20 \text{ cm}) \) as the reference length. The dimensionless time is obtained using the OGE reference time:

\[
 t^* = \frac{t}{t_0} \quad \text{with} \quad t_0 = \frac{b_0}{V_0}
\]

3.1 LIF visualizations

Figures 4 shows the three-dimensional LIF visualizations for \( h_0 = 0.5 \, b_0 \). At \( t^* \simeq 0 \), the vortex pair is generated and no change at the ground is observed. Figure 4b (\( t^* \simeq 0.07 \)) shows that, rapidly, the effects of the presence of the primary vortices are observable on the ground: the generated vorticity disturbs the initially quiescent dye. The boundary layer develops (figure 4c) and separates (figure 4d). Opposite-signed secondary vorticity, emanating from the separating boundary layer, is subsequently orbiting around the primary vortices (figures 4d to 4h). A notable observation is the apparent turbulent level of the structures observed (from the developing boundary layer at the ground to the orbiting secondary vorticity) compared to LIF visualizations of longitudinally uniform vortex pairs performed at \( Re_T \simeq 5000 \) [1] where the separation occurred in a very “laminar” way. The interactions between the primary vortices and the orbiting secondary vorticity result in a complex turbulent flow. Those dynamics are also shown in a cross-section on Figure 5. The development of the boundary layer as the primary vortex is approaching the ground is clearly observed (Figures 5a to 5c). The shear layer appears to be turbulent as soon as it separates from the boundary layer (Figure 5d). The separation point follows the lateral translation of the primary vortex. The secondary vorticity orbits around the primary vortex (Figures 5e to 5h). The vortex system appears to have reached a developed turbulent state once the secondary vorticity has performed one complete orbit around the primary vortex (Figure 5h). It is also seen that the primary vortex core remains coherent, at least up to the time of “bursting” which is discussed below.

Figures 6 and 7 respectively show the three- and two-dimensional LIF visualizations for \( h_0 = 0.25 \, b_0 \). The same global dynamics are observed but accelerated: as the altitude of vortex generation decreases, the whole process occurs earlier. This is confirmed by figures 8 and 9, showing the three- and two-dimensional LIF visualizations for \( h_0 = 0.125 \, b_0 \).

In figure 8, the boundary layer and secondary vorticity are visualized on one vortex only, allowing the visualization of the dynamics of the starboard primary vortex and the effects of the interactions with the orbiting secondary vorticity. Figures 8g and 8h shows that the primary vortex is affected by a perturbation propagating upstream (in the direction of the model displacement, from left to right). The phenomenon observed behind the front of the perturbation is very similar to end-effects: the vortex core increases and loses its coherence, the dye diffuses and seems to be transported by an axial flow component (in the same direction as the propagation of the perturbation: from left to right). This mechanism contaminates the visualization. However, preliminary experiments in the same configuration but OGE showed that end-effects tend to occur much later. Looking carefully at Figures 4e and 4f and at Figures 6e and 6f one can see that the same phenomenon occurs but at later times as the altitude of generation is increased. Since
the dynamics is accelerated for low initial altitudes, this phenomenon appears to occur at approximately the same stage of the dynamics (when the secondary vortex has performed one complete orbit around the primary vortex) for the three initial altitudes.

Two hypothesis are presented to explain the origin of this perturbation. First, it could be an end-effect due to the acceleration phase of the wing model, as is observed OGE. In that case, the propagating perturbation would be accelerated somehow as the initial altitude IGE decreases. It has been shown that, OGE, the propagation velocity is roughly equal to the maximum tangential velocity of the vortex, $V_{\theta_{max}}$ [4]. Thus it would imply that either the scaling would be different IGE, or that the maximal tangential velocity would be affected (increased) somehow by the presence of the ground during the roll-up process. This has to be verified with quantitative measurements. A second potential explanation for this observed phenomenon is the fact that we are visualizing the flow, evolving both in space and time, at a fixed position while the wing model is moving forward. We are thus observing the time evolution of the wake at a given position. At the initial times, the wake vortices are essentially laminar with vorticity concentrated in small cores. As time goes on, the core size increases slightly by diffusion, the vortices interact with the ground (i.e. with the ground generated secondary vorticity). After one complete orbit of the secondary vorticity, the primary vortex loses part of its coherence and becomes more turbulent. Since we are considering a space developing wake, this mechanism occurs first downstream, where the wake had the time to interact with the ground, and subsequently upstream. If we take a picture of the wake at a given time, the following picture is observed: it is more turbulent downstream, it is more coherent upstream, and, somewhere in between there is a limiting front. This type of front is also observed in the the numerical simulation of a space-developing wake IGE by Daeninck et al. [2]. Figure 10 shows the side, top and oblique views of the LES result. The bursting phenomena occurs approximately always at the same distance behind the win (inlet), also when the secondary vortex has completed one orbit around the primary one. Thus for an observed fixed to the ground, this bursting would propagate upstream. This hypothesis is also in agreement with the fact that the perturbation occurs at the same stage of the dynamics for all three configurations and that it occurs earlier for low initial altitudes (since the dynamics is accelerated IGE).

Figure 11 shows a volume visualization for $h_0 = 0.125 b_0$ similar to the ones in Figure 8 but with the boundary layer visualized for both primary vortices. An interesting point is that the vortex sheet emanating from the ground and orbiting around the primary vortex has here kept a relatively coherent structure: it is much less turbulent than for $h_0 = 0.5 b_0$ and $h_0 = 0.25 b_0$. This is probably due to the fact that the boundary layer is generated and separates very rapidly due to the very low initial altitude. Thus, turbulence has not developed yet when the secondary vortex is orbiting around the primary one. As a result, the orbiting phase, before transition to turbulence occurs after one complete orbit, is much more similar to longitudinally uniform vortices at low Reynolds numbers [1]. One can observe a short-wavelength instability that develops in the secondary vortex structure.

### 3.2 Comparison of the vortex trajectories for different altitudes of vortex generation IGE

In this section, vortex trajectories are presented and compared for the three altitudes of generations.
Figures 12 shows the vortex trajectories for the three initial altitudes. One can observe a roll-up process for $h_0 \simeq 0.5 \, b_0$ (Figure 12a): the vortex spacing is slightly decreasing before ground effect induces a dominant lateral velocity on the primary vortices. While for $h_0 \simeq 0.25 \, b_0$ and $h_0 \simeq 0.125 \, b_0$, the ground effect dominates the roll-up process. This is in agreement with [3] in which the influence of the vortex generation altitude on wake roll-up was investigated numerically: for $h_0 > 0.25 \, b$ (equivalent to $h_0 > 0.31 \, b_0$ in our case), it was concluded that ground proximity has no significant effect on the roll-up process.

One can also notice that the primary vortex trajectories do not form any loops as is commonly observed in numerical simulations and experiments of longitudinally uniform vortex pairs. This is due to the short time of the trajectory record obtained with dye visualizations. Due to the level of turbulence reached after a complete orbit of the secondary vorticity, the vortex position is not discernable (see the scattering in the vortex position at the end of the trajectories). PIV measurements would be useful to verify if the primary vortices have significantly decayed or if it is a visual effect (due to the turbulent diffusion of the dye). Recall that dye is not a marker of vorticity level.

Figure 13 shows the evolution of vortex altitude with respect to time for the three altitudes of vortex generation. The fact that the boundary layer separation (i.e. primary vortex rebound) and the subsequent phenomena occur at earlier times for vortices generated at lower altitudes above the ground is confirmed.

In Figures 12 and 13, the fact that the trajectory of both curves (port and starboard vortices) are superposed shows that the dynamics are relatively symmetric. When the two trajectories differ, one can suppose that the flow has become three-dimensional and complex, hence dissymmetric. Once again, this state is reached more rapidly for vortices generated at lower altitudes above the ground.
Conclusions

Laser Induced Fluorescence visualizations of space developing wake vortex pairs generated in ground effect have been carried out in a towing tank. Qualitative three- and two-dimensional visualizations of the primary vortices, the separating boundary layer and the secondary vorticity were presented, as well as vortex trajectories.

The interactions of the primary vortices with the vorticity emanating from the boundary layer and the rapid transition to a complex turbulent flow are clearly observed. The main observations are the following:

- The roll-up process appears to be affected by the ground proximity for low altitude of vortex generation ($h_0 \simeq 0.25 b_0$ and $0.125 b_0$) but not for higher ones ($h_0 \simeq 0.5 b_0$).
- The level of turbulence observed in the secondary vorticity that separates from the ground and orbits around the primary vortex is high. However, the primary vortex core remains coherent, at least up to the time of “bursting”.
- The dynamics IGE are accelerated when the vortices are generated at lower altitudes.
- The visualizations of the primary vortices are contaminated by a perturbation propagating upstream and leading to “bursting”. Two hypotheses have been presented: the “end-effect” that would be accelerated IGE, or a characteristic feature of space developing wakes generated IGE.

These observations are in good general agreement with the recent numerical simulations [3, 2, 7].

Finally, this experimental work has to be completed by the qualitative and quantitative investigations being carried out on similar configurations at DLR. The confrontation of qualitative visualizations to quantitative measurements will be of great interest.
Figure 4: Volume LIF visualization of a 2-vortex system generated at $h_0 = 0.5 b_0$. Estimated non-dimensional times from (a) $t^* \approx 0$ to (h) $t^* \approx 0.5$, uniformly spaced.
Figure 5: Two-dimensional LIF visualization of a 2-vortex system generated at $h_0 = 0.5 b_0$. Estimated non-dimensional times from (a) $t^* \simeq 0$ to (h) $t^* \simeq 0.35$, uniformly spaced.
Figure 6: Volume LIF visualization of a 2-vortex system generated at $h_0 = 0.25 b_0$.  
(a) $t^* \simeq 0$;  
(b) $t^* \simeq 0.04$;  
(c) $t^* \simeq 0.08$;  
(d) $t^* \simeq 0.12$;  
(e) $t^* \simeq 0.16$;  
(f) $t^* \simeq 0.20$;  
(g) $t^* \simeq 0.24$;  
(h) $t^* \simeq 0.28$. 
Figure 7: Two-dimensional LIF visualization of a 2-vortex system generated at $h_0 = 0.25 h_0$.  
(a) $t^* < 0$; (b) $t^* \approx 0$; (c) $t^* \approx 0.04$; (d) $t^* \approx 0.08$; (e) $t^* \approx 0.12$; 
(f) $t^* \approx 0.16$; (g) $t^* \approx 0.20$; (h) $t^* \approx 0.24$. 

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Figure 8: Volume LIF visualization of a 2-vortex system generated at $h_0 = 0.125b_0$.
(a) $t^* \approx 0$ ;  (b) $t^* \approx 0.0085$ ;  (c) $t^* \approx 0.017$ ;  (d) $t^* \approx 0.025$ ;  (e) $t^* \approx 0.034$ ;
(f) $t^* \approx 0.043$ ;  (g) $t^* \approx 0.051$ ;  (h) $t^* \approx 0.06$. 

Figure 9: Two-dimensional LIF visualization of a 2-vortex system generated at $h = 0.125 b_0$.  
(a) $t^* < 0$ ; (b) $t^* \approx 0$ ; (c) $t^* \approx 0.04$ ; (d) $t^* \approx 0.08$ ; (e) $t^* \approx 0.12$ ;  
(f) $t^* \approx 0.16$.  
Figure 10: Top, side and oblique views of a space-developing wake from a 3-D LES by Daeninck et al. [2] showing isosurfaces of vorticity.
Figure 11: Volume LIF visualization of a 2-vortex system generated at an altitude of $h_0 = 0.125 h_0$, for a dimensionless time $t^* \simeq 0.03$. Note that the time lies between Figures 8d and 8e and between Figures 9b and 9c.
Figure 12: Trajectories of both port and starboard vortices. (a) $h_0 = 0.51 b_0$; (b) $h_0 = 0.26 b_0$; (c) $h_0 = 0.122 b_0$. Symbols are shown at constant time intervals: small symbols at $\Delta t^* \simeq 0.025$, large symbols at $\Delta t^* \simeq 0.1$. 
Figure 13: Dimensionless altitudes of primary and secondary (in grey when available) vortices (port and starboard). (a) $h_0 = 1.45 b_0$ (OGE); (b) $h_0 = 0.51 b_0$; (c) $h_0 = 0.26 b_0$; (d) $h_0 = 0.122 b_0$. 
References


