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Short-wave instabilities in two-vortex systems

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Short-wave instabilities in two vortex systems


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This deliverable is the final report on the activities which have been performed in the subtask “Short-Wave instabilities in two-vortex systems” of the work package 1 on “Vortex instabilities and decay”. It contains the summaries of all the technical reports which have been provided during the project in the subtask.
Introduction

Short-wave instabilities (also called elliptic instabilities) are expected to develop in the near-wake during the interaction of wing vortices. As already reviewed in the Deliverable D1.0 on the “Previous work and present knowledge on vortex instabilities and decay”, these instabilities have been known for a long time in the context of strained vortices (Moore & Saffman 1975; Tsai & Widnall 1976), or for general elliptical flows (Kerswell 2002). Their analysis for a system of vortices is more recent (Meunier & Leweke 2001; Le Dizèes & Laporte 2002; Sipp & Jacquin 2003) and have suggested that short-wavelength instabilities could influence the merging process of co-rotating vortices, and therefore play an important role in the evolution process of the vortex system. However, the characteristics of this instability for vortices generated by a wing in which an axial velocity field is present, were so far unknown. One of the objectives of this subtask was to provide such instability characteristics, in order to identify the role that this instability can play in the evolution of the vortex system. The present report summarizes the complementary studies which have been performed during the project to reach this objective. In the first two sections, stability analysis of vortex pairs with axial flow have been performed using linear DNS combined with theoretical predictions (TR 1.2.1-2) and a global spectral analysis (TR 1.2.1-1). In the third section, the nonlinear development of the short-wave instabilities is addressed and is impact on vortex merging is discussed (TR 1.2.1-3). The fourth section concerns the spatial development of the instability and provides a spatial DNS of the dynamics of a co-rotating pair with axial flow (TR 1.2.1-6). Experimental results are presented in the last two sections. The first experimental evidence of the elliptic instability in wing vortices is first presented (TR 1.2.1-4). The effect of controlled turbulence on the dynamics of one vortex or two counter-rotating vortices is then analysed (TR 1.2.1-5).
Linear analysis of the elliptic instability in vortex pairs with axial flow
L. Lacaze, S. Le Dizès, C. Roy, K. Ryan, N. Schaeffer and M. Thompson

This work has been reported in TR1.2.1-2 and in the first part of TR1.2.1-3 and is the subject of two publications (Lacaze et al. 2007; Roy et al. 2008b).

The analysis has been first performed using both a theoretical and a numerical approach for identical counter-rotating Batchelor vortices. The vortices have been characterized by their circulation $\Gamma$, core radius $a$, maximum axial velocity $\xi$ and separation distance $b$, from which we have defined the parameters of the system: the Reynolds number $Re = \Gamma/\nu$ (\(\nu\) being the kinematic viscosity), the axial flow parameter $W_0 = 2\pi a \xi / \Gamma$, the non-dimensional radius $a/b$ and an equivalent strain rate $\varepsilon = (a/b)^2$. In the theory, the elliptic instability is described as the instability of a strained vortex (e.g. Moore & Saffman 1975). The instability is due to a resonant coupling of two quasi neutral normal modes (Kelvin modes) of the Batchelor vortex of azimuthal wavenumbers $m$ and $m+2$ with the underlying strain field. The growth rate associated with these resonances has been computed for different values of the azimuthal wavenumbers as the axial flow parameter is varied. We have demonstrated that the resonant Kelvin modes $m = 1$ and $m = -1$ which are the most unstable in the absence of axial flow become damped as the axial flow is increased. This has been shown to be due to the appearance of critical layer which damps one of the resonant Kelvin modes. However, the elliptic instability does not disappear. Other combinations of Kelvin modes $m = -2$ and $m = 0$, then $m = -3$ and $m = -1$ are shown to become progressively unstable for increasing axial flow. A complete theoretical instability diagram has been obtained as a function of the axial flow parameter for several values of the strain rate and Reynolds number.

The numerical study has first considered a system of two counter-rotating Batchelor vortices to validate the theory. The characteristics of the most unstable linear modes developing on the frozen base flow have been computed by direct numerical simulations for two axial flow parameters and compared to the theory. In both cases, a very good agreement has been obtained for the most unstable modes.

The numerical study has also considered co-rotating Batchelor vortices, for which no theoretical predictions were available. As for the corresponding counter-rotating case, when the axial flow parameter is increased, different instability modes have been observed and identified as a
Short-wave instabilities

FIGURE 2. Axial vorticity perturbation fields resulting from the instability of co-rotating vortices for \( Re = 14000 \) and \( a/b = 0.14 \). Each plot is associated with a number corresponding to a mode identified in figure 1. Contours are linear and symmetric around 0. The dashed line is a circle of radius \( a \) centred on the vortex centre. The same modes are obtained for co-rotating and counter-rotating vortices but at different locations in the \((W_0, ka)\) plane.

combination of resonant Kelvin modes of azimuthal wavenumbers \( m \) and \( m + 2 \) within each vortex. In particular, we have shown that the sinuous mode, which is the dominant instability mode without axial flow, is stabilised in the presence of a moderate axial flow. Although the same instability modes as for counter-rotating vortices exist, they are not obtained for the same axial flow parameter and axial wavenumber, and their growth rate is larger. For large Reynolds numbers or large \( a/b \), other instability modes have also been observed and associated with a combination of Kelvin modes with different labels. These other modes are less unstable than the principal modes (combination of Kelvin modes of same label), whose characteristics are almost invariant. But they make the vortex pair unstable in a large wavenumber band whatever the axial flow.
Temporal Stability Analysis of Two Vortex Systems

L. M. González and V. Theofilis

This work has been reported in TR1.2.1-1 and part of it is the subject of one publication (Gonzalez et al. 2007).

Highly resolved solutions of the two-dimensional incompressible Navier-Stokes and continuity equations, describing the evolution of a counter-rotating pair of vortices, have been obtained accurately and efficiently by spectral collocation methods and an eigenvalue decomposition algorithm (Lacaze et al. 2007; Sipp et al. 2000). Such solutions have formed the basic state for subsequent three-dimensional BiGlobal eigenvalue problem (EVP) linear instability analyses, which monitor the modal response of these vortical systems to small-amplitude perturbations, periodic along the homogeneous axial spatial direction, without the need to invoke an assumption of azimuthal spatial homogeneity. A finite-element methodology (FEM) (Gonzalez et al. 2007) has been adapted to study instability of vortical flows. Subsequently, the instability of the counter-rotating dipole has been analyzed; aspects monitored have been the dependence of the results on (a) the Reynolds number, (b) the value of the (non-zero) axial velocity considered and (c) the time at which the quasi-steady basic flow has been monitored. Essential to the success of the analysis has been the appropriate design of a calculation mesh, as well as exploitation of the symmetries of the basic state. The spatial structure of the amplitude functions of all unstable eigenmodes reflects the inhomogeneity of the basic state in the azimuthal spatial direction, thus providing a-posteriori justification for the use of the BiGlobal EVP concept.
Nonlinear dynamics of the elliptic instability in vortex pairs with axial flow
N. Schaeffer and S. Le Dizès

This work has been reported in TR1.2.1-3 and part of it is the subject of one publication (Schaeffer & Le Dizès 2008).

The nonlinear dynamics of the elliptic instability has been studied by Direct Numerical Simulation with the pseudo-spectral code used for the linear stability analysis.

As the main objective was to analyse the effect of the axial flow, we have first performed a series of simulations to better characterize the nonlinear dynamics of the elliptic instability without axial flow. We have considered the configurations of a single strained Lamb-Oseen vortex and of a system of two counter-rotating Lamb-Oseen vortices. For both cases, we have demonstrated that both weakly nonlinear and strongly nonlinear evolution of the elliptic instability were possible. The weakly nonlinear dynamics which has been observed very close to threshold is characterized by a limit cycle behavior. The strongly nonlinear dynamics, which has been obtained in most simulations, is much more violent but possesses some universal characteristic features. We have shown that it always follows the following steps [see fig. 5(a)]: (1) concentration of the vorticity in thin layers at the periphery of the vortex, (2) expulsion of vortex loops, (3) breakdown of the whole structure, (4) relaminarisation process leading to the reformation of a weaker and larger vortex [see fig. 5(b)]. The instability can start again and the process can repeat several times leading to larger and larger vortices. For co-rotating vortices and large Reynolds number,

![Image](https://example.com/image1.png)

**FIGURE 5.** (a) Elliptic instability in vortex pairs. Total vorticity maps in the plane containing both vortex axes at different times (from left to right, top to bottom: $t = 22$, $t = 42$, $t = 62$, $t = 78$, $t = 88$, $t = 100$). The color scale goes from white ($\omega = 0$) to black ($\omega > 5$) and is the same in each snapshot. (b) Mean vorticity profiles ($z$ and $\theta$ averaged) after 100 turnover times, obtained by diffusion only or with the action of elliptic instability, in the case of counter-rotating vortices. The profiles of the two vortices are almost the same.

the core size growth by this process is faster than by viscous diffusion, so the merging threshold $a/b \approx 0.22$ is reached faster in the presence of instability.

The effect of axial flow on the nonlinear evolution of the elliptic instability has been considered for a single vortex and vortex pairs. Viscous diffusion effects have also been quantified by considering both diffusing base flow and “frozen” base flow. We have shown that axial flow tends to weaken the nonlinear dynamics of the elliptic instability. In particular, the growth of the core radius by the instability is not as important as without axial flow [see fig. 6]. As a consequence, the impact of the elliptic instability with axial flow on the merging of co-rotating vortices is also

![Image](https://example.com/image2.png)
less important, especially when the initial separation distance is large \((b/a)_0 \geq 7\). Co-rotating vortices with axial flow will then merge sooner than 2D vortices but later than vortices without axial flow. Moreover, the vortex obtained after merging is wider and weaker than the one obtained in 2D but thinner and stronger than in 3D without axial flow [see fig. 7].

**Figure 6.** Evolution of the vortex radius of a single vortex in a strain field due to the elliptic instability

**Figure 7.** Axial vorticity profile of the vortex obtained by merging with or without elliptic instability for \(Re = 6280\).
Spatial DNS of two-vortex systems
L. Nybelen and H. Deniau

This work has been reported in TR1.2.1-6.

The present numerical study has been motivated by the challenge to simulate the three-dimensional spatial dynamics of a co-rotating vortex pair (Meunier et al. 2005), through the development of an elliptic instability (Le Dizès & Laporte 2002), using a high order solver of the compressible Navier-Stokes equations (numerical tools of CERFACS called NTMIX). The numerical problem is the choice of boundary conditions: for the inflow and outflow conditions as well as for the lateral boundary conditions to represent a fluid at rest. Indeed, for these boundary conditions the problem comes from the non-zero circulation of the vortex system considered. Thus, several two-dimensional and three-dimensional simulations were performed to choose the more appropriated boundary conditions for spatial simulations. As, the periodic and symmetry boundary conditions can be responsible of the generation and propagation of numerical waves which disturb the numerical solution or destabilize the calculation, we choose to implement new boundary conditions. Thus, the classic boundary conditions of Poinsot & Lele (1992) based on the characteristics wave approach have been modified to be more adapted to the physics considered here. This new boundary condition is based on the assumption of an irrotational flow close to the borders (in order to determine the magnitude of the waves), as the vorticity field is concentrated on the computational domain center where the vortex system is initially placed. To validate and evaluate the ability of this boundary condition to represent real conditions and their effects on the vortex dynamics, two- and three-dimensional temporal simulations were performed of a two co-rotating vortices dynamics. Then, two spatial simulations of the vortex breakdown phenomenon have allowed validating the numerical tools by comparison to the results of Ruith et al. (2003).

The merging process of equal co-rotating vortices through the development of elliptic instability with axial velocity were simulated by three-dimensional spatial simulations (Fig. ). Three vortex flow configurations were considered with different vortex systems and velocity peaks ratio (azimuthal and axial velocities). The values of characteristics parameters were chosen voluntarily to perform Direct Numerical Simulation (low Reynold number) and close to an experimental configuration. As consequences, the number of grid points is very high, exceeding 100 millions. So, we have performed massive parallel calculations (1024 processors of the Blue-Geen machine of CERFACS). In our knowledge, these spatial calculations are the first ones of such fundamental vortex flow configuration, using a compressible solver of the Navier-Stokes equations.

The gains of spatial simulations are to take into account the vortex system curvature and the axial velocity effects on the instability development. For the inflow configurations considered here, our preliminary results shown the development of elliptic instability, leading to the merging of the two co-rotating vortices, and the effects of the vortex core axial velocity on the instability development. However, further physical analysis is required. In particular, a detailed comparison of the results of the three configurations will be conducted by performing a Fourier series development in transversal planes around each vortex core to characterise the vortex perturbation shape during the development of elliptic instability.

In order to fully benefits from the spatial simulations, we will take into account the possible development of convective or absolute instability but also the curvature of the vortex system, or more generally, the three-dimensional effects, which can play a major role in the non-linear dynamics of vortex system.

To conclude, the numerical development allowed to perform spatial simulations of vortex dy-
Dynamics and more physical analysis are required. Moreover, such spatial simulations are limited by the computational resources (linked to the resolution and axial domain length to capture the merging process) and restricted to academic vortex flow configuration.

**FIGURE 8.** Spatial evolution of co-rotating vortices through the development of short wavelength instability illustrated by a selected isosurface of vorticity magnitude.
Experiments on the short-wavelength instability in vortex pairs

C. Roy and T. Leweke

This work has been reported in TR 1.2.1-4 and part of it is the subject of one publication (Roy et al. 2008a).

Experiments were carried out concerning the interaction of two parallel vortices (counter-rotating and co-rotating), presenting a jet-like axial velocity profile in their cores. The main results are here presented for the case of counter-rotating vortex pairs.

Vortex pairs with axial core flow were generated in a free-surface recirculating water channel with a 37 cm × 50 cm test section of length 150 cm, using two rectangular NACA 0012 airfoils of chord $c = 10$ cm, positioned vertically in the test section and facing each other tip to tip (Fig. 9a). When placed at the same angle of attack with respect to the free stream ($U = 57.5$ cm/s), two counter-rotating vortices, of circulation $\pm \Gamma$ and separated by a distance $b$, are generated at the wing tips. They present a longitudinal ($z$) velocity deficit near their axes, which in the frame of reference moving with the external flow represents a jet flow (directed upstream) in the vortex cores. Stereoscopic Particle-Image Velocimetry (PIV) was used to determine the three-dimensional velocity field of the vortices. An example of the radial profiles of axial vorticity $\omega$ and axial velocity defect $w = (U - u_z)$, azimuthally averaged around the given vortex, are shown in Fig. 9(b). Both are closely approximated by Gaussian distributions, $\omega = (\Gamma/\pi a^2) \cdot \exp(-r^2/a^2)$ and $w = wo \cdot \exp(-r^2/a_W^2)$, with characteristic radial scales $a$ and $a_W$ and amplitudes $\Gamma/(\pi a^2)$ and $wo$, respectively. For the present observations, the initial unperturbed vortex pair was characterized by the following non-dimensional parameters: Reynolds number $Re = \Gamma/\nu = 16800$ ($\nu$: kinematic viscosity), core size $a/b = 0.15$, velocity defect (inverse swirl number) $W = 2\pi awo/\Gamma = 0.44$, and axial velocity radius $a_W/a = 0.86$.

![Figure 9](image)

For the above parameters, both long- and short-wavelength instabilities have been observed in the experiments. Focusing on the latter, Fig. 10 shows a close-up side view of the short-wave core perturbation observed on one of the vortices at a downstream position $z/c = 10$, visualized by fluorescent dye injected at the airfoil tips and illuminated in volume by laser light. The initially cylindrical dye volume presents periodic edge deformations whose axial wavelength scales on the core diameter. The symmetry of the pattern, and the dye streaks linking a given crest with the adjacent opposite one, indicate that this perturbation is helical, with an azimuthal wave number $m = 2$. (For vortex pairs without axial flow, perturbation modes with $m = 1$ are generally observed.)

The wavelength $\lambda$ of the unstable mode can be measured directly from instantaneous side views as in Fig. 10. The experimental determination of the instability growth rate is much more...
difficult. Instantaneous PIV velocity measurements are too noisy, and the vortices are subject to time-dependent overall lateral displacements, caused by the growth of the Crow instability mode, but also in a random way by the fluctuations generated in the wake of the airfoils at this high Re, which excludes meaningful time-averaged measurements. Therefore, perturbation amplitudes $A$ were also measured from the dye visualizations, as shown in Fig. 10, at different downstream locations $z$, which were converted to the non-dimensional life-time $t^*$ of the vortex pair using $t^* = (z/U)/(2\pi b^2/\Gamma)$. The result of these measurements is plotted in Fig. 11(a). The growth appears indeed to be exponential, and a least-squares fit allows determination of the non-dimensional growth rate $\sigma^*$. The curve in Fig. 11(b) gives the growth rate of the most unstable short-wave perturbation mode, as function of the (non-dimensionalised) axial wave number $k = 2\pi/\lambda$, as determined by a numerical stability analysis (details are given in Roy et al. 2008b) of the experimentally measured vortex pair velocity profile. The distribution of the corresponding axial vorticity perturbation (see inset) corresponds indeed to an azimuthal wave number $m = 2$. The overall agreement between the theoretical/numerical prediction and the experimental measurement is good, considering the uncertainties of the latter, and in particular the unknown initial noise spectrum, whose characteristics could possibly explain why the observed wavelength is shorter than the one with the highest growth rate in the numerical study.

Very similar results were obtained for the case of co-rotating vortex pairs, before the onset of their merging.

In summary, the present experiments clearly show the existence of a short-wave elliptic instability in strained vortices with axial core flow. The observed instability mode is different from the one appearing in the absence of axial flow, and quantitative measurements of the growth rate are in agreement with theoretical/numerical predictions.
Wind tunnel experiments on wake-vortex decay in external turbulence


This work has been reported in TR1.2.1-5.

The decay of both single and double wing-tip vortices in external turbulence was studied experimentally in a long windtunnel with a test section of $0.7 \times 1.05$ m and a length of 8 m. The double wing-tip vortex was generated by two high-aspect ratio rectangular wing models mounted on opposite sides of the vertical tunnel walls, see Fig. 12. The separation distance and the vortex strength were adjusted such that vortex break-up can be realized within the given test section length for times of practical interest (up to 12 dimensionless time units – one dimensionless time unit being defined as the time for the vortex pair to descent over a distance equal to the spacing of the two vortices). A single vortex was generated with just one wing model mounted on the tunnel wall and extending to the tunnel centre line.

![Figure 12. Top-view schematic of the windtunnel test section.](image_url)

Turbulence levels upstream of the wing model were controlled by a turbulence generating grid which consists of a mesh of rotating rods with attached vanes. Both the rotational speed and the angular position of the vanes can be controlled as a function of time, but in the current setup the grid was used in passive mode (no rotation and fixed orientation of the vanes).

The technique of Particle Image Velocimetry was exploited to measure two-dimensional velocity fields within planes perpendicular to the mean wind direction. Hot-wire anemometry was used to characterise the turbulence in terms of the eddy dissipation rate and the turbulence intensity. The flow characteristic of both single and double wing-tip vortices were measured and analysed at different positions behind the model wings in order to study the effects of external turbulence on wake-vortex decay.

For a single vortex the decay of the maximum azimuthal velocity was found to be close to laminar, both with and without grid. The main effect of the grid turbulence is to enhance the wandering of the vortex center. Special attention was given to resolve the vortex core, since this has often been a region of difficulty in most experimental investigations. For a double wing-tip vortex, the external turbulence is found to promote the onset of the Crow instability and to enhance cross diffusion of vorticity. Smoke visualization studies clearly demonstrate the onset of the Crow instability (Fig. 13a) followed by a rapid destruction of the vortex pair by vortex linking (Fig. 13b). Fig. 13c shows the time variation of the instantaneous positions of both vortex centers in a plane perpendicular to the flow direction, which is characteristic to the Crow instability.

Vortex linking is supported by Fig. 14, which shows the total circulation around each vortex (evaluated in a plane perpendicular to the mean flow direction) as a function of the instantaneous vortex separation distance. A remarkable agreement is obtained with a simple two-dimensional model of two overlapping Lamb–Oseen vortices (indicated by the solid lines in Fig. 14).

External turbulence strongly affects the decay of total circulation (see Fig. 15a) and may be
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Figure 13. Smoke visualizations of (a) the Crow instability and (b) vortex linking. Panel (c) shows the time variation of the instantaneous positions of both vortex centers in a plane perpendicular to the flow direction.

Figure 14. Instantaneous total circulation of each vortex as a function of the instantaneous vortex separation. The decrease of circulation at the small separation distances is due to vortex linking. The solid line corresponds to a simple two-dimensional model of two overlapping Lamb–Oseen vortices with total circulation $\hat{\Gamma}$ and radius $\hat{R}$. Both the total circulation and the separation distance are normalized by their corresponding (constant) values at the first measurement station close to the model wings.

Quantified by an effective cross-diffusion coefficient that is based on the viscous diffusion of a pair of Lamb–Oseen vortices (see Fig. 15b). At very strong turbulence levels, core oscillations and decay of circulation are significantly present, though the Crow instability is no longer observed.
Conclusion

The works which have been performed during the 40 months of the Far-Wake project have followed the program initially defined in the contract. The linear temporal stability of the counter-rotating and co-rotating vortices with axial flow have been obtained for a large range of parameters. It has been shown that the instability could still be described as a phenomenon of resonance of (Kelvin) waves of each vortex with the underlying strain field generated by the other vortex. This has permitted us to understand some of the effects of axial flow on short-wavelength instabilities in vortex pairs, in particular the stabilization of the sinuous mode (the most unstable mode without axial flow) as axial flow increases, and the appearance of new instability modes involving combinations of Kelvin wave of different azimuthal wavenumber for specific values of the
axial flow parameter. However, interesting new and unexplained observations have been made such as the presence, for small separation distances, of large instability band involving complicated modes. The nonlinear dynamics of the elliptic instability has been analysed for various models (single strained vortex, counter-rotating vortices, co-rotating vortices, with and without axial flow, with and with viscous diffusion), leading to a better understanding of the impact of the short-wavelength instabilities in the dynamics of multiple vortices. In particular, we have shown that in general after the linear growth of the instability, a strongly nonlinear dynamics takes place, leading to vortex breakdown and the reformation of a weaker and larger vortex. The nonlinear dynamics and the core size of the reformed vortex have been shown to depend on the linear mode involved in the elliptic instability. This has permitted us to explain the weaker impact of the elliptic instability in the presence of axial flow. Direct numerical simulations of the spatial development of the instability up to vortex merging have been performed for the first time for co-rotating vortices with axial flow. A qualitative agreement with the temporal evolution has been observed. However, a more quantitative comparison has to be made to fully understand the role of curvature and of perturbation propagation in the nonlinear dynamics. The first experimental evidence of the elliptic instability in vortex pairs in the presence of axial flow has been obtained. Visualisations of the mode structure exhibiting a $m = 2$ azimuthal component and measurements of the growth rate have been shown to be in agreement with the theoretical/numerical predictions. The effect of controlled turbulence on the dynamics of wing vortices has also been analysed. Turbulence has been shown to increase vortex meandering and favor Crow instability in counter rotating vortex configurations. However, its effects on short-wavelength instabilities remains to be quantified.
REFERENCES


