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Comparison of two methods simulating highly resolved atmospheric turbulence data for study of stall effects

Christoph Knigge [a,*], Torsten Auerswald [b], Siegfried Raasch [a], Jens Bange [b]

[a] Institute of Meteorology and Climatology, Leibniz Universität Hannover, Germany
[b] Center for Applied Geoscience, Universität Tübingen, Germany

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ABSTRACT

We compare two different methods that provide highly resolved three-dimensional turbulent wind fields for numerical investigations of stall effects. The first is computationally very expensive and explicitly simulates the turbulent wind fields using large-eddy simulation (LES). The second method generates synthetic three-dimensional turbulent wind fields from one-dimensional time series data from flights in the atmosphere. The synthetic method is comparatively fast and cheap but reproduces only statistical features of the turbulent flow.

Since the focus in this study lies on the two methods by themselves, data generation is based on the same numerical simulation. The synthetic fields were generated from time series data obtained from virtual flight measurements within the LES. Different meteorological scenarios were analyzed in order to examine the influence of the different driving forces on the results.

Horizontally averaged turbulence parameters of the compared fields are in good agreement. Parameters are independent of height in the synthetic flow fields since the time series used for the generation do not contain height information. In the case of a stably stratified boundary layer, the velocity fluctuations have a near-Gaussian distribution and are therefore well-reproduced by the synthetic method. Although provided with the time series, the synthetic flow fields cannot generate the non-Gaussian distribution of the vertical velocity in case of the analyzed convective boundary layers. Angles of attack of a virtual airplane calculated with the vertical velocity of wind fields generated with the two different methods show large differences. The consequences of these findings for applications will be investigated in a future study by numerical simulation of the flow around wings initialized with the different velocity fields.

1. Introduction

In aviation, a stall describes a flow condition where a certain critical angle of attack (stall angle of attack) leads to a separation of the flow from an airfoil and thus to a decrease in lift. Especially during landing, the risk of stall limits the range of safe aircraft flights. Thus, the value of the angle of attack along the flight path of an aircraft is important for the investigations of stall effects (see e.g. [1,2] for a detailed description of the physics of stall).

A better knowledge of the angle of attack and stall limits is an important task to optimize air traffic. For example, it may allow for lower aircraft speed, which reduces noise and may allow for more flights. Moreover, the investigations on stall effects require numerical simulations of the flow around wings and nacelles, due to the high risk and cost of real flight experiments. For these investigations, it is essential to initialize computational fluid dynamics (CFD) models with atmospheric turbulence data. The rapidly changing turbulent flow in the atmospheric boundary layer (ABL) may strongly affect the stall of aircraft. Turbulence is highly influenced by the surface heterogeneity and radiation which is in turn controlled by clouds and the diurnal cycle. The ABL ranges in height from some hundred meters to 2–3 km. The turbulence is usually non-Gaussian distributed, and coherent structures develop which strongly depend on height (e.g. [3]).

Usually, the numerical models used for the simulation of flows around wings and nacelles provide atmospheric data only with the help of statistical models (e.g. [4–6]). These statistical models mostly use a Dryden or von Kàrmàn velocity spectrum where only two parameters control the generated turbulent flow. Therefore, they cannot account for the complexity of real atmospheric turbulence within the ABL.

* Corresponding author at: Institute of Meteorology and Climatology, Leibniz Universität Hannover, Herrenhäuser Straße, 30419 Hannover, Germany.
E-mail address: knigge@muk.uni-hannover.de (C. Knigge).

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The purpose of this study is to compare two different methods that produce highly resolved three-dimensional atmospheric turbulent wind fields. The first method uses large-eddy simulation (LES) and explicitly simulates three-dimensional turbulent wind fields of a realistic ABL; hereafter named the LES method. The second method generates synthetic three-dimensional fields using statistical quantities. These quantities can e.g. be derived from one-dimensional horizontal flight measurements (time series data) in the atmosphere. Hereafter, this procedure is named the synthetic method. It was discussed in detail by Auerswald et al. [7], who used the synthetically generated flow field to initialize an LES model capable for the simulation of the turbulent flow around a wing.

With the LES method presented here it is possible to simulate turbulent flows that typically occur in the lower atmosphere. High-resolution simulations with the LES model which contain turbulent structures affecting wings are computationally very expensive. In contrast, the synthetic method is comparatively fast. It uses a huge database of different meteorological scenarios collected during various flight experiments all over the world, but it reproduces only statistical features of the atmospheric turbulent flow. Hence, the main objective is to determine the differences in wind fields generated by these two methods. Ideally, the synthetic method as well as the LES method should produce wind fields that show the same features of the ABL, in case the same meteorological conditions are considered.

Since we want to investigate the methods by themselves we replaced the real flight measurements used for the synthetic method by virtual flight measurements that were carried out within the simulated wind fields of the LES (see also [20]). This allows us a more precise comparison of the LES and the synthetically generated wind fields because all results are based on the same data set. Hence it is possible to verify the synthetic method as well as to point out differences between both methods. Three different meteorological scenarios (free-convective, convection- and shear-driven, stably stratified) were simulated to cover different kinds of atmospheric flow conditions within the ABL and to analyze how they affect the results. Although the turbulence which can be expected in case of a stable stratified boundary layer may only play a minor role for stall of aircraft, this meteorological scenario was also investigated to cover the full range of typical meteorological boundary layer conditions and their reproducibility with the synthetic method.

This paper is composed as follows: the next section introduces the LES method. The applied LES model and the setup of the selected meteorological scenarios are described. Section 3 specifies the generation technique of the synthetic method. Furthermore, the approach of the virtual flight measurements is explained and the statistics of the virtual time series data required for the generation of the synthetic fields are analyzed. Section 4 presents and discusses the results of the comparison for each meteorological scenario. In Section 5 the results are summarized.

2. LES method

The LES method explicitly simulates highly resolved three-dimensional realistic wind fields of the ABL. The resulting wind fields have to fulfill two conditions in order to be used as initial state for a CFD-model for investigations of stall effects. First, the LES fields require a resolution which is fine enough to resolve turbulent elements which have an influence on aircraft flight characteristics. That means, that the resolved turbulence elements must be at least one order of magnitude smaller than the typical wing span of commercial aircraft (30–80 m, resulting grid spacing $\leqslant 2$ m). Second, the model domain has to be large enough to allow the development of the most important range of turbulence scales which usually occur in a realistic ABL (domain size of about 2 km^3 or larger). Both requirements result in a extremely large number of gridpoints ($\geqslant 10^9$). After introducing the applied LES model, the three meteorological scenarios, their setups and their boundary conditions are explained in detail. The approach of the virtual flight measurements carried out within the LES is presented in Section 3.

2.1. PALM – a parallelized LES model

The study presented in this paper uses the **pa**rallelized **L**ES **m**odel PALM developed by Raasch and Schröter [8]. It is a model for the atmospheric or oceanic boundary layer and was applied in former studies of e.g.: thermally induced oscillations in the CBL [9]; roll convection during a cold air outbreak [10]; or the urban canopy layer from street canyon to neighborhood scale [11]. PALM is written in Fortran 95 with single processor optimization for different processor architectures and uses MPI and/or OpenMP for parallelization.

It calculates the non-hydrostatic, incompressible Navier–Stokes equations in Boussinesq form, the 1st law of thermodynamics, and equations for subgrid-scale (SGS) turbulent kinetic energy (TKE) and scalar conservation. The equations are discretized using finite differences, and are filtered implicitly following the volume-balance approach [12]. Turbulence closure uses the 1.5th order Deardorff [13] scheme. Variables are staggered according to the marker-and-cell method/Arakawa C grid [14,15]. Advection scheme is the second-order Piacsek-Williams scheme [16] and time integration uses the 3rd-order Runge–Kutta scheme. Incompressibility is ensured by the fractional-step method, and the resulting Poisson equation for the perturbation pressure is solved by using FFT.

The lateral boundary conditions are cyclic. At the lower boundary no-slip conditions are used with the assumption of Monin–Obukhov similarity between the surface and the first computational grid level. A constant roughness length in all simulations is applied ($z_0 = 0.1$ m).

2.2. Setup of the three scenarios

Three meteorological scenarios were selected, which are each driven in three different ways, and have different influences on the stall of the aircraft. The first scenario is a buoyancy-driven convective boundary layer (CBL). The free convection is caused by a homogeneously heated surface. No mean background wind is present. This first scenario represents a typical meteorological condition of a mid-latitude high pressure situation over a homogeneous surface. The strongest turbulent elements in this CBL lead to vertical velocities up to $w = 8$ m s^{-1}. The second scenario is an extension of the first. In addition to buoyancy, it is driven by wind shear caused by a moderate geostrophic wind of $u_g = 5$ m s^{-1} (westerly) at the top of the boundary layer. The third scenario is a shear-driven stably stratified boundary layer (SBL). It is also known as nocturnal boundary layer (NBL). Although only weak turbulence occurs in this scenario due to the damping characteristics of the stable stratification, we chose it for an extensive comparison of the two turbulence generation methods at different meteorological conditions. All three scenarios were simulated over a period of 6 h to determine the statistical properties accurately. After 1 h, each flow reached a quasi-stationary state which meant that averaged turbulent quantities of the flow did not change much in time and the boundary layer growth rates of the CBLs were small. Data extracted during this state, were used for virtual measurements and statistical analysis.

For the first and the second scenarios, model domain sizes of $4 \times 4 \times 1.7$ km^3 and a grid resolution of 2 m were used. The vertical