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Final report on vortex instabilities and decay

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Final Report on Vortex Instabilities and Decay

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This deliverable is the final report on the activities which have been performed in the work package 1 on “vortex instabilities and decay”. For each subtask in the work package, it contains a short synthesis of the main results obtained during the project.

Introduction

The Work Package 1 on “Vortex Instabilities and Decay” has been dedicated to the analysis of phenomena related to intrinsic vortex dynamics, i.e., to the evolution of single vortices and systems of several vortices under self- and/or mutually-induced interactions. Generic vortex configurations, inspired by those existing (or anticipated) in real aircraft wakes, have been considered and treated as being isolated from the generating wing and from other external influences. The Work Package has been divided in four subtasks which have concerned the vortex meandering phenomenon (subtask 1.1.1), end effects and vortex bursting (subtask 1.1.2), short-wavelength instabilities in vortex pairs (subtask 1.2.1) and medium and long-wavelength instability in multiple vortex systems (subtask 1.2.2).

As stated in the contract, the objectives of the Work Package 1 were (1) To explore new fundamental ideas in order to provide explanations for the vortex meandering phenomenon; (2) To analyze and quantify wave propagation phenomena, in particular vortex bursting, associated with end effects or other abrupt modifications of wake vortices in simplified vortex models and realistic configurations; (3) To analyze the instabilities of multiple-vortex systems (vortex pairs and four-vortex systems), including their long-term evolution, in order to understand their role in the global aircraft wake decay. Most of these objectives have been fulfilled. A synthesis of the main results obtained in each subtask is provided in the following sections.

Subtask 1.1.1: Vortex meandering

D. Fabre

The aim of this subtask was to investigate through a number of theoretical, numerical and experimental studies the phenomenon known as “vortex meandering”, which consists of rapid and global displacements of the vortex core. Two different physical mechanisms were suspected to provide the explanation for vortex meandering, namely (a) a viscous instability affecting the vortex core, and (b) an energy growth mechanism related to receptivity of the vortex core to external perturbations. Both these mechanisms have made the object of a consequent numerical and analytical work.

Centre-modes (mechanism a) made the object of two studies. First, a complete description of these modes and their range of existence was provided using asymptotic methods (Le Dizès & Fabre, 2007; Fabre & Le Dizès, 2008). These studies were done in the general case in terms of the Taylor coefficients of the axial and azimuthal velocity laws at the vortex axis. As a consequence,
the results obtained are universal and can be applied to any particular vortex base-flow observed in trailing wakes as well as in many other contexts. Secondly, the spatial stability properties of these centre-modes were investigated for the $q$-vortex model (Parras & Fernandez-Feria 2007), as well as for the Batchelor solution which incorporated nonparallel effects (Del Pino et al. 2008). Here again, the results are quite general and can be applied for vortex flows observed in other contexts.

Transient energy growth (mechanism $b$) has been investigated through an optimal perturbation analysis (Antkowiak & Brancher, 2004; 2007) and a stochastic forcing analysis (Fontane et al., 2008). Both these studies revealed that the perturbations which are most likely to be obtained as a result of initial or continuous external noise are associated with very long wavelengths and consist in displacements of the vortex core as a whole. These perturbations are selected by a resonant excitation due to noise located outside of the vortex.

An experimental study was subsequently conducted. For this purpose, a single trailing vortex was generated in a water channel, using a half-wing. Dye visualisation and stereo-PIV measurements were used to investigate the properties of vortex meandering. The data were processed using POD to identify the most energetic modes present in the vortex. The results indicate that mechanism ($b$) is actually present in the experiment. In particular, the most energetic modes identified by PIV display both the characteristic structure, time scale and wavelength of the perturbations selected by transient growth. The presence of centre-modes (mechanism $a$) was not demonstrated in the experimental results. However, the Reynolds numbers reached in the experiment are not large enough to allow their existence. They could be present for larger values of the Reynolds number and provide an additional source of energy for vortex meandering, but are not expected to be the dominant mechanism in real trailing wakes because of their relatively small amplification rates.

Finally, it should be emphasised that all the theoretical studies conducted in this subtask were done for general vortices and are potentially applicable to many other contexts in fluid mechanics involving columnar vortices, such as hurricanes, rotating pipe flows, turbulent flows, etc...

Subtask 1.1.2: End effects and vortex bursting

L. Nybelen

The purpose of the subtask 1.1.2 was to investigate the wave propagation on vortices induced by end-effects and the vortex bursting phenomenon. End-effects usually referred to the effects associated with the finite size of experimental facilities (e.g. towing tank and catapult experiments). They are known to occur as sudden modifications of the vortex core structure, which propagate along the vortices in the form of wavepackets. The data analysis of the test campaigns at the catapult B20 of ONERA has demonstrated how the PIV measurements can be disturbed by such phenomena (ONERA TR. 1.1.2-4). In these campaigns, using a global criterion $\Gamma_2$ (Graftieaux et al. 2001) to determine the vortex position and its core size, and a Fourier transform to characterize the azimuthal structure of the perturbation, it was shown that end-effects were mainly associated with the propagation of axisymmetric and helical perturbations.

Wave propagation along the vortices is also observed in the far-field of an aircraft wake, after the reconnection of the two counter-rotating vortices (see Moet et al. (2005) and references therein). One of the goals of the subtask was to identify how and when end-effects or other localized perturbations can modify the vortex properties in a given region. A theoretical study was conducted by UPS-IMFT (TR.1.1.2-3) on the Kelvin waves and the singular modes of the Lamb-Oseen vortex, which is a vortex model widely used in the literature. A reconstruction method was employed to compute the response of the vortex to localized perturbations of various kinds. A comprehensive map of the eigenmodes was presented (Fabre et al. 2006) and the following results were obtained. For axisymmetric disturbances (azimuthal wavenumber $m = 0$), the perturbation propagates along the vortex under the form of Kelvin mode wavepackets at a velocity
close to the maximum of azimuthal velocity of the vortex. Helical disturbances ($m = 1$) split into several structures which also propagate along the vortex but at a velocity about half of the vortex velocity; while the elliptic or more complex perturbations ($m \geq 2$) do not lead to propagating structures.

A numerical study in both the linear and non-linear regime (ONERA TR.1.1.2-4) was also performed for the three azimuthal modes $m = 0, 1, 2$. For helical modes ($m = 1$), it was in particular observed by comparing simulations of different perturbation amplitudes, that the nonlinear dynamics is more complex and involves smaller vortical structures. The propagation speed was also observed to slightly increase with the perturbation amplitude.

Experiments on end effects were performed by IRPHE in water tank (TR.1.1.2-1) by considering the evolution of a vortex with a bend at $90^\circ$ at one of its extremity. The vortex characteristics were analysed through dye visualisations and by PIV measurements. Two types of perturbations were observed during the evolution: (1) An axisymmetric perturbation propagating slightly faster than the theoretical Kelvin modes ($m = 0$) and inducing a weak axial flow in the vortex core. (2) An helical perturbation, characterized by a vortex core undulation, propagating slower than the first one. In the experiments, these perturbations were sufficiently strong to alter the vortex structure. A numerical simulation of the same configuration was also performed by UCL (TR. 1.1.2-6). A similar wavepacket propagation was observed and a good agreement of the propagation speed with the theoretically predicted values was obtained.

Two others numerical studies were performed in this subtask which mainly differ by the manner the vortex was locally disturbed. In the first study, a local variation of the vortex core radius was considered which induces a minimum pressure gradient between the vortex region of higher radius and the vortex region with the smaller core (Moet et al. 2005, CERFACS TR. 1.1.2-2). This perturbation propagates along the vortex under the form of axisymmetric wavepackets. The main numerical result is the generation of an axial flow, which can be sufficiently strong to destabilize the vortex flow. In the second numerical study, abrupt variations of circulation, modeling the effect of accelerated/decelerated wing were considered (UCL TR. 1.1.2-6). Time- and spatial-developing simulations were performed, using the lifting line theory for the initialization. It was shown that the variation of the circulation also leads to the propagation of a pressure wave which induces a strong axial velocity destabilizing the vortex flow.

These investigations have led us to the following conclusions: (1) the wave propagation can be responsible of the loss of the vortex structure coherence. (2) the propagation speed is directly linked to the maximum of the vortex azimuthal velocity.

The vortex bursting phenomenon was analyzed by DNS simulations by CERFACS (TR. 1.1.2-5) by considering the collision of two waves propagating in opposite directions (waves coming from a local variation of the vortex core). The collision of the two waves was shown to increase the enstrophy and generate small scale structures. Defining vortex bursting from these quantities, a simple criterion for its occurrence has been established. This criterion has permitted us to show that for initial vortex core radius variation lower than 40% between the two vortex regions, the collision does not lead to vortex bursting, while for perturbations higher than 40%, there is a clear and sudden change of the vortex core leading to a turbulent flow in the region of collision.

**Subtask 1.2.1: Short-wavelength instabilities**

*S. Le Dizès*

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 Dizès & 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. As the characteristics of this instability for vortices generated by a wing in which an axial velocity field is present, were unknown at the beginning of the project, one of the first objectives of this subtask was to analyse the effect of the axial jet on the stability characteristics. Another objective was to further document the role played by this instability during the evolution of the vortices in the near-wake of aircraft. As initially planned in the contract, several complementary studies have been performed during the 40 months of the project to reach these objectives.

The linear stability properties of vortex pairs with axial flow have been examined using three different techniques (theory, linear DNS, global spectral analysis). It has been first shown (see TR 1.2.1-2) that the stability characteristics of vortex pairs can be obtained by analysing a single strained vortex. This has permitted us to provide a physical mechanism responsible for the short-wavelength instability in vortex pairs. It has been shown that, as in vortices without axial flow, the instability is due to the resonant coupling of two quasi neutral normal modes of each vortex of azimuthal wavenumbers $m$ and $m + 2$ with the strain field induced by the other vortex. This interpretation has provided an explanation for the results obtained by linear Direct Numerical Simulations. As the axial flow is increased, we have shown that the sinuous mode, corresponding to $m = 1$ and $m = -1$ azimuthal mode coupling, present in vortex pairs without axial flow, becomes damped and is replaced by other modes involving $m = 0$ and $m = 2$ modes, $m = 1$ and $m = 3$ modes, etc. Complete instability diagrams have been obtained for several Reynolds numbers and separation distances for a large range of axial flow strength. For large separation distances, a good agreement between the theory and the numerics for Batchelor vortex pairs in both counter-rotating and co-rotating configurations has been demonstrated (see TR 1.2.1-2 and TR 1.2.1-3). For small separation distances, new interesting and unexplained observations have been made such as the presence of large instability band involving complicated eigenmodes (see TR 1.2.1-2 and TR 1.2.1-1).

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 without viscous diffusion), leading to a better understanding of the impact of the short-wavelength instabilities on the dynamics of multiple vortices (TR 1.2.1-3). We have shown that in general, in each vortex, after the linear growth of the instability, a strongly nonlinear evolution 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. In particular, we have observed that the dynamics is more catastrophic for vortices without axial flow, the vortex core size being able to increase by up to 25% by the elliptic instability. Moreover, we have shown that the instability can repeat several times leading to larger and larger vortices even when the viscous diffusion of the base flow is artificially suppressed. For the large Reynolds number vortices obtained in the near wake of aircraft, we suspect that it is by this process that the vortex core size increases and reaches rapidly the 2D merging threshold of co-rotating vortices. By this mechanism, the early merging of vortices in the near wake could then be explained.

Controlled experiments and numerical simulations of the spatial evolution of vortex pairs were the two challenging steps which were planned in the FAR-Wake project to try to confirm this scenario. For the first time, the spatial growth of the instability, its nonlinear evolution up to vortex merging have been simulated with success for three sets of parameters, and a good qualitative agreement with the temporal evolution has been observed (see TR 1.2.1-6). A more quantitative comparison has now 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 also been obtained in this project (TR 1.2.1-4). Dye visualisations of the vortices have
demonstrated the existence of an helical instability mode with an azimuthal wavenumber $m = 2$ as predicted by the theory. Measurements of the growth rate and of the axial wavenumber have also been found to be in agreement with the numerical temporal stability properties obtained with the vortex profiles measured in the experiments.

The effect of controlled turbulence on the dynamics of wing vortices has also been analysed (TR 1.2.1-5). 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.

Subtask 1.2.2: Medium and long wavelength instabilities

L. Jacquin

The partners investigated different aspects of the major mechanism which may disorganize an aircraft wake. The activities mainly focused on the so-called 4-vortex-Systems (4VS) which model aircraft wakes composed of two vortex pairs in a co- or in counter-rotating configurations. This may be produced by realistic aircraft in landing or taking-off configurations after recombination of the different sources of vortices produced at their flap edges and/or at tail tips. If vorticity is conveniently distributed among these 4 vortices, the system becomes unstable and undergoes turbulent interactions. These interactions transform the 4VS into a vortex pair where the vortices are weaker and more unstable than those produced by an unflapped wing having the same lift. The objective of the work was to clarify this physics and to evaluate its potential in terms reduction of wake vortex lifetime.

By combining experiments, CFD and theory, the collaborative work conducted by the partners has provided some decisive clarifications on this subject. The main results are:

- The lifetime of a 4VS is significantly smaller that that of an equivalent 2VS. A reduction by at least a factor 2 is attained. This property has been verified by way of experiments conducted in a very large Towing tank.

- A good part of the underlying flow physics has been described, thanks to careful numerical simulations. The mechanism by which the lifetime is reduced is a non linear amplification of the Crow instability mediated by a rapid merger between the two vortex mediated after development of an optimal perturbation of the initial configuration. The mechanism by which energy is transferred from the initial optimal wavelength to the Crow wavelength looks to be a turbulent one, but this remains to be clarified.

- The 4VS system may be view as a passive control mean (no energy input needed, except noise). But an active control scenario based on the forcing of the Crow wavelength in the 4VS, is also feasible. This has been also investigated. The active control provided nearly the same benefit in terms of wake vortex lifetime than the passive one.

- Progresses have also been made concerning basic 2 vortex configurations. In particular, a way of accelerating ”passively” the Crow instability has been found from theory. This allows also a reduction of more than a factor 2 of the life time of a 2VS. Evaluation of the applicability of this idea is underway.

REFERENCES


