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ORIGINAL PAPER

Estimating the turbulent energy dissipation rate in an airport environment

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Abstract This note reports on the influence of aircraft wake vortices on the estimation of the turbulent energy dissipation rate using sonic anemometer measurements near the runway threshold. The wake vortex traces, which are generated at a height of about 65 m and subsequently evolve in ground effect, are clearly visible in the velocity components and temperature. The observed temperature increase of 1 K appears related to the stably stratified atmospheric surface layer. The dissipation rate is estimated from the longitudinal velocity power spectrum for a sample in a nocturnal boundary layer with and without a wake vortex signal. In both cases an inertial subrange is found. For the analyzed sample the estimated dissipation rate is a factor of ten larger compared to the undisturbed sample. Implications for operational wake avoidance systems are discussed.

Keywords Airport · Sonic anemometer · Turbulent energy dissipation rate · Wake vortex

1 Introduction

Already existing and expected capacity limits at major airports have triggered research towards reducing separation of approaching and departing aircraft (for an overview on wake vortex research, see Gerz et al. 2005). Up to date fixed separation distances are prescribed to aircraft in order to avoid wake vortex encounters. The aircraft wake vortex consists of two counter rotating vortices whose strength is dependent on the weight, span and speed of the aircraft. Wake vortices descend due to their mutually induced downward velocity. The International Civil Aviation Organization (ICAO) has proposed three aircraft weight categories with respective separation distances

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depending on the leading and following aircraft. Those separations have proved to be safe and often are considered as over-conservative (Frech and Zinner 2004). It appears that there is potential for a safe reduction of separation distances that, however, requires that the transport and decay of wake vortices out of the glide path corridor have to be predicted.

The decay of aircraft wake vortices is governed by atmospheric turbulence, static stratification and wind shear. In principle, the decay process of wake vortices in a turbulent or stratified environment is well understood (Holzäpfel 2003). The demise of wake vortices due to turbulence is best parameterized in terms of the turbulent energy dissipation rate (EDR, Sarpkaya 2000; Holzäpfel 2003). The correlation of turbulent kinetic energy and vortex demise time is weak because large eddies, which contribute most to turbulent kinetic energy, do not represent the optimum length scale for triggering perturbations of the wake vortex pair, with subsequent onset of rapid decay due to instability mechanisms. More important for operational applications, the reliability of turbulent kinetic energy estimates is very much dependent on the choice of the averaging interval in time and space in order to capture all relevant turbulent length scales, in particular the energy containing large eddies. Dissipation rate estimates in this context are more robust. Dissipation rate estimates from measurements are usually obtained from velocity power spectra applying Kolmogorov's theory of a universal spectral slope in the inertial subrange. The inertial subrange represents length scales that have better sample statistics compared to turbulence production scales. Reliable EDR estimates from spectral methods using sonic anemometer data can be obtained even under nonstationary conditions (Piper 2001). Alternatively, the dissipation rate can be estimated by computing the second-order or third-order structure function in the inertial subrange (Katul et al. 1994).

A reliable estimate of the energy dissipation rate to predict wake vortex decay in an operational environment requires measurements of the atmospheric state in the airmass within which the wake vortex evolves (Holzäpfel and Robins 2004). This means that measurements have to be carried out in an environment that sometimes is challenging for micrometeorological and remote sensing instruments because of the land-surface heterogeneity of the airport environment, ground and air traffic, and due to the presence of wake vortices themselves.

Estimates of EDR from sonic anemometer data taken close to the runway threshold also serve as ground truth for remote sensing instruments and model predictions that provide profiles of eddy dissipation rate. Those profiles are used to predict the wake decay and transport along the glide path as part of a wake vortex prediction and monitoring system (Gerz et al. 2005).

The decay of wake vortices evolving in ground proximity is thought to have little or no dependence on atmospheric turbulence (Proctor et al. 2000). However, based on data from a recent wake vortex measurement campaign at Frankfurt airport, superior wake vortex prediction skill could be achieved using EDR estimated from 10-min samples of sonic anemometer measurements together with Sodar-measured wind profiles (Holzäpfel and Steen 2007). This forecast performance is based on the analysis of over 110 lidar-measured wake vortices from heavy aircraft. In general, the turbulence generated by the wake vortex interaction with the ground itself triggers the wake vortex decay process, which apparently is enhanced by atmospheric boundary-layer turbulence. In the Frankfurt data a somewhat degraded forecast performance is observed for some cases, which, after close inspection, seemed to be due to a dissipation rate bias. This bias can be attributed to vortices advected over the sonic anemometer introducing a source of turbulence additional to that of the natural atmospheric surface layer.

In this note, the effect of vortex traces on the computation of the energy dissipation rate will be investigated in more detail. A 30-min long sequence was measured in the early morning hours of 11 September 2004, just around the start of the morning traffic peak at Frankfurt airport. About 20 min of the sample represent measurements of an undisturbed nocturnal boundary layer before the first wake vortex is detected. Within the last 10 min of the sample five wake vortex traces can be identified from aircraft that landed on runway 25L. First, we give a brief introduction on how wake vortices typically evolve close to the ground. The overall structure and turbulence statistics are discussed for samples with and without wake vortices. The resulting dissipation rate levels and their representativeness for wake vortex prediction are analyzed. Implications for operational applications are addressed.

2 Wake behaviour in ground effect

A wake vortex pair descends due to a mutually induced velocity. The downward propagation velocity can be estimated as $w_0 = \Gamma_0/2\pi b_0$, with Γ_0, the root circulation of the wake vortex and b_0, the initial vortex spacing. The initial strength of a wake vortex, which is expressed in terms of the root circulation Γ_0, depends on flight speed, wing span, aircraft weight and air density . The characteristic time scale t_0 is the time it takes for a wake vortex pair to descend one vortex spacing. For a heavy aircraft b_0 and Γ_0 are on the order of 40 m and 400 $m^2\,s^{-1}$, respectively, and the descent speed is typical in a range of 1.5–2 m s^{-1}.

If the wake is roughly 1.5 wing spans above the surface, the wake starts to interact with the surface, i.e. it is in ground effect. In a kinematic framework, each vortex interacts with his image vortex causing a lateral divergence of the main vortex due to mutual velocity induction. Neglecting viscous effects, the main vortex finally would move parallel to the surface with the vortex core at $z = b_0/2$. In reality, the vortices induce a vorticity sheet at the ground surface that eventually detaches and rolls up to a secondary vortex. This secondary vorticity interacts with the main vortex causing a rebound. Depending on the crosswind profile, the rebound of the vortex pair can be asymmetric since the vorticity of the secondary vortices also interacts with the vorticity of the wind profile. In the presence of a crosswind, the upwind vortex systematically shows a weaker rebound compared to the downwind vortex (Holzäpfel and Steen 2007).

Typically, the wake vortices are disturbed in the atmospheric boundary layer causing a three-dimensional deformation of the coherent vortex where sections may link with the surface and others may rebound (Proctor and Switzer). Therefore, the vortex is often visible in all three velocity components when a wake vortex drifts over an anemometer close to the surface (Hallock et al. 2003).

3 Instrumentation and set-up

The measurements were taken during a wake vortex measurement campaign at Frankfurt airport during autumn 2004. A METEK SODAR DSDPA.90-64 with a 1290 MHz RASS and a USA-1 sonic anemometer at 10-m height were deployed close to

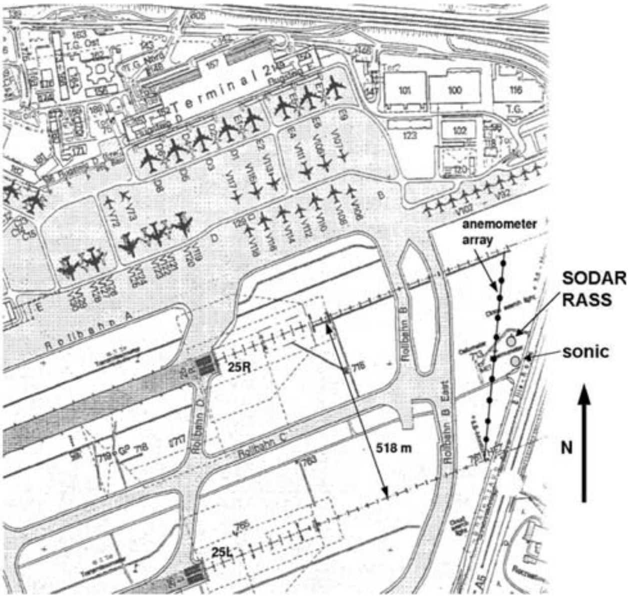

Fig. 1 Layout of sensor location near the thresholds of runway 25L/R. Also shown is the anemometer array operated by Deutsche Flugsicherung DFS

the thresholds of runways 25L and 25R (Fig. 1). The SODAR/RASS measurements provide 10-min averaged profiles of all three wind components and virtual temperature. The vertical resolution of the profiles is 20 m, and the first measurement level is 40 m (which represents an average between 30 and 50 m). The sonic anemometer provided all three velocity components and temperature at a sampling rate of 16.7 Hz. In accordance with the Sodar sampling interval, non-overlapping samples of 10-min duration are chosen for analysis. A lidar system south of runway 25L measured the wake vortices of landing aircraft. The meteorological sensors were deployed in order to characterize the wake vortex evolution and decay based on the meteorological background conditions. Aircraft approaching on runway 25L (25R) pass the sonic at a height of 64 m (66 m).

4 Data analysis

We investigate a sample that was measured in the early morning hours on 11 September 2004, between 0240 and 0310 UTC (0440–0510 local time). Sunrise was at 0455 UTC. This time period experienced some light rain with surface winds between 2.3 and 3.6 m s^{-1} from the south as measured by the sonic, and air temperature was 18°C. Up to a height of 60 m the wind direction remains constant with a substantial increase of the crosswind up to 7.1 m s^{-1}. The stability parameter z/L varies between 1.4 and 3.8 indicating a stable stratified situation (Table 1, z being height and L the Obukhov length). Compared to the undisturbed boundary layer the friction velocity increases by about a factor of 2 during the passage of the vortices.

Table 1 Conditions just before and during the vortex observations at $z = 10$ m. Shown is the wind speed U, wind direction α, runway parallel wind component u_p and the runway crosswind u_c. $u_p < 0$ denotes a head wind, $u_p > 0$ a tail wind. The sign convention for the crosswind is such that a negative crosswind denotes a wind towards north. S_v/S_u is median of the ratio between the transverse to streamwise spectra within the inertial subrange. In addition the stability parameter z/L is shown

	0240 UTC	0250 UTC	0300 UTC	0310 UTC	1230 UTC
u (m s^{-1})	2.3	2.8	2.9	3.4	9.5
α (°)	176	184	198	195	249
u_p (m s^{-1})	−0.6	−1.1	−1.8	−1.9	−9.5
u_c (m s^{-1})	−2.2	−2.5	−2.3	−2.8	−0.2
u_c (m s^{-1}) ($z = 60$ m)	−5.5	−6.0	−5.6	−7.1	−0.9
z/L	1.4	2.1	3.8	1.4	−1.4
u_* (m s^{-1})	0.23	0.23	0.24	0.41	0.73
S_v/S_u	1.24	1.16	1.14	1.40	1.11
ϵ (10^{-3} m^2 s^{-3})	0.86 ± 0.01	1.4 ± 0.02	1.1 ± 0.02	8.8 ± 0.2	144 ± 2.8

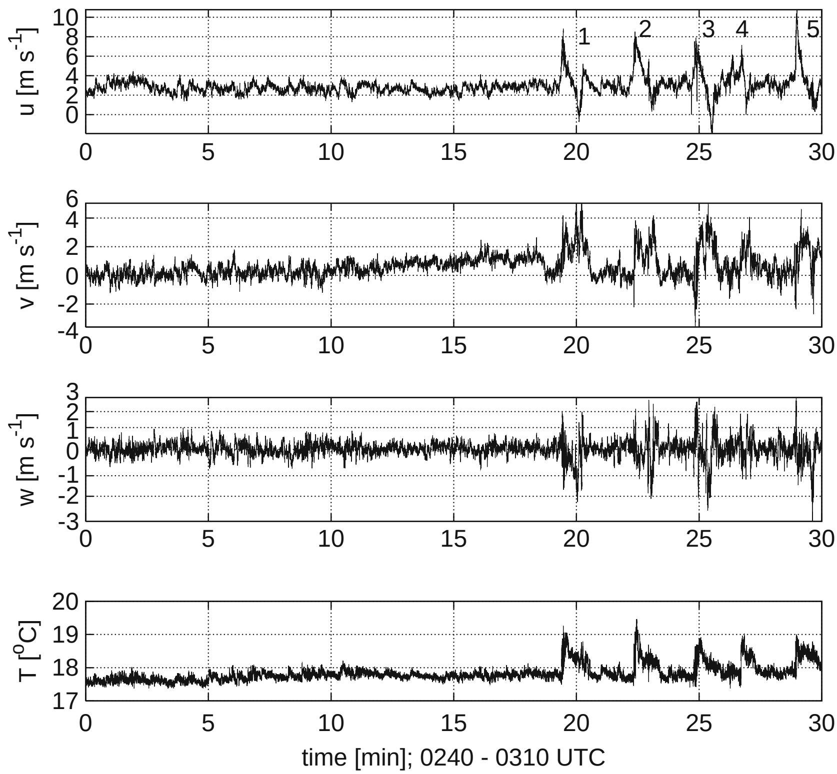

Fig. 2 Time series of the velocity components u, v and w and temperature T between 0240 and 0310 UTC, 11 September 2004. The five vortices are numbered in the series of the u component

The time series of the three velocity components u, v, w are shown in Fig. 2. Until about minute 20 the situation is rather calm before we notice the first wake vortex at minute 20, around 0300 UTC, which marks the onset of typically dense air traffic in the morning at Frankfurt airport. In total five vortex traces can be identified during a 10-min interval, which can be attributed to a sequence of MD-11, B747, A340, B757 and B777 aircraft. Considering the prevailing wind direction, the detected signals belong to the downwind (starboard) vortices of aircraft landing on 25L. Based on the landing times, the detected vortices have an estimated age of about 20–40 s. The vortices are also clearly visibly in the temperature signal as a ramp like structure with an amplitude of 1°C. Considering the age of the vortex the origin of this temperature increase presumably is not related to the jet exhaust being captured by the wake vortex (Gerz et al. 1998). There, it is shown that the temperature excess of the exhaust reaches the ambient temperature level within about 20 s. From Sodar/RASS observations, we find a virtual potential temperature of $\theta_v = 294.3$ K at $z = 100$ m, $\theta_v = 293.2$ K at $z = 60$ m and $\theta_v = 293.0$ K at $z = 10$ m (last based on sonic data). Thus, the observed stable static stratification in the boundary layer between 10 and 60 m cannot explain the observed temperature excess if we assume that the air entrained by the vortex at the originating level warms up adiabatically during descent. However, the 100-m temperature value could explain the observed temperature excess of 1 K by taking into account that spatial averaging of the RASS measurement smooths out sharp temperature gradients. We have also analyzed other velocity traces of wake vortices during daytime conditions in our sonic data where no such temperature signal can be detected. For these cases, the boundary layer shows near-neutral stratification such that no temperature excess should be expected in the absence of jet effects.

As a typical example we show the close-up view of the third vortex observation (Fig. 3). Here we show fluctuations of the runway parallel wind component u_p and the corresponding crosswind component u_c. In addition, we show the temperature time series. This particular vortex was generated by an A340-300 aircraft. The wake vortex passage through the sonic lasts about 60 s, which implies an effective lateral transport velocity of 0.3 m s^{-1} at this position where we assume a vortex size of $l = 20$ m. During the passage we find a variation of the lateral and longitudinal wind components u'_c and u'_p in the range of −4 to 4 m s^{-1}. Both the beginning and the end of the vortex passage is associated with an updraft and a downdraft with a magnitude of 2 m s^{-1}, respectively. The vortex shows no smooth velocity profile and appears turbulent; it is observed in all three velocity components implying a tilting of the main vortex axis. Similar features can be seen for the other vortices as well. The strong tilting can explain the rather low lateral transport velocity.

We now investigate how the presence of wake vortices affects the magnitude of the turbulent energy dissipation rate. The mean dissipation rate ϵ is computed from the longitudinal velocity power spectrum by fitting a curve in the inertial subrange (e.g. Klipp and Mahrt 2003).

$$\frac{fS_u(f)}{T_{uu}} = \alpha_u \epsilon^{2/3} \left(\frac{2\pi f}{U}\right)^{-2/3} \tag{1}$$

with the spectral value S_u of the longitudinal velocity component at frequency f. The Kolmogorov constant is set to $\alpha_u = 0.53$. The Taylor correction term T_{uu} (Wyngaard and Clifford 1997), which accounts for inaccuracies in using Taylor's

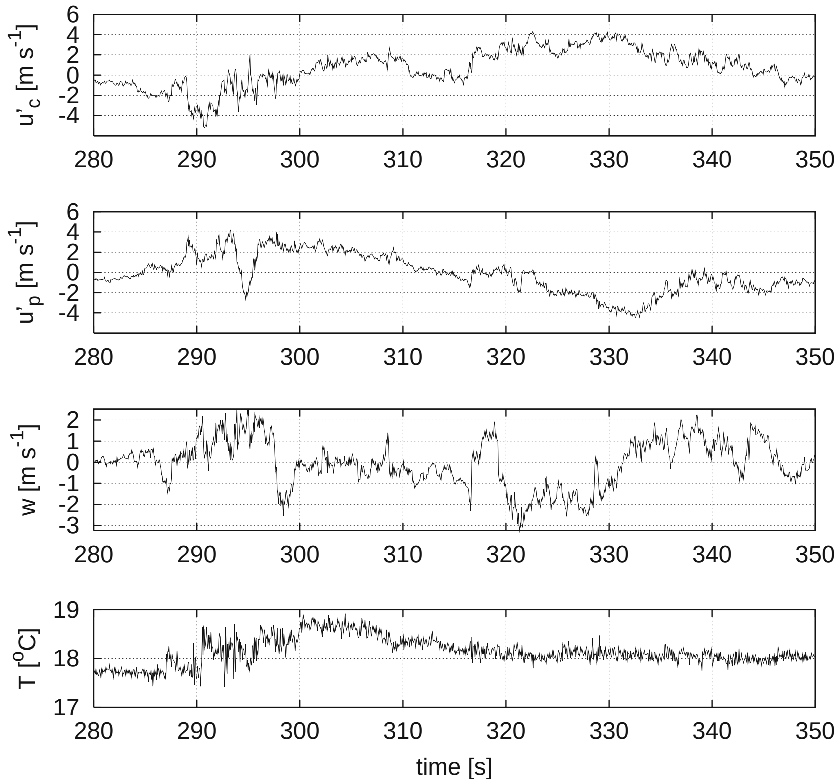

Fig. 3 Close-up view on the third vortex observation. u_p' (u_c') denotes the fluctuations of runway parallel (cross) wind. The 10-min averaged horizontal wind components are subtracted

hypothesis in low wind speed conditions, is on the order of 1.02–1.08 for the time period analyzed.

First of all, the velocity spectra all show an inertial subrange with a $-2/3$ slope (Fig. 4). High kinetic energy input introduced by the wake vortices can clearly be seen in particular at the production scale below 0.2 Hz. There, the energy content is about one order of magnitude larger compared to the undisturbed nocturnal surface-layer case. The midday sample of an unstably stratified and shear driven surface layer without any wake traces shows a similar energy content in the production range as the wake sample. However the spectrum containing wake vortices seems to be not in equilibrium, which is suggested by the rather steep decrease in spectral energy before reaching the inertial subrange.

As an indicator for the existence of an inertial subrange we can investigate the mean ratio of the transverse to longitudinal spectra S_v/S_u, which should converge to a 4:3 ratio. This ratio is computed as a function of frequency and the mean is computed in the frequency range of the $-2/3$ slope. The values are given in Table 1. We find values around 1.1 and 1.4, which are close to the 4:3 ratio. The observed deviations from the theoretical value may be related to the presence of the ground.

The computed values for ϵ are given in Table 1, where the uncertainty of ϵ is computed from the uncertainty of the linear regression. We find that the dissipation rate

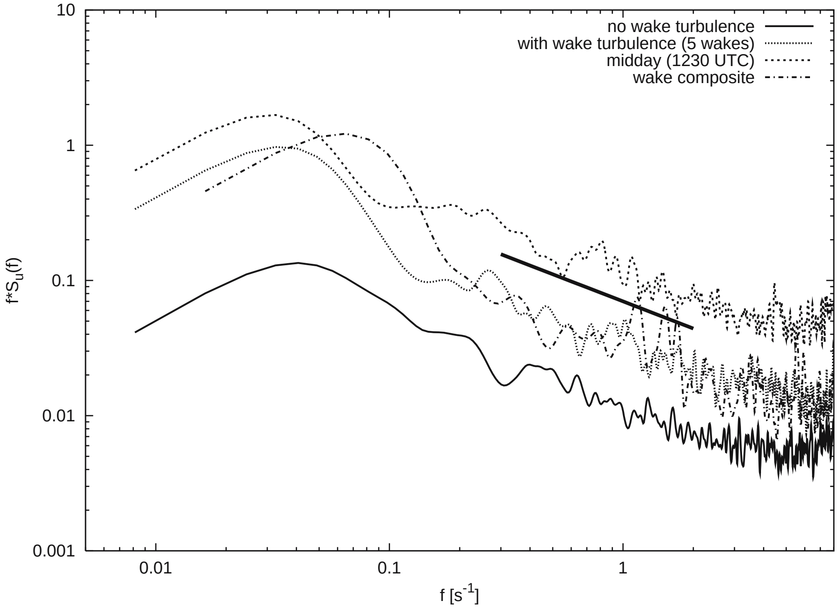

Fig. 4 Longitudinal velocity spectrum of four 10-min samples: without wake turbulence, with five vortices in the nocturnal boundary layer and a midday example without wake vortices. In addition, a composite of the velocity spectra computed from the five individual wake traces is shown. As a reference, the −2/3 slope of the inertial subrange is shown

increases by a factor of 10 for the 0310 UTC sample compared to the undisturbed sample at 0240 UTC. The daytime sample shows more than a magnitude larger dissipation rate compared to the wake sample, presumably due to strong shear driven turbulence.

5 Discussion

We have shown how the presence of wake vortices in sonic anemometer measurements affect the spectrum and the estimate of the turbulent energy dissipation rate. Even though the atmospheric boundary layer is disturbed by the presence of wake vortices, an inertial subrange can still be identified in the power spectrum from which ϵ can estimated. In our example, the dissipation rate is increased by a factor of ten compared to the dissipation rate of the undisturbed nocturnal boundary layer just before the beginning of dense air traffic in the morning. Frequent landing aircraft may cause an increase of ambient turbulence by wake vortices, which in turn may affect the decay rates of vortices evolving in such a disturbed environment, in particular if the atmosphere is weakly turbulent.

We have observed a clear temperature increase during the passage of a wake vortex over a sonic anemometer. This increase in temperature can be attributed to the air engulfed by the vortex at the level where the vortex is generated. In the case of a stably stratified surface layer, air with higher potential temperature is transported downward and mixed with cooler air near the surface.

In the study by Holzäpfel and Steen (2007) it was found that the skill of a wake predictor degraded somewhat when using ϵ from measurements containing a wake vortex signal. The observed overestimation of ϵ leads to an earlier onset of rapid wake vortex decay in the model of Holzäpfel et al. (2003) by $\approx 30\,\mathrm{s}$.

To be on the conservative side, anemometer measurements in the vicinity of the flight corridor not contaminated by wake vortices should be used for a dissipation rate estimation. In this respect the anemometer line in Frankfurt, that consists of ten sonic anemometer, is ideal since identifying an anemometer not affected by wake vortices will be possible most of the time. This requires a wake vortex detection algorithm that has to applied to the 10 sonic anemometer measurements. A possible candidate is discussed in Hallock et al. (2003). The upper (including wakes) and lower (without wakes) limits of ϵ may be estimated using the anemometer line.

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