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Numerical Simulations of Real Case Aircraft Wake Vortices under Complex Environmental Conditions

Thomas Hofbauer & Ulrich Schumann

Institute of Atmospheric Physics, DLR Oberpfaffenhofen, D-82234 Weßling, Germany

Tel +49/8153/282506, Fax +49/8153/281841, Email: Thomas.Hofbauer@dlr.de

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As an unavoidable consequence of lift, aircraft generate counter-rotating pairs of trailing vortices which constitute a potential hazard to following aircraft. With the introduction of large aircraft such as the Boeing B747 thirty years ago, the number of air traffic incidents and accidents due to wake vortex encounters severely increased. Subsequent programs investigated the behaviour of aircraft wakes which eventually led to regulations that prescribe a weight dependent minimum separation distance between aircraft on the same flight path. These purely empirical regulations however limit the throughput capacity of some major airports. Since the meteorological situation was found to have significant impact on the behaviour of the wake vortices, recent attempts aim at optimizing these regulations by taking into account ambient turbulence intensity, wind and wind shear, and thermal stratification. For flight safety reasons, situations of persistent vortices which remain in the flight corridor are of special interest.

From LDV* field measurements conducted at London-Heathrow Int'l Airport, Greenwood and Vaughan (1997) report such a case. As depicted in Figure 1, the upwind vortex of a Boeing B747-200 in terminal approach was found to rebound back to flight level after an initial descent. 70 seconds after the aircraft passage, this vortex again attains generation altitude with practically undiminished strength. Apparently, this situation might have been critical to a follower aircraft, considering typical temporal aircraft spacings of 90 – 120 seconds. Greenwood and Vaughan suppose that the trees which are also depicted in Figure 1 may well have been important in creating the updraft to carry the vortex. Other reasons might have been stable stratification, gusts or a low-altitude jet layer which could have been intensified by the presence of the trees.

In order to point out the possible reasons that are responsible for the observed vortex behaviour, Large-Eddy simulations (LES) and direct numerical simulations (DNS) are conducted. Owing to the complexity of this problem, the simulations have to capture the details of this case, namely the vegetation, the instationarity of the wind, and ambient turbulence. In a series of simulations, combinations of these details are taken into consideration. The comparision of the results is expected to outline the importance of each detail for the observed vortex behaviour.

**Laser Doppler Velocimetry* – Technique to determine the line-of-sight velocity component by measuring the Doppler shift of a Laser beam.

For the simulation, the initial conditions with respect to appropriate and fully developped turbulence is obtained by a preparatory run which in turn starts by superimposing the mean wind with homogeneous isotropic turbulence following the $-5/3$ energy slope law. Once the turbulence has adapted to the inhomogenicity of the environmental conditions, e. g. the ground, and a quasi steady-state is reached, the wake vortices are injected.

During the field measurement, a second LDV – approximately $30m$ upstream of the first one – was used to measure the ambient wind velocity. In the numerical simulations, this instationary mean wind profile is enforced through a relaxation method. The relaxation domain size covers roughly one forth of the entire domain size and is chosen in such a way that the ambient turbulence can adapt to the modified flow.

The trees which are suspected to influence the vortex trajectories are modeled by embedding a momentum sink into the computational domain, whereupon the drag is a function of altitude and local velocity magnitude. This technique is shown to be adequate for modeling vegetation as pointed out by Shaw and Schumann (1992).

The initial fields preparation, the relaxation scheme, and the tree modeling were tested separately and have proven satisfactory results. Figure 2 shows isolines/isosurfaces of λ_2 (a measure for coherent vortex structures) at $t = 19s$ after vortex injection of a preliminary DNS. At this stage, the upwind vortex almost reached its lowest altitude and is just about to reverse its lateral movement direction, forming the characteristic loop of the trajectory which is presented in Figure 1. The smoothness of the flow as well as the mean wind profiles as a function of different times (not shown here) indicate the validity of the relaxation scheme.

While in real cases typical Reynolds numbers Re_Γ are of order $\mathcal{O}(10^7)$, we hardly achieve Reynolds numbers of order $\mathcal{O}(10^4)$ with direct numerical simulations, whereas the Reynolds number for Large-Eddy simulations (LES) would be – at least from a theoretical point of view – infinite. This fact represents the one major argument against DNS's. By LES sensitivity studies, Darracq *et al.* (1999) however outlined that the gross behaviour of a vortex pair is primarily independent of the Reynolds number – even for variations several degrees of magnitude. This could be probably explained by the aposteriory determined effective Reyolds number which is – at best – only 2...5 times higher for LES's than for comparative DNS's. This issue will be discussed in detail.

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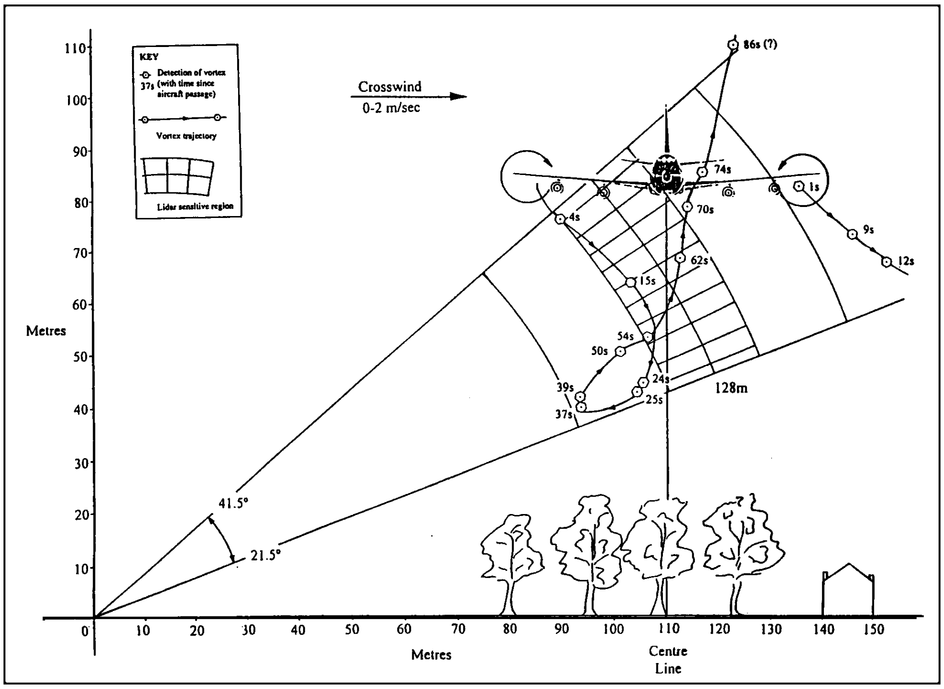

Figure 1: Reconstruction of vortex trajectories from measured LDV data of a Boeing B747-200 in terminal approach (from Greenwood & Vaughan, 1997)

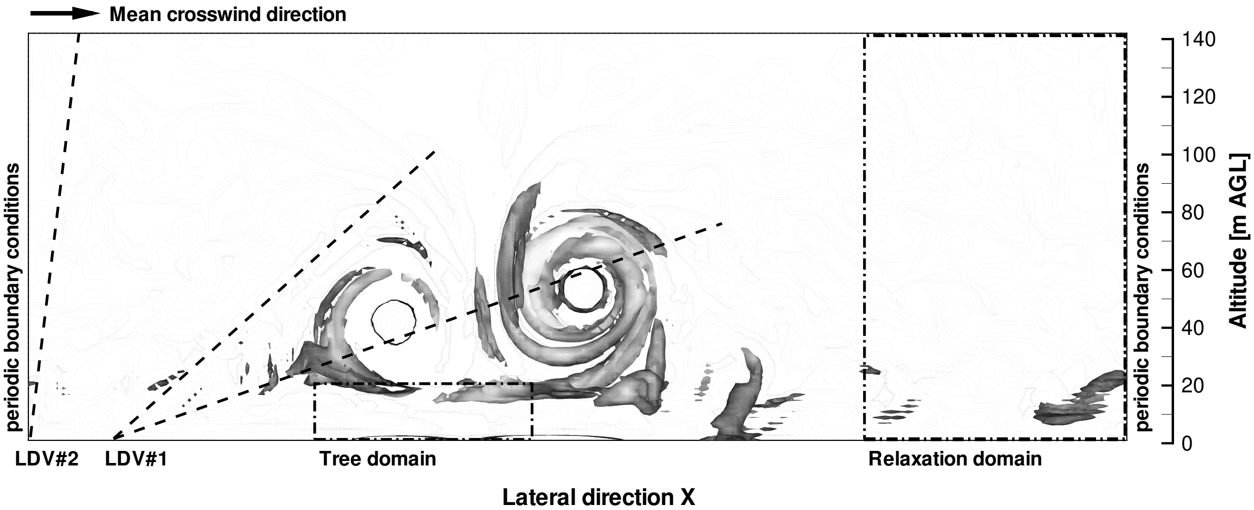

Figure 2: Cross section of simulation at $t = +19s$ after vortex injection – λ_2 isolines for medium/weak ambient turbulence, λ_2 isosurfaces for intense vortical structures