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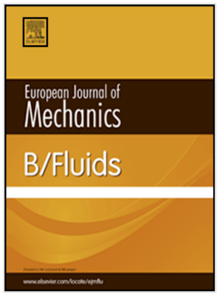

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Reynolds-averaged and wall-modelled large-eddy simulations of impinging jets with embedded azimuthal vortices

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Abstract

We have performed simulations of an impinging jet with embedded azimuthal vortices, a model of the wake of a helicopter hovering near the ground. This problem has considerable practical importance since, when the landing area is covered with sand or snow, the interaction between the helicopter wake, the rotor-tip vortices and the solid particles on the ground can result in the liftup of a cloud of sediment that limits the pilot's vision, causing accidents and potentially loss of life. We compare the results of well-resolved large-eddy simulations (LES) at laboratory scale, with solutions of the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations with three turbulence models, and also with LES in which the wall layer is modelled (WMLES), using the Delayed Detached Eddy Simulation (DDES) approach, or employing approximate boundary conditions. The URANS solutions do not yield a reliable prediction of the development of the azimuthal vortices (a well-known shortcoming of most eddy-viscosity turbulence models in this type of configuration), while the WMLES and DDES predict vortex decay in good agreement with the resolved LES data. Simulations at a Reynolds number higher by a factor of 20 (intermediate between the laboratory scale and the real configuration) were also carried out. All the simulation methods predict very little effect of the Reynolds number: the flow appears to be driven by the evolution of the large-scale embedded vortices. The trends are the same observed at laboratory-scale: the RANS turbulence models predict a much faster decay of the embedded vortices compared to the WMLES and DDES. The need for reliable experimental data is highlighted.

Keywords: helicopter brownout, impinging jet, vortex dynamics, RANS, WMLES

1. Introduction and Motivation

When a helicopter hovers near the ground, the wake of the rotor is a downward-directed jet that impinges on the ground and spreads radially, forming an axisymmetric wall jet. Coherent helical vortices generated at the rotor tip are embedded into the jet, and vortex sheets generated by the inner part of the blade occur inside it. The rotor-tip vortices are convected towards the ground by the rotor wake, and interact with the turbulent flow near the solid boundary [1]. Their passage may produce localized adverse pressure gradients in the wall region, and local separation [2]. The vortex passage also induces strong localized downwash and upwash velocities, which are intensified when two vortices pair. An undesirable effect of this phenomenon is the lifting up of sand particles that may be entrained in the wake and affect the pilot's visibility ("helicopter brownout"). When the helicopter lands on snowy ground, similar events occur, but are referred to as "helicopter whiteout". These phenomena may results in considerable damage to the aircraft, and sometimes loss of life [3]. Their mitigation requires detailed understanding of the physics of the wall layer, and of the particle transport.

A laboratory-scale visualization of the flow field that causes this phenomenon is shown in Figure 1*(a)*. As they reach the ground, the rotor-tip vortices lift up fluid from the near-wall region. This entrainment is associated with low shear stress and pressure, and liftup of solid sediment. The vortices then decay as they are convected along the wall.

The flow field generated by a rotor hovering near the ground is quite complex: the Reynolds number Re_D (based on the rotor diameter and the downwash velocity) is very high, of order $10^7 - 10^8$, the blades rotate and generate helical vortices, and sediment is lifted up and transported in the axisymmetric wall-jet. For this reason most models used to predict helicopter brownout (reviewed in detail in [4]) use very strong simplifying assumptions; typical approaches use an inviscid-flow approximation, in which the wake of the rotor is modeled using vortex filaments. The flow induced by the wake and by the vortices, which move downward and impinge on the ground, is used to determine the particle liftup and transport. However, the strong interaction between the turbulent flow in the impingement region and the vortices is likely to result in a significantly different vortex development than that pre-

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