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Doppler Lidar Investigation of Wake Vortex Transport Between Closely Spaced Parallel Runways

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The paper demonstrates the potential of the Doppler lidar technique for the investigation of aircraft wake vortices. During several extended field experiments at the Frankfurt/Main Airport, the DLR laser Doppler anemometer has measured the vortex properties of a large variety of landing aircraft. These data are used to increase the understanding of the behavior of wake vortices with special emphasis on the horizontal vortex transport in ground effect. In particular, the results of the vortex transport considerations are the basis for air traffic control to enhance the efficiency of closely spaced parallel runway systems with respect to wake vortices.

Nomenclature

h = height above ground level
r = radius coordinate measured from the vortex axis
r_{co} = radius of the vortex core
V_{cc} = cross component of the wind field
V_{si} = self-induced vortex motion
v = tangential velocity of the vortex
(y_1, z_1) = spatial coordinates of vortex 1 of a vortex pair
(y_2, z_2) = spatial coordinates of vortex 2 of a vortex pair
Γ_0 = total vortex circulation

Introduction

SINCE the beginnings of powered flight it has been known that all aircraft produce trailing wake vortices as a result of generating lift. Especially during landing and takeoff, the strong vortices of heavy aircraft present a potential hazard to other aircraft following closely behind. Separation standards based on wake vortex have been established. But they have proved to be a strong restriction on the capacity at major airports.

Besides this single-runway problem, wake vortex influence on parallel runway systems has to be taken into account. Vortices generated on the glide slope of one runway may be transported to the glide slope of the parallel runway. A separation of more than 775 m (about 2500 ft) between the parallel runways has been defined to allow vortex-independent operation under all weather conditions. The justification for the 2500-ft rule has no direct basis in measurements or practice on runways spaced by 2500 ft but is a best educated guess at an appropriate standard.

At airports where this separation standard is not met, the relations between vortex transport and atmospheric conditions have to be considered in detail. The aim is to find procedures allowing at least a part-time operation of both runways independently with respect to wake vortices. This is of special importance for safety and capacity considerations at the highly frequented Frankfurt/Main Airport where the separation between the parallel runways is only 518 m (see Fig. 1). Therefore, the German Wake Vortex Program has been established; its main objectives are the investigation and prediction of the vortex transport between parallel runways under special consideration of orographic and atmospheric conditions and the determination of the vortices of newer aircraft types, such as the B757, B767, and A320.

During the past two decades, several sensing techniques have been applied to investigate vortex generation, transport, and decay: visualization using aircraft- and tower-mounted smoke generators (Garodz et al.[1]), conventional wind or pressure sensors mounted on towers (Eisenhuth et al.[2]) or distributed along horizontal paths (Hallock and Wood[3]), remote sensing systems like sodar (Balser et al.[4]), radar (Chadwick et al.[5]), and lidar (Bilbro et al.[6]). The experimental efforts were supported by model calculations and by wind-channel and water-tank investigations. The different methods are characterized by specific advantages as well as limitations.

Extensive experience in the United States and Germany has proved that the continuous-wave (cw) infrared Doppler lidar is the most effective and flexible remote sensing method for wake vortex detection, measurement, and tracking. Therefore, it was obvious to use the laser Doppler anemometer (LDA) developed by the German Aerospace Research Establishment (DLR) for the purposes of the Wake Vortex Program.

The results of these experimental investigations have been used for the development of a wake vortex warning system that will be installed at Frankfurt/Main Airport for operational application. The scientific background of the warning system is described by Franke et al.[7]; it will not be treated in the present paper.

Wake Vortex Transport Between Parallel Runways

The phenomena of wake vortices can be described by means of large statistical databases and theoretical models. A com-

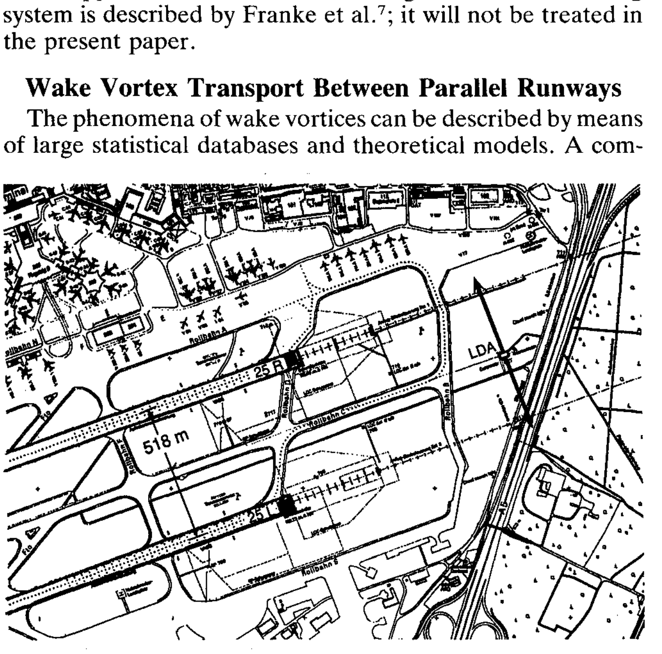

Fig. 1 Runway configuration at the Frankfurt/Main Airport.

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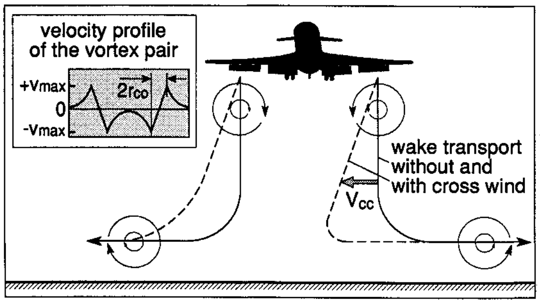

Fig. 2 Structure and transport of a wake vortex pair in ground vicinity.

plete review of the fundamental physics of vortex generation, structure, transport, and decay is given by Hallock and Eberle.[8] For the present considerations, the vortex transport in ground proximity, as sketched in Fig. 2, is of special interest.

After a roll-up period of a few seconds duration, the pair of counterwise rotating vortices has formed. The distribution of the tangential velocity within one vortex, for example, can be approached by the "simple" model used by Burnham and Hallock[9]:

$$v(r) = \frac{\Gamma_0}{2\pi} \cdot \frac{r}{r^2 + r_{co}^2} \tag{1}$$

where r_{co} is where the velocity is maximum and the circulation is half the total circulation.

The transport of the vortex pair is primarily determined by mutual induction, which is the vortex motion caused by each vortex being immersed in the velocity field of the other vortex or near the ground in the velocity field of "image vortices." This results in a vertical motion of

$$\frac{dz}{dt} = \frac{\Gamma_0}{2\pi(y_2 - y_1)} \cdot \frac{-4z^2}{4z^2 + (y_2 - y_1)^2} \tag{2}$$

where z is the vertical coordinate of the vortex pair, and y_1 and y_2 are horizontal coordinates of vortex 1 and vortex 2, respectively. When the vortices approach the area of ground effect, which is at a height of 0.3 to 0.4 times the wing span of the vortex-generating aircraft, they tend to move in opposite directions:

$$\frac{dy}{dt} = V_{cc} \pm \frac{\Gamma_0}{4\pi z} \cdot \frac{(y_2 - y_1)^2}{4z^2 + (y_2 - y_1)^2} \tag{3}$$

It follows from Eq. (3) that the mutual- or self-induced horizontal motion V_{si} is superimposed on the cross component of the ambient wind field V_{cc}.

Experimental investigations in low-Reynolds-number conditions have shown that the vortex core grows because of turbulent diffusion at the core boundary from its initial core radius $r_{co}(0)$ to a value

$$r_{co}(t) = \sqrt{r_{co}(0)^2 + 5 \cdot 10^{-4} \cdot \Gamma_0 \cdot t} \tag{4}$$

whereas the core appears to be more stable in high-Reynolds-number wake vortices.

Dissipative effects gradually lead to vortex demise if it is not destroyed first by one of two catastrophic decay mechanisms: core bursting (Tombach et al.[10]) or Crow instability (Crow and Bate[11]). For more detailed considerations of the vortex transport additional effects like wind shear, buoyancy and vortex bouncing have to be taken into account.

Laser Doppler Anemometer

The DLR laser Doppler anemometer has been developed for wind and turbulence investigations in the atmospheric boundary layer (Köpp et al.[12]). It is a cw system based on a 4-W CO_2 laser (eye-safe wavelength of 10.6 μm) and a transceiver telescope 30 cm in diameter. The measured quantity is the line-of-sight (LOS) component of the wind vector in the atmospheric volume where the laser radiation is focused. By changing the focal length of the telescope, the system range can be varied between 40 and 1000 m. The flexible scanning device enables one to point the measuring beam in all directions. From a number of LOS components measured in different directions, the wind vector can be derived, for example.

The control of the scan procedures, the data acquisition, and the on-line data evaluation are performed by a Compaq 386. Up to 160 frequency or velocity spectra per second can be stored. Moreover, the spectra are displayed on the oscilloscope to allow real-time monitoring of the vortex signatures, which is necessary for vortex tracking by manual range setting. These features are the basis for precise vortex measurements with an elevation-angle resolution of 0.1 deg, a localization accuracy of a few meters, and a scan repetition rate of a few seconds. Some LDA properties are listed in Table 1, and a picture of the LDA container at Frankfurt/Main Airport is shown in Fig. 3.

Experiment

The Frankfurt/Main Airport is situated in the wide valleys of the rivers Rhein and Main (average altitude 105 m) with a chain of hills, the Taunus (max. altitude 880 m), to the north. The prevailing wind direction is westerly with the exception of some high-pressure conditions. The configuration of the parallel runway system is represented in Fig. 1. In the western part of the airport area (not shown in the figure),

Table 1 Laser Doppler anemometer system parameters

Laser, CO_2, cw	
Output power, W	4
Short-term stability, kHz	3
Transceiver telescope	
Aperture, cm	30
Focal length, cm	90
Detector, mercury cadmium telluride, cooled to 77K	
Sensitive area diameter, mm	0.5
Detectivity, cm(Hz)$^{1/2}$/W	5.8×10^{10}
Range resolution	
At 100-m range, m	6
At 500-m range, m	150
Spectrum analyzer, surface acoustic wave	
Frequency resolution, kHz	30
Corresponding velocity resolution, m/s	0.15
Scanning device	
Elevation-angle resolution, deg	0.1
Acquisition of frequency spectra	
Maximum acquisition rate, Hz	160

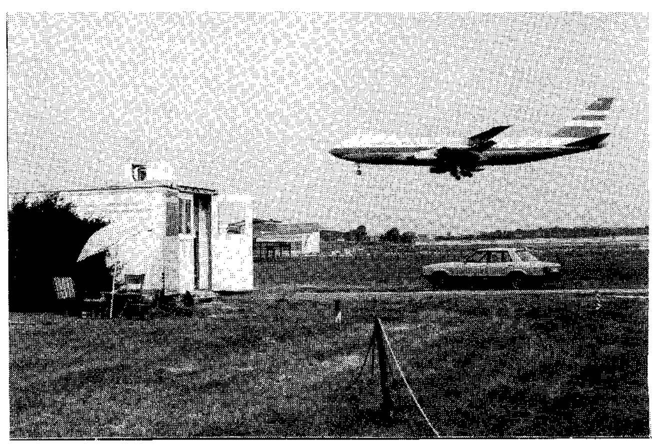

Fig. 3 LDA container at the Frankfurt/Main Airport with the scanning device on top of the container roof.

there is the additional runway 18 that can only be used for takeoff to the south. All landings have to be handled on the closely spaced runways 07L/25R and 07R/25L. According to the present regulations, the distance of 518 m between these parallel runways is not sufficient for wake vortex independent operation.

The area east of the thresholds of the parallel runways between both glide slopes was chosen for the measurements for two reasons: the most critical site for an aircraft to encounter a wake vortex is located close to the landing threshold, and corresponding to the prevailing wind direction, most of the inbound traffic is coming from the east. The LDA is positioned between the landing corridors of both runways, 720 m in front of the threshold of 25R and 947 m in front of the threshold of 25L, as indicated in Fig. 1.

The investigation of the wake vortex transport in ground vicinity necessitates a strategy that covers the area between the parallel glide slopes within a height layer approximately 100 m thick. By assuming the vortex is a very long, more or less homogeneous tube of vorticity, the investigations can be reduced to a two-dimensional vortex slice only showing tangential velocity components. Then it is sufficient to measure in a plane perpendicularly oriented to the direction of the glide slopes (see Fig. 1). The aircraft penetrate the measurement plane at an altitude of 60 m, on the average. The precise height assignment for each landing event is realized by a video monitoring system.

In Fig. 4, one-half of the measurement plane pointing toward the approach corridor of the landing aircraft is sketched. A section of that plane is covered by a fast elevation scan at fixed range setting. The right side of the figure shows the measured velocity profile, here the profile of a B747 port vortex. This profile is the superposition of the vortex rotational field and the lateral vortex transport including the crosswind component. Even though the LDA is operated in homodyne mode, it is possible to distinguish positive and negative velocity components by using the known crosswind direction for reference. In this example, the profile branch above a 34-m altitude has to be reflected to negative velocities. After the vortex has passed that sensing region, the next one is chosen by changing the range setting. As soon as the vortex has reached the LDA position, the measurement half-plane is turned in azimuth by 180 deg, and the vortex tracking is continued toward the parallel runway.

During several extended field experiments in the years 1983–85 and 1989–90, the LDA system has been operated at Frankfurt/Main Airport measuring the vortices of more than 1400 landing aircraft of both a heavy and large variety. In that way, many experimental results have been acquired, which are the basis for the present study.

The LDA measurements were supported by an array of mast-mounted propeller anemometers operated by the University of Hannover (Franke et al.[13]) and during several campaigns by the instrumentation of the German Weather Service for the description of the meteorological background. The results acquired with both instrumentations also yield important information for the Wake Vortex Program. In the present paper, they are only used where a correlation of the LDA data and the atmospheric conditions is taken into account.

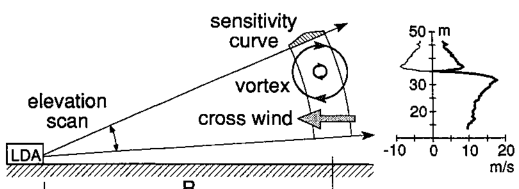

Fig. 4 Strategy of the wake vortex measurements using the LDA system.

Wake Vortex Properties

The potential of the Doppler lidar method for wake vortex investigations can be illustrated by means of some selected examples, concerning phenomena like structure, strength, and aging of wake vortices.

The velocity profiles of the vortex pair generated by a landing B757 aircraft are drawn in Fig. 5. Both profiles were measured at a fixed range setting of 97 m from the LDA system. They show a symmetrical shape on both sides of the actual crosswind value of 4.4 m/s. The upper curve represents the compact downwind vortex measured 28 s after aircraft passage. Its core axis lies 46 m above ground level, and the core diameter is less than 4 m. In contrast to that, the 33-s old upwind vortex centers at a 24-m altitude. Because of its ground proximity, the core diameter is increased to 6 m, and the velocity maxima are already reduced.

The B757 measurement shown in Fig. 5 is a pronounced example of vortex-pair tilting induced by crosswind shear, as described by Brashears et al.[14] The 22-m height difference and the 5-s time delay can be converted in a slant distance of 32 m between the vortex cores. That distance is in good agreement with the theoretical value of approximately 80% of the wing span, in the case of a B757 aircraft: 0.8 × 38 m. Considering the vortex pair embedded in the so-called wake oval, this oval is drifting above the ground with a tilt angle near 45 deg.

The process of vortex aging can be observed, for example, by means of a single vortex generated by a landing C5A Galaxy. Figure 6 shows the passage of the downwind vortex at a 63-m range setting, before the azimuth rotation (55 s) and afterwards (87 s). Driven by the crosswind of 2.5 m/s plus the self-induced velocity, the vortex has traveled the distance of 2 × 63 m in this time period. Thereby, the vortex center rose from 31 to 33 m, and the core diameter grew from 4 to 8 m. That vortex growth is the beginning of the decay process.

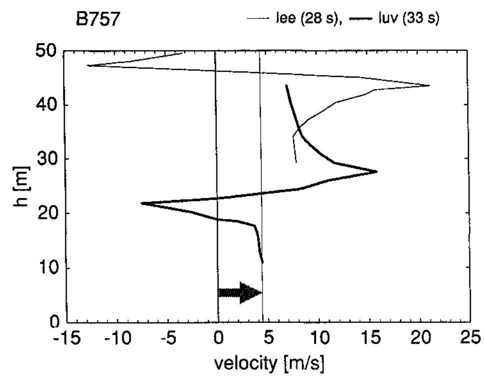

Fig. 5 Velocity profiles of the lee and luv vortex of a landing B757 aircraft.

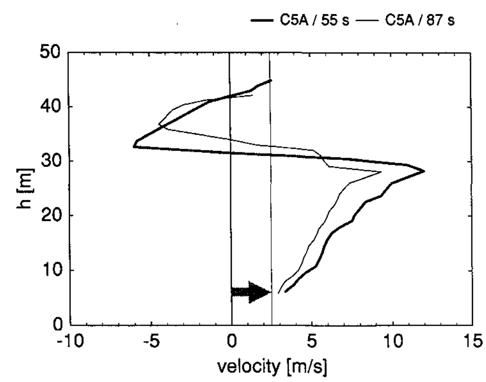

Fig. 6 Comparison of C5A velocity profiles measured 55 s and 87 s after vortex generation.

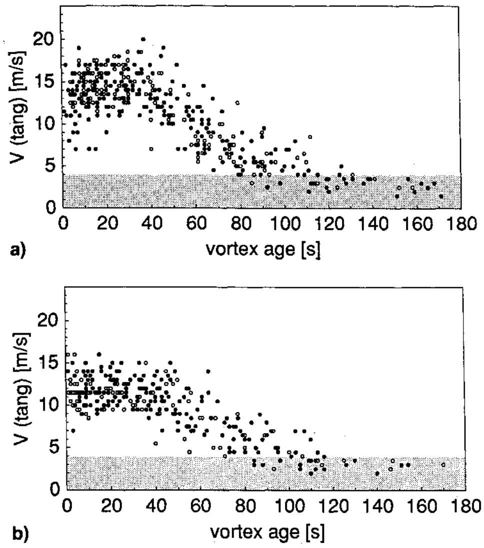

Fig. 7 **Temporal behavior of the maximum tangential velocities measured in the vortices of aircraft classes a) (B747) and b) (other of weight >136 tons). The atmosphere is characterized by low stability (open circles) and neutral to unstable conditions (full circles).**

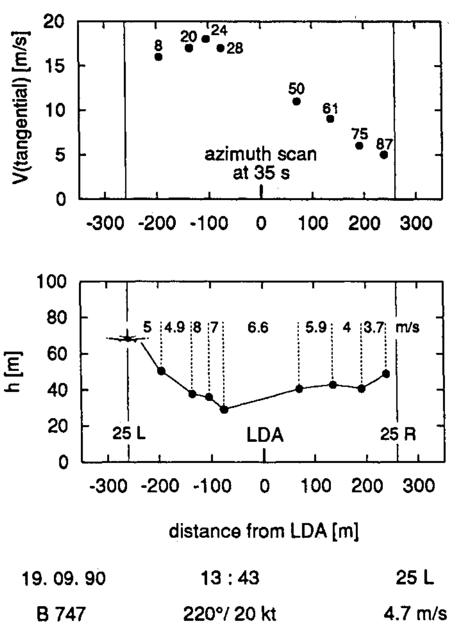

Fig. 8 **Results of one complete measurement sequence, showing the vortex strength in the upper part (the numbers indicate the vortex age in seconds) and the vortex location in the lower part (the numbers indicate the velocity of the lateral vortex motion in meters per second).**

In principle, the vortex circulation can be evaluated by integration over the velocity profiles. But it is more convenient to describe the vortex strength by the maximum tangential velocity measured. A velocity of about 4 m/s has been identified as a critical value for an encountering aircraft of 16-m wing span flying exactly along the vortex axis.[13] For example, Fig. 7 comprises the temporal behavior of the tangential velocities measured in the vortices of different aircraft classes. After a roll-up period of a few seconds, the velocity remains almost constant for about 40 s. Then the decrease phase begins and the velocities approach the grey 4-m/s area after 80 s.

The spread of the data points in Fig. 7 is rather large. Since the objective of this work necessitates worst-case considerations, the envelopes of the distributions have to be taken into account. Vortices with critical strength (≥4 m/s) are not observed with lifetimes of more than 140 s for B747 aircraft and 120 s for other aircraft of weight >136 tons.

It is known from fluid-dynamical considerations that atmospheric stability tends to increase the vortex lifetime. Turbulent effects, for example, accelerate the growth of the vortex core and hence the decay of the vortices. Stability information derived from ground-based equipment has been used to verify this behavior. The experimental results in Fig. 7 can be assigned to low stability (open circles) and neutral to unstable conditions (full circles). But no correlation can be observed because there is not enough data for achieving good statistical results.

Vortex Transport Between the Glide Slopes of Parallel Runways

As pointed out, the horizontal vortex propagation in ground effect is of special interest for the operation of parallel runways with separations of less than 775 m, as in our case at the Frankfurt/Main Airport.

In Fig. 8 the results of one complete measurement sequence are compiled, which is the landing of a B747 on runway 25L. In the upper part, the maximum tangential velocities are shown; the vortex ages in seconds are labeled by the numbers. The lower part shows the positions of the downwind vortex during the transport extending over the LDA container toward the parallel runway.

Driven by the crosswind, the vortex descends on a slant slope to ground proximity. There, the lateral motion is intensified by the self-induced velocity, as described by Eq. (3). In this example, the horizontal drift velocity is at a maximum value of 8 m/s immediately after descent and approaches the crosswind value of close to 4 m/s after 61 s. Under crosswind conditions of that amount, the vortices actually reach the safety area of the parallel runway with high probability, in this case after 87 s, still exhibiting critical tangential velocity.

In the upper part of Fig. 9 the temporal behavior of the self-induced horizontal velocities are shown for the vortices of a number of B747 aircraft. For the evaluation of the velocities of one sequence a constant crosswind is assumed that has been determined as 1-min average in the undisturbed atmosphere before aircraft passage. Since the crosswind is not constant during the observation period of 2–3 min, the self-induced velocities have a considerable spread. During the descent phase no horizontal self-induced component is ob-

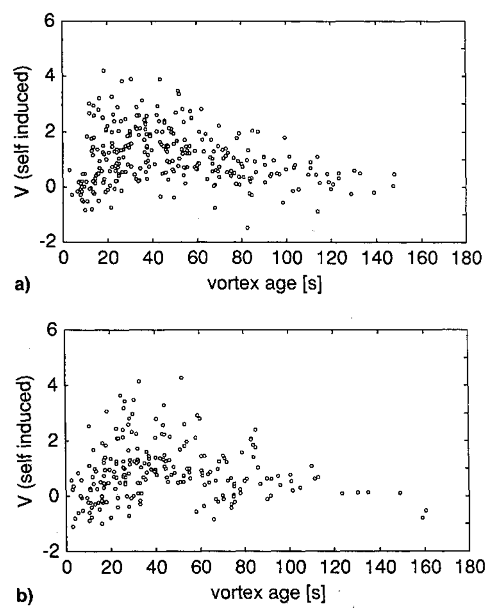

Fig. 9 **Self-induced horizontal velocities of the vortices of aircraft classes a) (B747) and b) (other of weight >136 tons).**

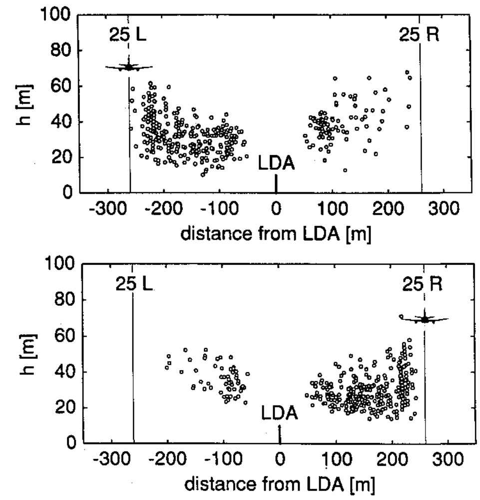

Fig. 10 Propagation of B747 vortices generated on runway 25L (upper part) and 25R (lower part) toward the parallel runways.

served. As soon as the vortex turns into the horizontal direction, the induced velocity values are higher than 2 m/s and approach to zero after 80 s, on the average. A similar behavior can be observed for the other large aircraft (weight >136 tons). There, the spread of the self-induced velocities is further increased by the variety of aircraft types.

For the consideration of vortex transport between closely spaced parallel runways, mainly the horizontal transport of the downwind vortex is of interest, since for that vortex the self-induced velocity and the crosswind have the same direction. Only these vortices can reach the safety area of the parallel runway even under lower crosswind conditions. The combination of the derived vortex lifetimes and self-induced horizontal velocities allows an estimate of the crosswind limits where the vortices do reach, may reach, or cannot reach the safety area of the parallel runway. These quantities are the main parameters for the Wake Vortex Warning System. The figures experimentally determined for the atmospheric and orographic conditions at Frankfurt/Main Airport may be used to estimate the corresponding limits for other airports with similar conditions.

Besides the horizontal propagation, the transport curve of Fig. 8 shows the tendency of increasing height after the vortex has reached ground proximity. Figure 10 illustrates that this so-called bouncing effect is not an isolated case but is more or less common behavior. The vortices of a number of B747 landing on 25L and 25R, respectively, partly show a steep ascent toward the parallel runways. This bouncing effect may enhance the hazard, since the vortices have the tendency to cross the parallel runway near the altitude of the approaching aircraft.

Conclusions

During several extended field experiments at Frankfurt/Main Airport, the DLR laser Doppler anemometer acquired excellent data sets from the vortices of more than 1400 landing aircraft. They are the basis for the investigation of vortex structure, strength, and decay and for the understanding of vortex transport in the area of ground influence.

Concerning the main objective of the experimental program, namely, the vortex transport between closely spaced parallel runways, some conclusions can be stated.

1) Besides the self-induced vortex velocity, the horizontal vortex transport near the ground is mainly determined by the cross component of the wind field.

2) The crosswind limits where the vortices do reach, may reach, or do not reach the safety area of the parallel runway have been determined. These values are the main input for the Wake Vortex Warning System, which is under development.

3) It is necessary to use the mean value of the crosswind component determined for the area between the parallel runways.

4) The correlation of the parameters important for the vortex transport with quantities describing the stability of the atmosphere proved to be very difficult. The reason might be the lack of enough events for good statistical treatment.

5) A considerable bouncing effect of the vortices was often observed.

The experimental results are primarily valid for the Frankfurt/Main Airport. But they may also be applicable to other airports, especially those with similar atmospheric and orographic conditions.

In future, the monitoring of exhaust gases from aircraft engines in airport vicinity will become important. The remote sensing systems being deployed for that purpose can work much more effectively when the location of the main gas plume is known. In the case of aircraft jet exhaust, the gas is mostly wrapped up in the wake vortices. Therefore, it is recommended that a laser-based (LDA) vortex detection and tracking system be installed to support the gas sensors.

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