Characterization of wind gusts using a large eddy simulation model

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Abstract

During the design process of aircraft, it is of utmost importance to consider the influence of atmospheric turbulence on the flight characteristics. Strong loads are caused by isolated wind variations from the mean wind flow, what is also known as wind gusts. Existing one-dimensional analytical models describing discrete gust events of the small scale atmospheric turbulence are based on very simple approximations such as the one-cosine-law. The aim of this study is to characterize gusts by amplitude, form and spatial expansion. High resolution large eddy simulations (LES) were carried out to simulate the turbulent flow of the atmospheric boundary layer in a fine spatial resolution adequate for aircraft design studies. Virtual wind measurements from instantaneous flow fields of the LES at different altitudes provide data to analyze the one-dimensional structure of existing gusts. In comparison with previous analysis of gusts by aircraft and mast measurements the approach of the LES also yields the opportunity to analyze the height dependence of the gust characteristics within the complete boundary layer.

Results show significant differences compared with the classical one-cosine shape. These differences as well as the dependence on height and gust size is considered in a simple mathematical approach presented here. For each velocity component this gust shape formula shows a good agreement with the gust shapes obtained from LES data.

Nomenclature

A	Amplitude [$\mathrm{m\,s^{-1}}$]
A_{min}	Minimum Amplitude [$\mathrm{m\,s^{-1}}$]
k	Gust length depending variable
k_h	Gust height depending variable
k_u	Velocity component depending variable
t	Time [s]
T	Duration period of a gust [s]
u	Streamwise velocity component [$\mathrm{m\,s^{-1}}$]

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u	Scaled streamwise velocity component [$\mathrm{m\,s^{-1}}$]
v	Spanwise velocity component [$\mathrm{m\,s^{-1}}$]
v^*	Scaled spanwise velocity component [$\mathrm{m\,s^{-1}}$]
w	Vertical velocity component [$\mathrm{m\,s^{-1}}$]
w^*	Scaled vertical velocity component [$\mathrm{m\,s^{-1}}$]
x	Streamwise Cartesian component [m]
x^*	Scaled streamwise Cartesian component [m]
y	Spanwise Cartesian component[m]
z	Vertical Cartesian component[m]
z_0	Roughness length [m]
θ	Potential temperature [K]
τ	Gust length [m]
∂	Partial derivative

1 Introduction

Atmospheric turbulence has a significant influence on flight behavior of aircraft. Variations in the wind compared to the quasi-steady mean wind field lead to gust loads which can be subdivided into fatigue loads caused by the continuous turbulence and maximum loads due to single gust events. The latter can be described in form, amplitude and duration by discrete gust models (e. g. Hoblit [1]). An often used approximation is the one-cosine law which is described in the Federal Aviation Regulations for Transport (FAR Part 25 [2]). This gust shape approximation was introduced by Pratt and Walker in 1954 [3] and has been for the last decades in aircraft design processes. The common time depending formula for the used one-cosine-law can be written as:

$$u(t) = (A/2)(1 - cos(2\pi t)/T)\;, \tag{1}$$

with A as amplitude and T as duration period. Assuming that the frozen turbulence hypothesis is applicable, the spatial extension can be calculated by replacing time with the stream-wise component in space. The reasons for using equation 1 as approximation for gust shapes are its simple mathematical description and usefulness in practical application of loads calculations, on the one hand. On the other hand, there are limited possibilities to get data from measurements showing the total complexity of the structure of the turbulence. Previous investigations often used long term meteorological mast measurements at typical heights up to 100 m or 150 m which show one-dimensional time series of the horizontal velocity amount (e. g. Camp [9]; Kristensen [4]). Flight measurements which provide data from higher altitudes however show only short term velocity fields from single flight legs (Sleeper's measurements e. g. [11] have a duration of less than five minutes).

The approach of using LES data for gust analysis is new and gives the opportunity to examine single gust events in the entire atmospheric boundary layer within predefined meteorological conditions. Previous analysis of the turbulent structure of the boundary layer have shown that the used model PALM is very suitable for these investigations (e. g. [5]). The mean gust shape (average over several gusts) depending on the altitude and spatial extension is examined as well as the frequency of its occurrence. All three components of the velocity vector are considered to get a good overview of the existing discrete gusts in the complete wind field.

This paper is organized as follows: A short description of the numerical and analysis methods is followed by the results which primarily show the mean gust shape obtained from the LES data. At the end the conclusions containing a short outlook complete this article.

2 Numerical method and data processing

To perform numerical simulations of the atmospheric turbulence and, hence, wind gusts a numerical model which resolves the corresponding scales of the turbulence is necessary. The model used for the investigation presented here is the **PA**rallelized **L**arge eddy simulation **M**odel (PALM) which has already been used for previous analysis in the framework of this project (FOR 1066). Simulation results of the structures of the turbulent atmospheric boundary layer in comparison with data from field measurements are summarized in [5]. A short description of the LES model PALM is given in subsection 2.1. The second subsection of this chapter describes the methods of analyzing the data output from PALM.

2.1 PALM - parallelized LES model

The LES model PALM used for this study has been developed at the Institut für Meteorologie und Klimatologie at the Leibniz Universität Hannover since the early 1990s [6] [7]. PALM is written in FORTRAN 95 and uses MPI and/or OpenMP for parallelization. PALM is applicable to simulate the atmospheric or oceanic boundary layer. It is based on the the filtered non-hydrostatic, incompressible Boussinesq equations, the first law of the thermodynamics and the equation for turbulent kinetic energy (TKE). Incompressibility is assured by solving a Poisson equation for the perturbation pressure using fast Fourier transformation (FFT). Subgridscale (SGS) turbulence is parametrized according to Deardoff [8]. Advection scheme used is a 5th order Wicker-Skamarock.

The equations are discretizised using finite differences method. Time step scheme is a third order Runge-Kutter. The variables are calculated on a staggered Arakawa C grid. Boundary conditions are cyclic in lateral directions, Monin-Obukhov similarity is assumed at the bottom and Dirichler conditions at the top of the model area.

2.2 Setup

One typical meteorological scenario causing intensive turbulence and hence large amplitude wind gusts is a stormy low-pressure system. Since the limited computational resources make it currently impossible to perform a simulation of a complete low-pressure system with a LES, only the lowest several hundred meter near the ground were simulated. In this part of the atmosphere the turbulence due to intensive wind shear caused by the high magnitude of the along wind component and the friction at the bottom is of great importance for flight behavior. To simulate the situation described above, the following numerical setup was used:

An initial profile of the potential temperature is given at the beginning of the simulation. Neutral conditions up to 700 m are followed by an inversion with a gradient of $\partial\theta/\partial z = 2\,\mathrm{K}/100\,\mathrm{m}$. The stream-wise geostrophic velocity component is set to $30\,\mathrm{m\,s^{-1}}$ which leads to strong mean wind and stormy gusts at ground level (10 m) comparable to a stormy low-pressure system. An inversion, which is not typical in such meteorological conditions is necessary due to the limited computing resources mentioned above. The vertical grid is stretched from 800 m up to the total height of the model domain 1800 m. The horizontal length scales are 2000 m in both directions. With a grid resolution of 2 m a total number of $1023 \times 1023 \times 448$ grid points is reached. The roughness length z_0 is set to 0.5 m which corresponds to a suburban area and represents a possible airport surroundings.

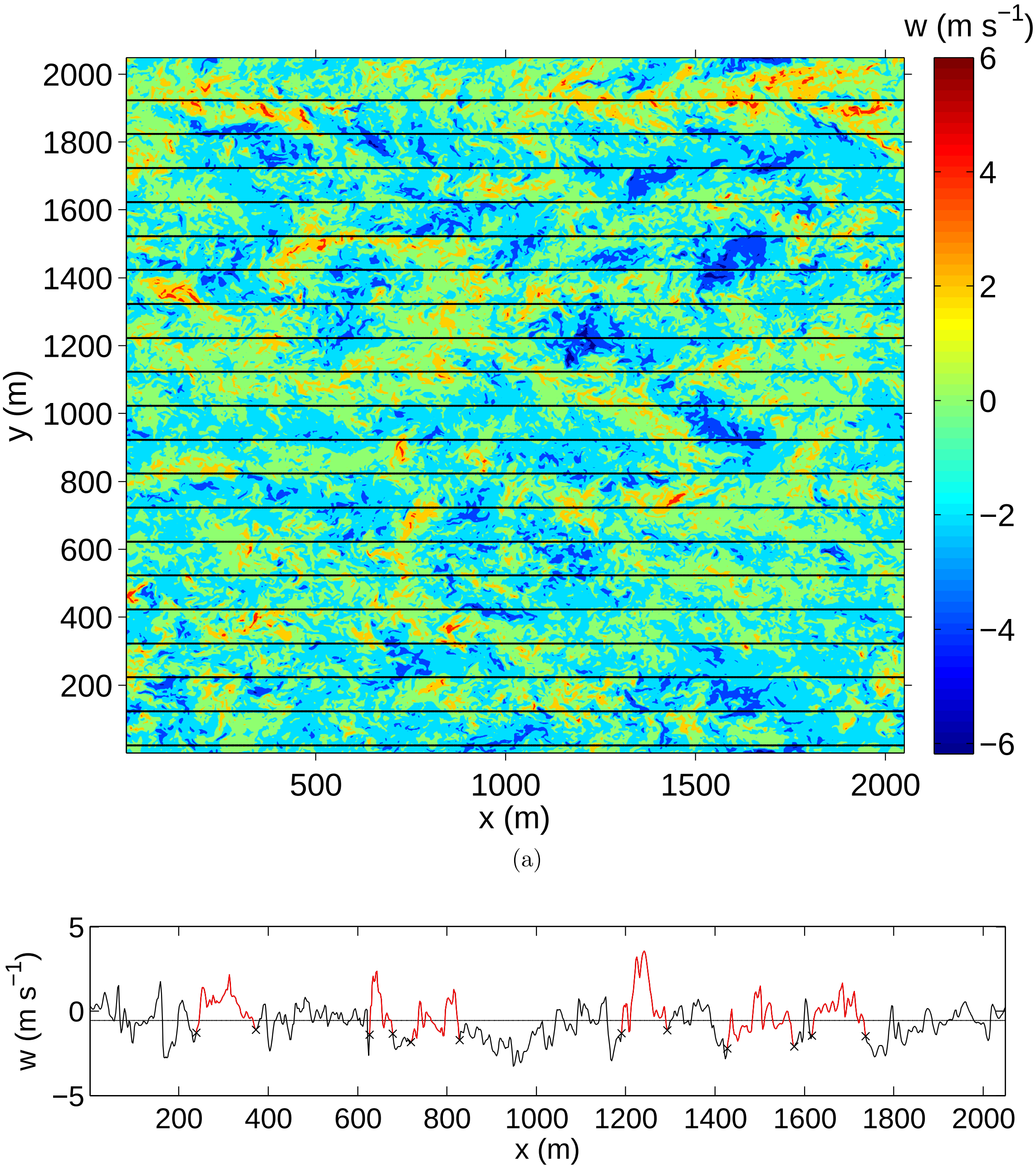
The simulations have been carried out at the HLRN (North-German Supercomputing Alliance) on the SGI Altix ICE2 system. The simulated time period of three hours took about 2.7 days of CPU time on 1024 processors.

2.3 Methods of analysis

To get one dimensional information of gusts from the time depending three dimensional simulation, one can either extract time series at fixed points during the simulation or do virtual measurements in instantaneous velocity fields which depend on space. The latter way was chosen for the investigation presented here. The reasons for this are the practicability on the one hand. The instantaneous flow fields are part of the default output in PALM. On the other hand these direct "snapshots" of the turbulent status of the boundary layer need no application of the Taylor hypothesis to get information of the spacial dimensions of the gusts like it is often made in local time depending measurements in nature. To consider the height dependence of the gusts, instantaneous x-y-planes at different altitudes have been cut out which contains the information of all three velocity components. These have been extracted along 20 paths parallel to x-axis. An example can be seen in figure 1a, where the vertical velocity field after one hour simulation time in $z = 100$ m is shown. The paths of the virtual measurements are visible by the horizontal black lines. Figure 1b shows the vertical velocity w along the lowest path at $y = 23$ m. The discrete gusts which are included in the statistics presented in the next section are plotted in red. The beginning (or starting point) and the end of each gust (end point) are marked with crosses. All gusts of the different heights and velocity components fulfill the following criteria:

- The minimum difference between the maximum value and the starting point (minimum amplitude: A_{min}) is $3\,\mathrm{m\,s^{-1}}$.
- The gust length is between 25 m and 150 m.
- The minimum value between the starting point and the gust end point is larger than the starting point value.
- The difference between the end point value and the starting point value is less than 10% of A_{min}.

These steps of extracting gusts are similar to those of Camp [9] except that Camps gusts have been calculated relative to a mean velocity value of short term series (2 min.). Differences in the method like different values of A_{min} ($A_{min} = 0.5\,\mathrm{m\,s^{-1}}$ at Camp) and the duration period which is comparable to the spatial expansion used can be explained by the method of collecting data. Camp's analysis of long term series of mast measurements contain the complete range of possible meteorological scenarios at the observed area. Hence his method of extracting gusts is adapted to these measurements. Camp's gust definition relative to the mean wind was not applied here because this method cut parts of the gusts below the mean value which are in our opinion not insignificant (see figure 1b, the mean wind is shown by the black line). Further approaches of extracting gusts from a velocity signal are summarized in Kristensen [4]. Mostly, the main criteria are a minimum amplitude and a time or length range for a definition as applied here.



(a)

(b)

Figure 1: Example of gust extraction from the horizontal velocity plane. In (a) the horizontal black lines show where the data were extracted from the instantaneous horizontal x - y plane of the vertical velocity. The velocity w obtained from the lowest black line in (a) is shown in (b). The single gusts obtained are marked in red. Crosses indicate the starting and end points of each gust (see text for more information about the gust extraction process).

All gusts obtained using the definition above were classified into different gust lengths between the minimum and maximum length listed above at point two. Class intervals are 25 - 50 m, 50 - 75 m, 75 - 100 m, 100 - 125 m and 125 - 150 m. The total range has been chosen to capture gusts affecting a civil aircraft of the typical length scale of about 30 m (like the Airbus A320).

After classifying all gusts, a mean gust shape has been calculated for each gust length class. Therefor each single gust has been scaled in the length before ($x^* = x/\tau$, with τ as gust length). A scaling in the gust amplitude has been done after averaging the data of all gusts ($u^* = u/A$, $v^* = v/A$ and $w^* = w/A$).

3 Results

In order to generate a sufficient amount of gusts, 19 instantaneous x - y cross sections were generated and gusts as determined by the procedure described in the section before were calculated. Based on visual inspection of the results, we estimated that more than about 50 gusts are needed to obtain a adequate convergence in the mean gust shape. A frequency distribution of gusts of the three velocity components can be seen in Figure 2, where the total number of gusts is shown in some selected altitudes. Each column is additionally partitioned into the different length scales of the gusts. Above an altitude of 200 m (u - component) respectively 300 m (v - and w - component) the amount of the smaller gusts reaches the critical value of about 50. (Remember, the initial inversion height is at 700 m). Due to entrainment, a gradually stabilization of upper part of the boundary layer occurs. For this reason no higher altitudes than 500 m and no longer simulation than 3 h have been performed. At lower altitudes than 500 m, the total amount rises exponentially. Up an altitude of 100 m nearly the same number of gusts is visible for each class and height (see Figure 2). Above this altitude, a significant reduction of smaller gusts compared to the longer gusts occurs.

The distribution of the classes is concerned with the freely chosen value of A_{min}. Not shown here but visible in data is that for lower minimum amplitudes, the ratio of small to large gusts is rapidly increasing. A greater number of small or short gusts was also observed by Camp [9]. As mentioned above his minimum amplitude has a value of $A_{min} = 0.5\,\mathrm{m\,s^{-1}}$. Since the focus in this study lies on large-amplitude gusts affecting aircraft, the value of A_{min} was chosen to be larger than $0.5\,\mathrm{m\,s^{-1}}$ but small enough get a sufficient amount of gusts (50 or more gusts) of each class for a good statistic.

The calculated mean gust shapes show significant differences depending on the gust length, the altitude and the velocity component (see Figure 3). In Figure 3 the three heights 30 m, 100 m and 300 m (starting from the bottom) and the velocity components u, v and w (from left to right) are presented. (For a better orientation, the middle of the length scale is marked with a dotted vertical line and the one - cosine gust shape from equation (1) is shown.) In each Figure, larger gusts tend to have a sharper increase and decrease as well as a longer, partially constant middle section compared to the shorter gusts. This is particularly visible in Figure 3i, where nearly 80% of the total gust length of the longest gust has a constant middle part. Starting from Figure 3i, this trapezoidal of longer turns into a much more rounded form by going to greater altitudes and the other two velocity components. Especially for the u - component the shortest gusts (25 m - 50 m) agree best with the one - cosine shape. A further remarkable characteristic of the gust shapes in Figure 3 is a slight asymmetry visible in the leaning of the curves to the right. It is the most distinctive in the short gusts of the u and w component of the lower altitudes (see Figure 3d, f, g, i).

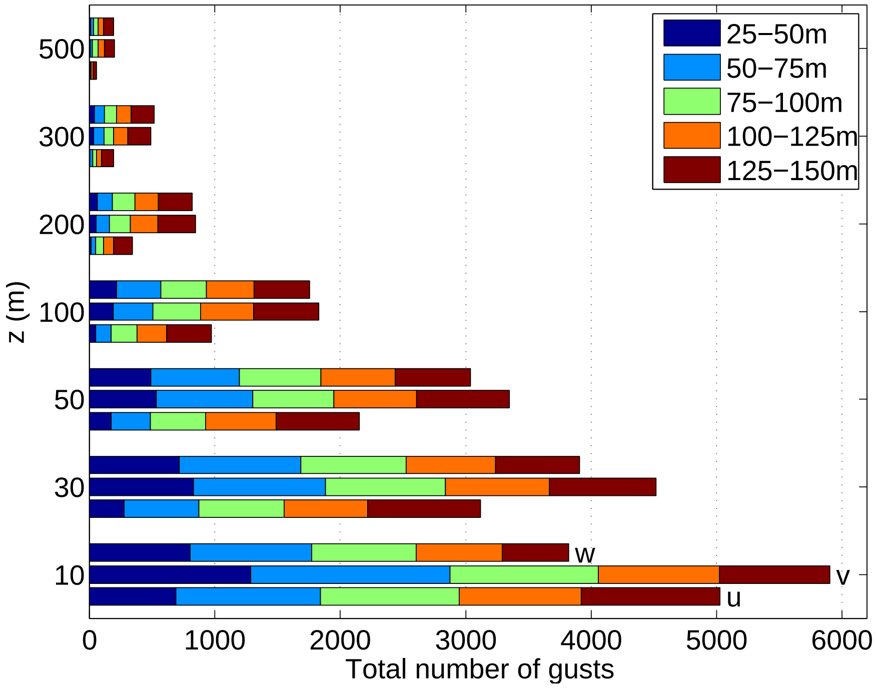


Figure 2: Frequency distribution of gusts extracted from altitudes up to 500 m and velocity components u, v and w. Different gust classes are color coded.

In aircraft design, gust are generally described by the one-cosine law (see eq. 1). As pointed out above, the gust shapes calculated from LES data show a distinctly different form, especially the larger gusts. An other approach describing gust shapes proposed by Frost [10] based on the data from Camp [9] considers these differences better. As the asymmetry in the shown gust shapes is not as strong as in the gusts observed by Camp [9], the mathematical description of Frost [10] has been slightly modified. The new suggested gust shape is:

$$u(x^*) = 1.58(1 - \exp(-\sin(\pi x^*)^k)) \ , \tag{2}$$

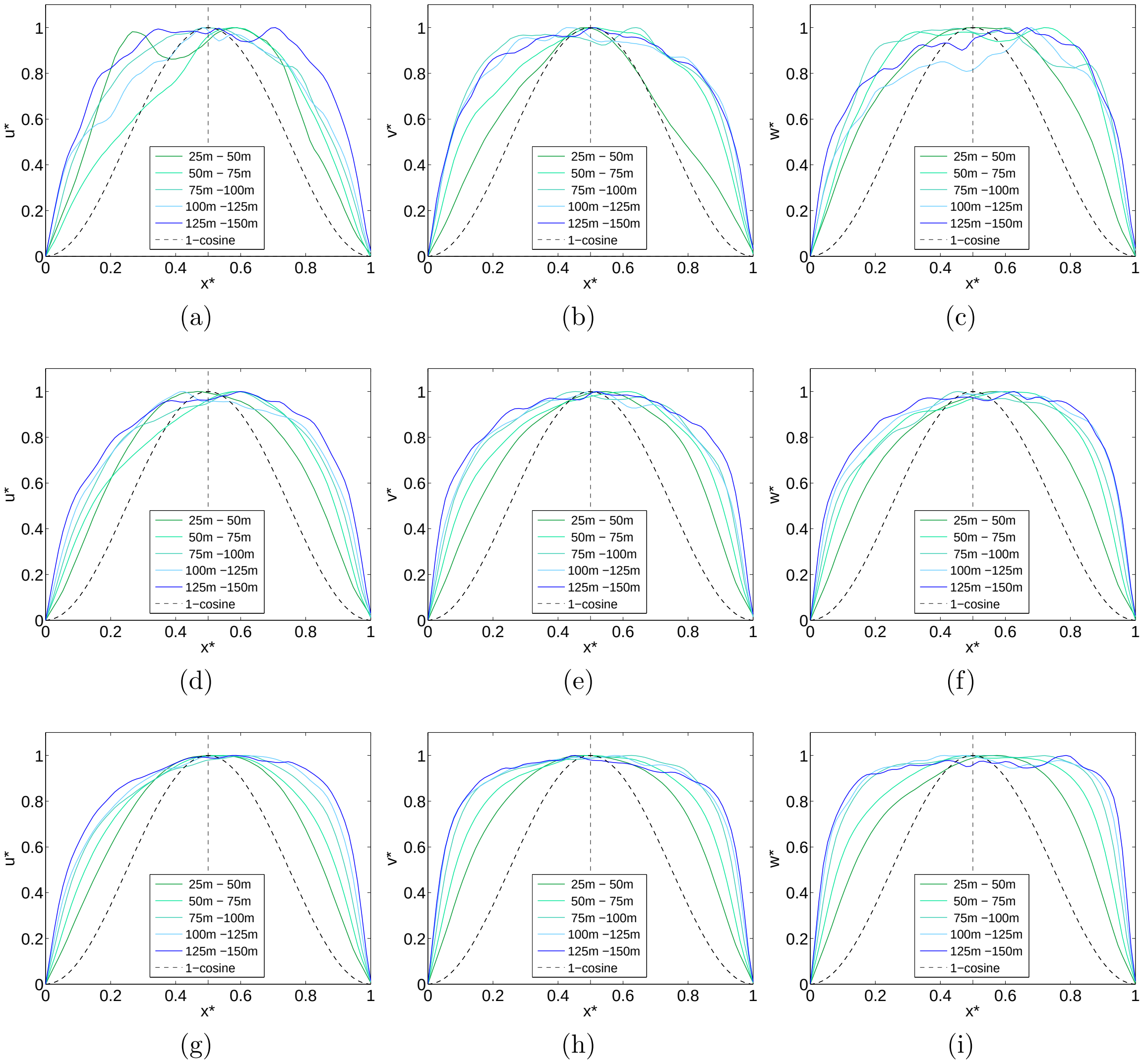
with k as a gust length depending variable for each velocity component:

$$k = 1/(k_h \tau) \ , \tag{3}$$

k_h is calculated as follows:

$$k_h = k_u + 1/50 \ln(z) \ , \tag{4}$$

where τ is the length of the gust in meters. For the different velocity components u, v and w the constant k_u hast the value 0.008, 0.014 respectively 0.016. The reasons for modifying the original gust shape formula of Frost [10] are that there are some significant differences between the measurements of Camp [9] where the Frost formula is based on and our virtual measurements. As already mentioned, Camps long term series contain all meteorological scenarios occurring in that area (the mast stands in Florida at the Kennedy Space Center). The gust definition of Camp is different to our (especially the value of A_{min} see text above) and the measurements were made with cup anemometers so that only the amount of the horizontal velocity was obtained. Since Figure 3 shows clear differences between the velocity components, the application of the exact mathematical concept seems to be impossible for our results. The main characteristics considered in equation 2 compared to the original formula of Frost are the



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 3: Mean gust shapes of the three velocity components u (a), (d), (g), v (b), (e), (h) and w (c), (f), (i) at different heights of 30 m (g), (h), (i), 100 m (d), (e), (f) and 300 m (a), (b), (c). The fife gust classes are colored and the one-cosine gust shape is dotted.

differences in the gust classes, the differences in the velocity components and the less distinctive asymmetry in the gust shapes obtained from our LES.

For a comparison of the modified gust shape formula with the results obtained from the LES four selected gust shapes of Figure 3) are compared with the corresponding analytical shapes using formula (2) (see Figure 4). The examples are the stream-wise horizontal velocity and the vertical velocity in altitudes of 30 m respectively 100 m. They show the differences pointed out above the most distinctive (like a broader form of the w - component gust shape compared to the u - component as well as the expansion in form depending on the gust length). Both characteristics are well reproduced by the analytical description. Slight differences are visible in the asymmetric form of the gusts from the LES data. The left half of the gust shapes is a bit overestimated, while the right part is rather underestimated.

A modification of equation (2) considering the asymmetry is possible but has not been done yet.

4 Conclusion

Wind gust characteristics, in particular mean gust shapes of all three wind components, have been extracted from a three-dimensional large-eddy simulation. The LES data provided a sufficient amount of gusts to obtain a good statistic up to a height of about 300 m.

Mean gusts shapes show differences depending on the spatial dimension as well as depending on the altitude in each velocity component. Compared to the simple one-cosine form all presented gusts show a broader form with a steeper increase and steeper decrease. The middle part is, depending on the wind component and altitude, rather narrow or constant over a length up to 80% of the gust size.

The analytical approximation proposed is based on a suggestion of Frost [10] but modified to consider the gust class and the altitude of the scaled gust shapes. Asymmetries are not considered yet. Nevertheless the resulting mean gust shape formula shows a good agreement with the mean shapes measured in LES data.

The method of using LES data to investigate discrete gusts was a new approach which shows good results for the one dimensional gust shape presented here. A further advantage of the LES data is that they are three dimensional in space, so that the next step is to examine the two or three dimensional gust shape. Asymmetric forms as observed in the one dimensional gust shapes may be caused by the magnitude of the along wind component and seems to appear only in the along wind direction. In addition, the two-dimensional spatial gust shape could show the maximum velocity gradients which can be expected over the span-wise expansion of an aircraft flying through such a gust.

Acknowledgments

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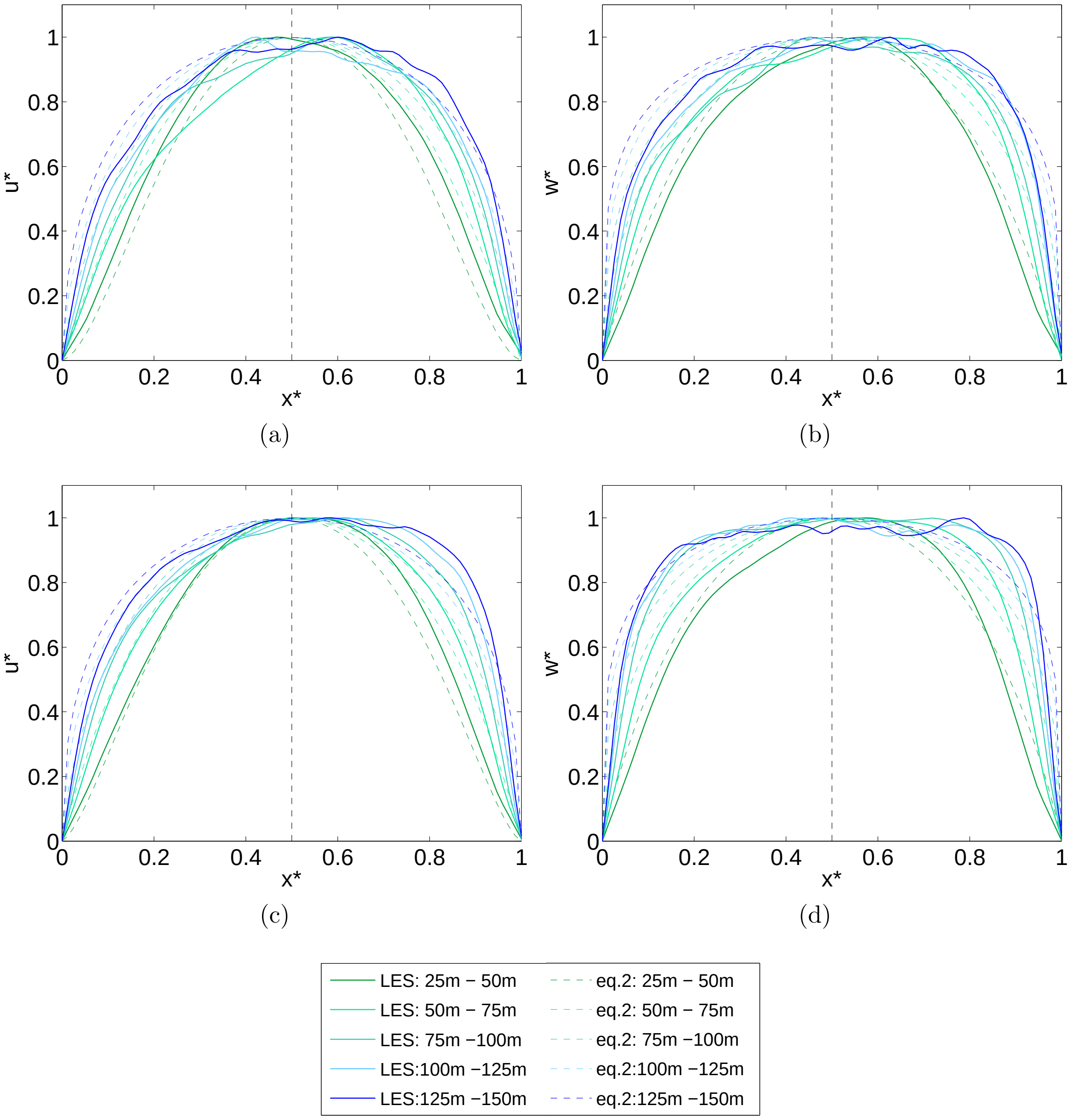

Figure 4: Comparison of mean gust shapes obtained from LES (solid lines) and equation 2 (dotted lines) of the velocity components u (a), (c) and w (b), (d) at different heights 30 m (c), (d) and 100 m (a), (b). The fife gust classes are colored.

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