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Aircraft trailing vortices/Tourbillons de sillages d'avions

Aircraft trailing vortices: an introduction

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Abstract

Flow momentum that is deflected in a persistent way by a wing, or by another flow, becomes organised in coherent and energetic vortex structures. This phenomenon is briefly introduced here by comparison with other phenomena such as the production of vortices by impulsive forces (e.g. during animal flight), or the production of turbulence by jets. These considerations aim at underlining the fundamental nature of this strange mechanism, which is usually hidden behind engineering models produced by aerodynamic science. The control of these mechanisms, for applications to the safety of the airplanes for example, opens a vast multidisciplinary field of research. ***To cite this article: L. Jacquin, C. R. Physique 6 (2005).***

Résumé

Tourbillons de sillages d'avions : une introduction. On observe que la quantité de mouvement d'un écoulement défléchi de manière persistante par une aile ou par un autre écoulement s'organise en tourbillons énergétiques cohérents. Ce phénomène est ici brièvement introduit par comparaison avec d'autres phénomènes tels que la production de tourbillons par des forces impulsives, chez les animaux par exemple, ou la production de la turbulence par des jets. Ces considérations visent à souligner la nature fondamentale de ce mécanisme étrange, qui se cache usuellement derrière les modèles d'ingénieurs produits par la science aérodynamique. Sa maîtrise, en vue d'applications à la sécurité des avions par exemple, ouvre un vaste champ de recherches multi-disciplinaire. ***Pour citer cet article : L. Jacquin, C. R. Physique 6 (2005).***

Keywords: Aircraft wake vortices; Jets; Turbulence; Lift; Drag; Aerodynamics

Mots-clés : Tourbillons de sillages d'avions ; Jets ; Turbulence ; Traînée ; Portance ; Aérodynamique

1. Vortex force

Vortices are important in aerodynamics because they are intimately related to forces. A good illustration of this is provided by the flight of animals. An insect for instance acquires thrust and lift by producing a system of coherent vortices (namely vortex rings) which are thrown downward in order to obtain, by reaction, a force oriented upward. Fig. 1 illustrates insect hovering. It shows the generation of a pair of vortices (Fig. 1(f)), that form after the combination of vortices produced at the leading edge and at the trailing edge of the insect wing during its procession. This vortex pair is sinking downward through mutual induction, see [1]. So, after a complete cycle the insect has been subjected to an upward impulsive reaction force felt on its wings and body by producing these sinking vortices which convey a certain amount of downward vertical momentum. The same occurs behind a steady wing as shown by the wind tunnel experiment of Fig. 2. The wing of an aircraft is conceived so as to deflect

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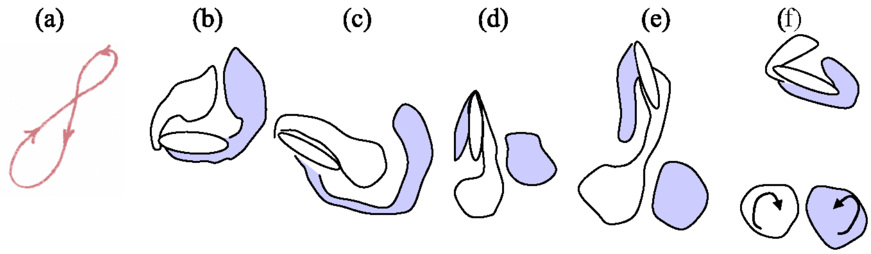

Fig. 1. Formation of a sinking vortex pair by a flapping wing: (a) wing trajectory, (f), (b) downstroke and rotation, (c), (d), (e) rotation and upstroke; adapted from [2].

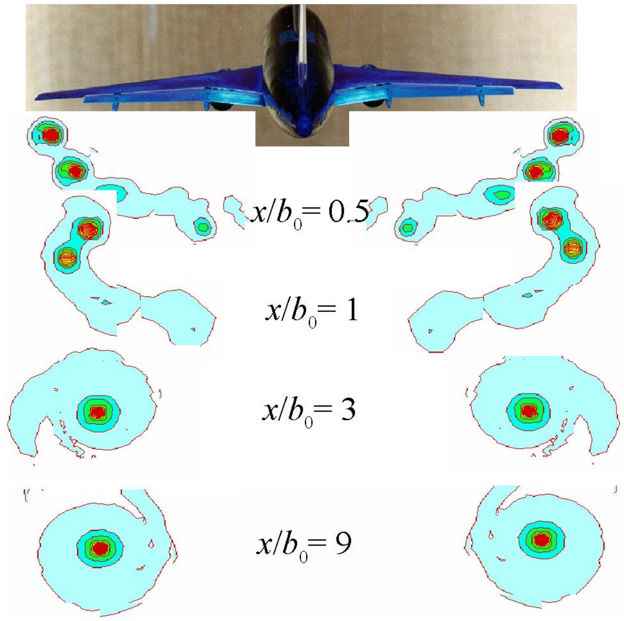

Fig. 2. Formation of a vortex pair downstream of a flapped aircraft model: iso-values of the longitudinal vorticity obtained by Laser Doppler Velocimetry in four different vertical planes downstream (b_0 denotes the model span); compiled from [3].

part of the impinging flow momentum into a normal component. This produces, by reaction, a normal force which is opposite to this momentum component. As seen in Fig. 2, after the merger of different vortices produced by the wing, a single pair of counter-rotating vortices forms. The flux of momentum of this vortex system is equal and opposite to the lift of the aircraft (or to its weight if the flight is steady). The trailing wake vortices of Fig. 2 may be viewed as the spatial development of the vortex dipoles created by an impulsive force as in Fig. 1. Note that a wing is not the only means of producing lift: a rocket for instance uses reaction to a jet. Impulsive blowing makes vortices (think of a smoke ring), like flapping wings. However, if the ejection is steady, the vortices break into turbulence. Now, if the jet penetrates into a cross-flow, as in Fig. 3, it is deflected downstream by viscous and pressure interactions on its interface (also in a shock wave in supersonic regimes) and this leads to the development of a vortex pair which conveys the jet momentum, see Fig. 3. Again, we may consider these trailing vortices as a sort of spatial development of impulsive jet rings. In all cases, we recognize that trailing vortices form into a steady flow when momentum is deflected. Another important conclusion is that steady flight, which needs momentum deflection, always produces trailing vortices.

2. Hazard

Trailing vortices, such as those of Fig. 2, form after deflection and roll-up of the fluid particles travelling in the proximity of the wing surface. The very origin of these variations in the flow momentum may be attributed to the action of viscosity which takes place in the boundary layers of the wing, and in shock waves in the case of a transonic or supersonic flight. Part of

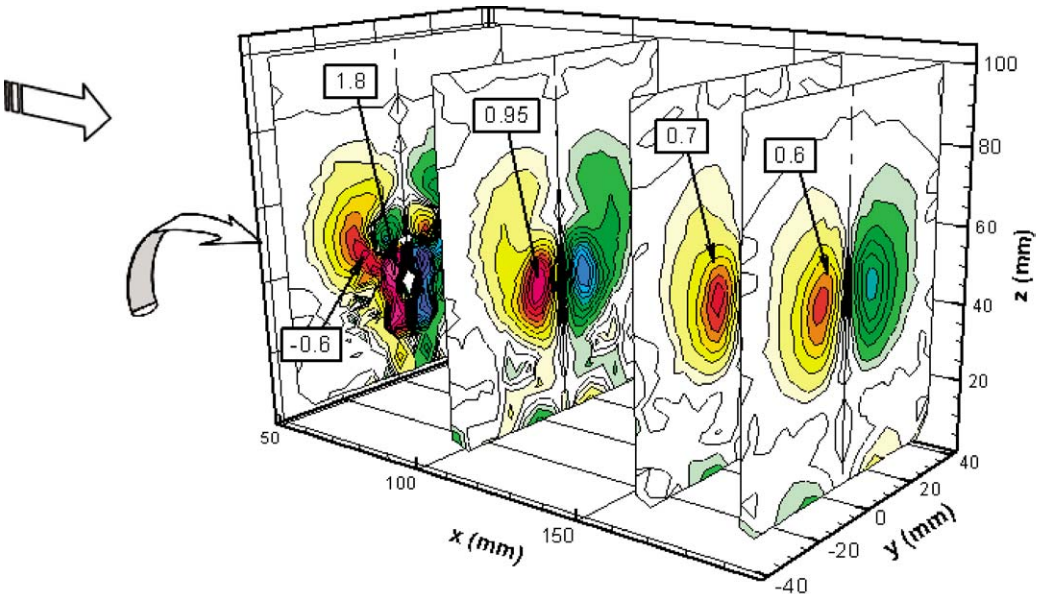

Fig. 3. Formation of wake vortices after deflection of a heated supersonic jet normal to a supersonic cross-flow: iso-values of the longitudinal vorticity measured by Laser Doppler Velocimetry (values are $\Omega_x d_j / U_\infty$ with $U_\infty = 526\ \mathrm{ms}^{-1}$ the free-stream velocity and $d_j = 11$ mm, the jet nozzle exit diameter. The flow conditions are: exit jet Mach number $M_{\mathrm{jet}} = 2$, jet total temperature $T_{i,\mathrm{jet}} = 930$ K; free-stream Mach number $M_\infty = 2$, free-stream total temperature $T_{i,\infty} = 310$ K; total pressure ratio $p_{i,\mathrm{jet}}/p_{i,\infty} = 10$; from [4].

the energy expended to steadily maintain an airplane is quickly dissipated by viscosity, i.e., irreversibly transformed into heat. This energy corresponds to the work of the so-called 'viscous drag'. A 'wave drag' also contributes in the presence of shock waves. These contributions typically amount to more than sixty per cent of the total drag. Another part of the energy, which is used for lift (and to form the trailing vortices) corresponds to the work of the so-called 'induced drag' (also called 'vortex drag'). For a conventional aircraft, this contribution amounts to nearly a third of the total drag. This means that lift absorbs typically a third of the power delivered by the propulsion unit of an aircraft. The corresponding energy is momentarily stored in the trailing vortex system and could, in principle, be restored (by convenient wind turbines) before this breaks up. After break-up, the vortices quickly dissipate. Using the language of modern thermodynamics, wake vortices may be considered as a 'dissipative structure', that is, an energetic and self-organised pattern which develops temporarily while the flow returns to equilibrium. These structures convey high energy and this is why they are potentially dangerous. This energy is proportional to the weight of the generating aircraft so that severity of upsets resulting from encounters of a following aircraft with the vortices depends on its relative weight. The separation standards are based on this rule and are considered to be improvable today.

3. Turbulence

A popular expression used about the trailing-vortex hazard is 'wake turbulence'. We explain here why this is an inappropriate expression. Fully developed turbulence may be viewed as a field of randomly interacting three-dimensional vortices of various scales which continuously form and break-up through mutual straining. This mechanism allows the kinetic energy of the flow to be dissipated after 'cascading' down to vortices whose scale is small enough to be finally eliminated by viscous friction [5]. The lifetime of these interacting vortices is, on average, very short, so they can hardly be observed. However, an isolated free vortex is, surprisingly, very stable in spite of its strong internal shear. This intriguing property is attributable to its rotation. So, concentration of the vertical momentum behind a wing into big and weakly interacting vortices is the opposite of a turbulent process. Break-up finally occurs through mutual interaction of these structures, but this takes a long time. An encounter with an aircraft wake is thus potentially dangerous because high energy is concentrated there and because turbulent diffusion before break-up is absent. Mitigation of this intrinsic stability of the vortices is one of the fundamental topics relevant to alleviation of aircraft wake hazard.

4. A multi-disciplinary topic

So, trailing vortices are an unavoidable and potentially dangerous by-product of fixed-wing aircraft. Now, some of the concrete questions posed to the research community are: what are the main mechanisms driving trailing vortices? Is it possible to break them prematurely? Can we control them, by means of an airborne system for instance? How can different control concepts be evaluated? Is it possible to increase airport throughput while enhancing the current level of safety? What are the impacts of airplane wakes on the environment? This volume describes research efforts in vortex dynamics, computational fluid dynamics, micro-physics, chemistry, weather forecasting, laser based measurement techniques, all of which are concerned with these questions.

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