PhD thesis
Dynamics and stability of wake vortices

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The proposed thesis is part of a project called DESTINS, which aims to study the dynamics of vortices downstream of aircraft using direct numerical simulation tools and global stability, accompanied by tests on our department's wake bench (DAEP). The thesis in question here will be devoted to the theoretical and numerical aspects and therefore to the implementation of the numerical tools that will accompany the future experimental campaigns.

Context

Vortex dynamics has always been a subject of great interest to the scientific community because of its involvement in many engineering applications.

These vortices are induced by the generation of lift on wings of finite span and contribute to induced drag (see figure 1a). Even with the presence of winglets, their formation is unavoidable, and their presence can be very dangerous for following aircraft due to the induced rolling moment. This aspect plays an important role in the configuration of UAVs in formation or swarms of UAVs, as well as in the imposition of limitations on take-off and landing frequencies between two consecutive aircraft, limitations which are essential for air traffic control [1].

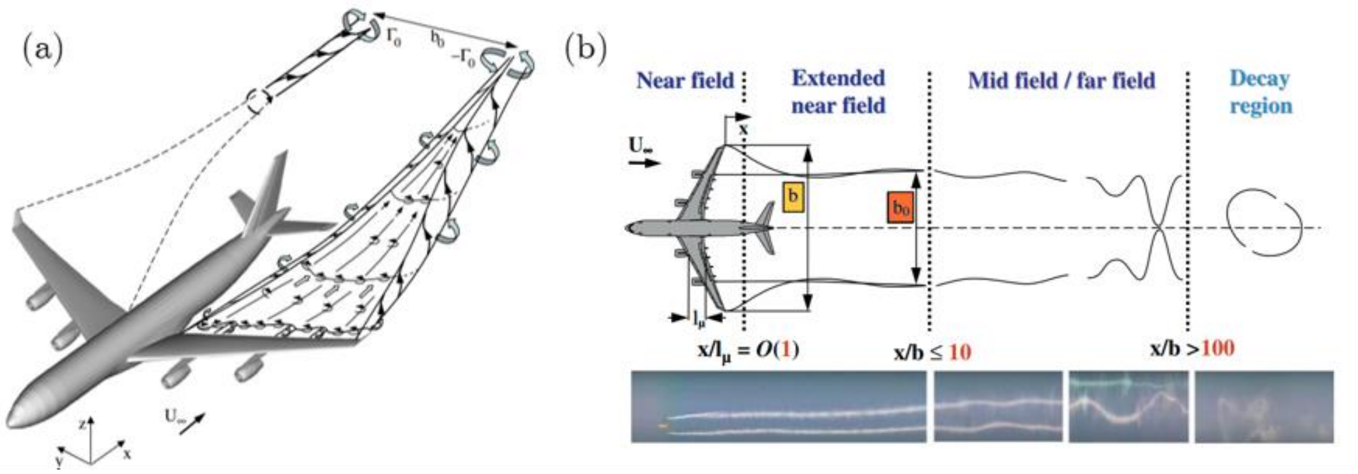

Figure 1: Evolution of the vortex sheet and winding process (a) [2]. Determination of the wake vortex evolution regions as a function of the position at the rear of the aircraft (b), figure adapted from [3].

The interaction of wake vortices with the outgoing jets from a hydrogen engine, for example, is the basis for the formation of contrails, which have a significant influence on radiative forcing under certain atmospheric conditions (see figure 1b). This is why their persistence at flight altitude has been identified as the main effect of the climatic impact of aviation [4-5].

In addition to these critical issues, it should also be emphasised that vortex dynamics also give rise to acoustic problems. For example, in the aeronautical industry, in hyper-weighted flight configurations, the vortices generated by the deployment of the trailing edge flap are a source of noise [6].

For all these reasons, a scientific effort to improve our understanding of their dynamics and design control strategies is necessary. One of the control strategies relies on the excitation of three-dimensional instabilities [7-8], which need to be studied using fully global approaches in order to gain a detailed understanding of the physical mechanisms.

Objectives and challenges

The aim of this thesis is therefore to study the dynamics of different flow configurations involving one or more wake vortices by means of direct numerical simulations and global stability analysis tools that can provide quantitative information on their intensity, the frequencies involved and their lifetime.

Furthermore, the use of stability and sensitivity analysis for high Reynolds regimes represents a powerful tool for the design of new actuator strategies to control these vortices and, more broadly, the flow around and downstream of an aircraft. It is therefore easy to understand the importance of studying the dynamics of these vortices, which is also preparatory to the design of new aircraft wings capable of minimising the intensity of tip vortices, their lifetime and/or reducing flap edge noise.

The first challenge from a technical point of view will be to implement the turbulent terms in the part of the code that integrates the linearised Navier-Stokes equations in time. This step is necessary to ensure the overall stability of complex three-dimensional flows in each flow regime. Once the turbulent terms have been implemented in the IC3 code, we will be able to consider flows at high Reynolds speeds ($Re \sim 10^6$).

A second challenge will be the application of Newton-GMRES (Generalized Minimal Residual) type methods in IC3. The presence of Krylov-type methods in the code will make it easier to implement these methods. Until now, we have relied on SFD (Selective Frequency Damping) methods to calculate the stationary solutions (base states or fixed points) of the Navier-Stokes equations. However, even for low Reynolds regimes, there may be cases where SFD does not work because the flow undergoes a bifurcation or because there is no dominant frequency. In these cases, the application of Newton-GMRES type methods becomes necessary. The implementation of such an iterative method is therefore one of the objectives of this project. Its implementation in IC3 will make it possible to address not only cases where there are no

dominant frequencies, but also those where the flow regime is more complex and/or turbulent, such as high Reynolds wake vortices.
Using optimisation methods based on the adjoint operator, we will also be able to carry out sensitivity analyses which will enable us to identify the most receptive paths for the transition to turbulence. In addition, sensitivity analysis can be used to identify regions of the flow that are more or less sensitive to changes in the basic flow or to the application of control forces. This analysis represents a <u>third challenge</u>, since such analyses at high Reynolds numbers are rarely carried out in the scientific community. Sensitivity analysis at high Reynolds in a RANS and LES framework can therefore represent a powerful tool for the design of new actuator strategies for the control of these vortices and, more generally, of high Reynolds flows.

Once all the numerical methodologies have been implemented and validated, we will then be able to consider a more complex flow with the presence of a three-dimensional wing of the NACA 4412 type with a finite span and study the generation of the tip vortex.

The physical analysis of the dynamics of these vortex flows also represents a challenge in itself. This analysis will be based on numerical simulations and advanced post-processing tools to better characterise and understand the unsteady behaviour of this type of flow.

Planning

First year

The first year of the study will be devoted to getting to grips with our numerical solver, namely IC3 is the department's massively parallel code. The <u>first challenge</u> will be to carry out global stability analyses on simple cases using spectral methods. At the end of the first year, we will begin to tackle the first technical challenge, which is the implementation of the turbulent terms in the part of the code that integrates the linearised Navier-Stokes equations in time. This step is necessary to be able to compute the global stability of complex three-dimensional flows in each flow regime.

Second year

The second year will be devoted to finalising the implementation of turbulent terms and applying Newton-GMRES (Generalized Minimal Residual) type methods in IC3 (<u>second challenge</u>). The presence of Krylov-type methods in the code will facilitate the implementation of these methods. Indeed, their implementation in IC3 will make it possible to tackle not only cases where there are no dominant frequencies, but also those where the flow regime is more complex and/or turbulent.

Third year

The third year will be devoted to exploiting the results and setting up the sensitivity analysis which represents the <u>third challenge</u> of the thesis as well as its highly innovative character. These analyses will enable us to identify the most receptive paths for the transition to turbulence, but above all they can identify the regions of the flow that are most sensitive or least sensitive to modifications to the basic flow or to the application of control forces.

Application process

This project is funded by the French Ministry of Defense through financial support of the Agence Innovation Défense and therefore **only candidate with European citizenship** can apply. The candidate has a MSc with a strong background in stability analysis of fluid flows and/or CFD. Coding skills (Python and C++) are expected. Oral and writing skill in English is mandatory. Please send a cover letter, a CV as well as contact details of two referees to jerome.fontane@isae-supaero.fr and gabriele.nastro@isae-supaero.fr

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