Experimental and Numerical Study of Counter-Rotating Vortex Pair Dynamics in Ground Effect

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Abstract:

A counter-rotating vortex pair interacting with a wall is investigated experimentally and numerically using 2D and 3D direct numerical simulations. Qualitative and quantitative results (circulation and trajectories in particular) are presented. The simulation and experimental results compare very well with each other. Flow visualizations are also supplied. Finally, the short-wavelength instability mechanism observed in both the experiments and the 3D simulations is studied in more detail.

Résumé:


Key-words:

vortex dynamics, ground effect, vortex pair, wake vortices, elliptic instability

1 Introduction

In this paper, the interaction of a pair of straight counter-rotating vortices with a flat wall is investigated, both experimentally and numerically. This generic flow may be seen as an idealization of the interaction of aircraft trailing wake vortices with the ground during landing or take-off phase. However, the vortices studied herein have a larger core size than that of aircraft wake vortices.

The first experimental observations of wake vortices in ground effect during flight test measurements took place in the late 1960s. An upward motion of the vortices after their descent was observed. This phenomenon, called vortex rebound, cannot be explained by the inviscid theory of a vortex dipole approaching a wall, because it then predicts a hyperbolic trajectory. To explain this behaviour, Harvey and Perry (1971) performed wind tunnel tests of a wing in ground effect. They also observed the rebound and explained that it is due to the separation of the boundary layer that develops on the no-slip wall. This was confirmed by two-dimensional simulations of vortices in ground effect (see, for instance Peace and Riley, 1983). However, Luton and Ragab (1997) showed, using numerical simulations at low Reynolds number that the interaction of a straight vortex pair with a wall leads to a three-dimensional flow through
a short-wavelength instability of the secondary vortex. They considered this instability as an example of the Widnall instability (named after Widnall et al. (1974)).

In this study, we investigate the behavior of a vortex pair in ground effect at moderate Reynolds number using two- and three-dimensional direct numerical simulations as well as experimental visualizations and PIV measurements in a water-tank. The objective is to compare both approaches qualitatively and quantitatively and to further study the instability mechanism. The experimental results were obtained in the EC-funded FAR-Wake project (Fundamental Research on Aircraft Wake Phenomena). As long as the flow is still essentially two-dimensional, the numerical results and the PIV measurements are in very good agreement with each other and with the literature. The experimental results also show the onset of instabilities and a detailed analysis is performed using the 3D simulation.

This paper is organized as follows: the experimental and numerical setup are first briefly described. Then, the various results and comparisons are presented. Finally, some conclusions are drawn.

2 Experimental Setup

The experiments were carried out in a plexiglass water tank measuring $1.36 \times 0.56 \times 0.56 \text{ m}^3$. Vertical vortices were generated at the edges of two impulsively rotated flat plates. The set-up and procedure are similar to the ones described in Leweke and Williamson (1998). The two flat plates, fixed to a common base, were moved in a symmetrical way by a computer-controlled step motor. Two counter-rotating starting vortices were generated at the free edges of the plates and continued to move away due to their mutually induced velocity. To simulate the presence of the ground, a flat plate was positioned parallel to the plane containing the two vortices, at a distance of approximately $2.8 b_0$ from the initial position of the plates edges (the initial vortex spacing, $b_0$, being typically equal to 2.5 cm after roll-up and assumed to be approximately constant in the early times of the dynamics, i.e., out of ground effect).

The dynamics of the counter-rotating vortex pair interacting with the ground were investigated qualitatively and quantitatively using Laser Induced Fluorescence (LIF) visualizations and Particle Image Velocimetry (PIV). The former technique consisted in painting fluorescein dye on the edges of the two plates. The flow was illuminated using a 5-W argon laser by either a light sheet to obtain cross-cut visualizations or by a light cone to obtain volume visualizations. PIV was also performed to provide quantitative measurements. For this method, the flow was seeded using small plastic particles and illuminated by a sheet of light from a Nd-YAG pulsed laser. Velocity fields were calculated from particle displacements with a two-step cross-correlation algorithm described in detail in Meunier and Leweke (2003). PIV measurements were used to determine the initial conditions. The initial time, $t^* = 0$ ($t^* = \frac{\Gamma_0}{2\pi b_0}$ being the dimensionless time with $\Gamma_0$ the initial vortex circulation), is defined when the initial altitude equals two initial vortex spacings: $z_0 = 2 b_0$. The circulation-based Reynolds number of the case presented here is $Re_\Gamma = \frac{\Gamma_0}{\nu} = 3500$.

3 Numerical Setup

Two different simulations were performed to try to reproduce the experimental results. The whole experiment, including the vortex generation by the flapping plate device, was simulated in two dimensions using a vortex element method. Then a 3D simulation, using $4^{th}$ order finite differences, was done with rolled-up vortices as initial condition.
3.1 2D “flapping plate” simulation

A vortex element method (VEM) combined with the boundary element method (BEM) is used. It is based on the method for DNS of flows about bodies of general geometries by Ploumhans and Winckelmans (2000). The method was generalized to allow for the relative displacement of the bodies: the Biot-Savart velocity induced by the rotational rate of each body and the vorticity flux correction due to the moving walls are taken into account. Because of the “grid-free” behavior of the method, cases where the bodies have complex, large amplitude movements (including close relative approaches) are handled conveniently.

The setup of the 2-D computation reproduces as closely as possible the experimental setup: the exact same geometry and motion law is used for the moving plates. The only difference being that the 2-D computation simulates the flow in a truly semi-infinite domain. The experiment is bounded by the side and upper-walls, albeit at large distances compared to the characteristic length of the flow. The time step and “grid” size ($h = 1.25 \times 10^{-4}$ m, thus $h \approx 5 \times 10^{-3} b_0$) used in the 2-D simulation was dictated by the need to accurately capture the initial vortex generation phase. The subsequent evolution and vortex-wall interaction is thus very well captured.

3.2 3D Simulation

The Navier-Stokes equations are solved using a fractional-step method with the “delta” form for the pressure described by Lee et al. (2001). The convective term is integrated using an Adams-Bashforth scheme and the diffusion term using an ADI Crank-Nicolson scheme. The equations are discretized in space using the fourth order finite difference scheme of Vasilyev (2000). This discretization of the convective term conserves energy on Cartesian stretched meshes. The Poisson equation for the pressure is solved using an efficient multigrid solver with a line Gauss-Seidel smoother. The code is designed to run efficiently in parallel.

The computational domain is a box of length $4b_0 \times 8b_0 \times 4b_0$ with $b_0$ is the initial vortex spacing ($320 \times 512 \times 256$ grid points). The mesh is stretched in the wall-normal direction ($z$). The simulation is initialized using a pair of Gaussian vortices ($\sigma = 0.2b_0$) uniform in the $x$-direction and placed at a height $z_0 = 2b_0$. A low-level white noise perturbation is also added to trigger any possible instability. The flow is assumed periodic in both wall-parallel directions while a slip condition is applied at the top and a no-slip condition at the wall.

4 Results

Initially, the vortex pair descends because of the mutually induced velocity. The impermeability condition at the ground, that can be modeled by a pair of mirror vortices, forces the primary vortices to move away from each other. This leads to the hyperbolic trajectory predicted by the inviscid theory. Fig. 1 shows that it corresponds to the trajectory obtained initially. However, the boundary layers that develop at the ground, because of the no-slip condition, separates when the vortices are close enough to the ground. This opposite sign secondary vorticity is lifted-up and generates secondary vortices. The right secondary vortex is clearly visible in Fig. 3. The upward velocity induced by the secondary vortices is responsible for the rebound and the loop visible in Fig. 1. The trajectories from the numerical simulations are close but not identical. The difference is likely due to the periodic boundary conditions of the 3D simulation that restrain the boundary layers and cause them to separate a bit earlier. It can be seen in Fig. 3 that the secondary vortex in the 3D simulation is ahead of the one in the 2D simulation. The experimental position almost collapse with the numerical results especially with the 2D flapping plate simulation which corresponds to a true open domain simulation with the ground.
Figure 1: Position of the vortex center: trajectory (left) and time history of the altitude (right): axially averaged 3D simulation (thick solid), slice of the 3D simulation (o), 2D flapping plate simulation (thin solid), experimental PIV results (●) and theoretical inviscid trajectory (thin dash).

The strength of the vortices is an important diagnostic as it is directly related to hazard for real wake vortices. A good measure of the strength of the vortices in ground effect is $\Gamma_{\text{max}}$ defined as

$$\Gamma_{\text{max}} \equiv \max_r (\Gamma(r)), \quad \Gamma(r) = \int_0^{2\pi} \int_0^r \omega_x^R(r') r' dr' d\theta, \quad \omega_x^R = \begin{cases} \omega_x & \text{if } y, z \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

where $r$ is the distance from the center of the vortex and the coordinate system $(x, y, z)$ being defined in Fig. 3. The time history of $\Gamma_{\text{max}}$ is shown in Fig. 2. As long as the vortices are away from the wall, $\Gamma_{\text{max}}$ is conserved and is equal to the initial circulation. The decrease of $\Gamma_{\text{max}}$ observed after $t^* = 2$ is due to the large core size of the vortices studied here. Indeed, as the primary vorticity is widely spread in the vortices, some secondary vorticity can be closer to the primary vortex center than some primary vorticity. This limits the maximum reached by $\Gamma(r)$ that is computed by integrating over disks. The small increase of $\Gamma_{\text{max}}$ after $t^* = 5$ in the simulations is also an artefact of the definition of $\Gamma_{\text{max}}$ when dealing with deformed fat vortices surrounded by opposite vorticity.

The two numerical simulations exhibit a similar behavior even if they differ quantitatively. The difference can likely be explained by the significant difference in the initial distribution of circulation at $t^* = 0$. The cores are very similar but the outer layers of the vortices generated in the flapping plate simulation are fatter than the Gaussian fit used in the 3D simulation as shown in Fig. 2. This may significantly affect the $\Gamma_{\text{max}}$ criterion when coming into ground effect. The experimental results obtained using the PIV measurements are very close to the numerical simulations. The decrease of $\Gamma_{\text{max}}$ is also observed when $t^* = 5$. The dramatic drop of $\Gamma_{\text{max}}$ occurring between $t^* = 5$ and 8 is probably a spurious result.

In the experiment as well as in the 3D simulation, it can be observed that the secondary vortices are unstable. The structure of the instability is revealed by the axial perturbation vorticity field (i.e. local deviation from axial mean) of the 3D simulation shown in Fig. 3. The instability mechanism can be related to the elliptic instability of Widnall et al. (1974), also observed experimentally by Leweke and Williamson (1998) in the case of equal strength counter-rotating vortices. This short-wavelength instability grows while the secondary vortex is orbiting around the primary one. A modal analysis has been performed, revealing that the wavelength of the most unstable mode is $\lambda/b_0 \approx 4/7$ and its dimensionless growth rate is $\sigma^* \approx 2$. The instabil-
ity eventually saturates and creates coherent loops that are wrapped around the primary vortex in a way similar to that observed by Leweke and Williamson (1998). The flow is then fully three-dimensional and this eventually leads to a turbulent vortex system. In the 3D simulation, the diagnostics computed from a slice and from the axially average field are then significantly different (see Fig. 1 and 2). The decay rate of the system is also much enhanced.

5 Conclusions

The behavior of a pair of counter-rotating vortices in ground effect has been investigated experimentally and numerically at moderate Reynolds number. The experiment was performed in a water-tank where the vortices were generated by two flapping plates. A 2D simulation was done to reproduce the whole experiment including the generation of the vortices by the flapping plates, while a 3D simulation was done to study the onset of instabilities in the system.

The results of the various approaches are in very good agreement both qualitatively and quantitatively. The classical rebound phenomenon and the time-history of the circulation are correctly predicted by the numerical simulations. The experiment shows the onset of short-wavelength instabilities on the secondary vortices. They are also observed in the 3D simulation. Those are an example of the elliptic instability of a vortex in a straining field.

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References

Figure 3: Visualization of the flow in the right half plane. Isocontours of the axial vorticity $\omega_x b_0^2/\Gamma_0$ (negative values: thin, positive values: thick) at $t^* \simeq 4$ obtained from the PIV measurements (top left), from the 3D simulation (top center) and from the flapping plate simulation (top right), also LIF experimental visualization (bottom left) and axial perturbation vorticity field in a slice of the 3D simulation and one contour of axial mean vorticity (bottom center). Visualization of the 3D simulation at $t^* \simeq 7.8$ using 2 iso-surfaces of the vorticity magnitude (bottom right).


