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Concept of Wake Vortex Behavior Classes

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The concept of wake vortex behavior classes is introduced. Rather than consider the individual wake vortex evolution, diagnosis of the meteorological situation causing a characteristic wake vortex behavior is proposed. We define four wake vortex behavior classes that explicitly refer to both the wake vortex transport and the decay behavior. The statistical analysis of the Memphis wake vortex database supports this new concept and also shows the distinct influence of weather on wake vortex behavior. The analysis indicates that the high-level safety of International Civil Aviation Organization (ICAO) separations between consecutive aircraft is primarily due to the transport of wake vortices out of a flight corridor. It is found that, depending on atmospheric conditions, a significant fraction of wake vortices does not decay enough to satisfy the existing ICAO separations. Of these wake vortices, a small fraction is within a safety corridor and therefore poses a potential risk to a following aircraft. A simple crosswind criterion with a threshold of 2 m/s provides a safety corridor that is free of wake vortices under radar separation. This demonstrates the large potential for safe reduction of aircraft separation under crosswind conditions. This is supported by an analysis of a wind climatology representative for Frankfurt airport.

Nomenclature

b_0	=	initial vortex spacing, m
g	=	gravitational acceleration, m/s^2
m	=	mass of aircraft, kg
N	=	Brunt–Väisälä frequency, 1/s
N^*	=	normalized Brunt–Väisälä frequency, Nt_0
Ri	=	Richardson number, N^2/S^2
S	=	shear number, 1/s
t	=	time, s
t_e	=	detection time, s
t_0	=	characteristic time scale, s, b_0/w_0
t^*	=	normalized time, t/t_0
$\bar{U}$, $\bar{V}$	=	mean horizontal wind components, m/s
u_c	=	crosswind, m/s
y	=	lateral position, m
w_0	=	initial vortex sink speed, m/s, $\Gamma_0/2\pi b_0$
z	=	vertical coordinate, m
Γ_0	=	initial root circulation, m^2/s, $mg/\rho U b_0$
Γ^*	=	normalized circulation, Γ/Γ_0
Δz	=	vertical height difference, m
ϵ	=	Turbulent dissipation rate, m^2/s^3
ϵ^*	=	normalized turbulent dissipation rate, $(\epsilon b_0)^{1/3}/w_0$
$\bar{\theta}_v$	=	mean virtual potential temperature, K
ρ	=	density of dry air, kg/m^3
σ_{Γ^*}	=	standard deviation of normalized circulation

Subscript

0	=	initial value

Superscript

$*$	=	normalized quantity

Introduction

MAJOR airports face increasing capacity problems for which solutions are needed in the near future. One possible solution for this is to safely reduce the separation of approaching aircraft. Currently, International Civil Aviation Organization (ICAO) requires prescribed separation distances that are based on the weight of the leading and following aircraft in order to avoid wake vortex hazard.

Observations and numerical results suggest that the existing separation rules appear overconservative and indicate that atmospheric conditions often favor rapid decay and/or transport of wake vortices (WVs) out of the glide path corridor. This is evident from the small number of known encounters that have been observed under visual flight rules where the approaching aircraft are often staggered with a radar separation that is between 2.5 and 3 n miles. On the other hand, WVs with a life span of 100 s or longer were observed, where 100 s approximately corresponds to a separation of 4 n miles. This means that there are weather situations that do not favor a rapid decay of WVs.

Examples of systems that aim at a relaxation of separation distances are the Vortex Advisory System,[1] the Aircraft Wake Vortex Spacing System (AVOSS),[2] the Wake Vortices Warning System (WVWS) at Frankfurt Airport,[3] and Syage.[4] For various reasons none of these systems are operational to date. The conventional approach is to consider WV behavior that employs a deterministic real-time WV transport and decay model. Aside from aircraft parameters, the ability of these models to predict WV behavior depends heavily on the quality and availability of the meteorological input data. Typically, a real-time WV model requires, as meteorological input, vertical profiles of the wind components, temperature, and turbulent kinetic energy or, alternatively, eddy dissipation rate along the glide path. These environmental data, and especially the profiles of turbulent kinetic energy or eddy dissipation rate, are difficult to measure and predict with high vertical resolution in an operational environment where simplicity and robustness is very important.

As an alternative approach we explore the concept of wake vortex behavior classes (WVBCs), which aims to classify WV behavior based on meteorological conditions.[5] If we are able to identify these meteorological conditions that favor a distinct WV behavior, then the deterministic prediction of an individual WV history is not needed. Here, the distinct WV behavior is interpreted in terms of the potential to provide a safety corridor that is free of WVs along a glide path. Such a classification scheme may then be used instead of deterministic modeling approaches. The goal is that the definition of a WVBC should be based on meteorological parameters that are forecasted with standard weather forecasting tools. This type of classification scheme may also simplify the risk assessments of new operational systems where WV behavior is an important element.

The term wake vortex behavior class considers the influence of weather parameters on WV evolution. We call these weather

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parameters WV weather. For example, turbulence favors quick WV decay; therefore, it can be viewed as adverse weather for a WV even though a meteorologist would consider turbulence as a meteorological parameter that can be attributed to various well-defined weather situations (e.g., the convective boundary layer, strong wind shears).

In this paper we will introduce the WVBC and use the comprehensive Memphis database[6] to validate the new concept. The strategy of the analysis is to consider a large number of samples, rather than just case studies, to obtain a broad statistical basis for an evaluation of the new concept of WVBC.

Wake Vortices in the Atmosphere

The knowledge of WV behavior in the atmosphere has grown considerably in recent years.[7] Besides the effect of ground proximity, the trajectories and decay of aircraft WVs are determined by crosswind, turbulence, stable thermal stratification, and wind shear. This list is approximately ranked according to the ability of a phenomenon to destroy the vortices or to transport them out of a safety corridor. In the following we briefly discuss the effect of the meteorological conditions on the evolution of WVs.

In general, turbulence favors quick vortex decay.[8] Weak ambient turbulence may enhance cooperative short-wave and long-wave instabilities, whereas strong turbulence erodes each vortex individually.[9,10] This includes all weather situations where the level of turbulence is significant, whether it is driven by buoyancy or shear. For example, buoyancy-driven turbulence arises in a convective boundary layer.[11] Shear-generated turbulence may be associated with situations with moderate to strong persistent winds.

The effect of a stable stratified atmosphere depends on the strength of the stratification. In a weakly stable stratified atmosphere the vortices descend due to their self-induced descent but at a somewhat reduced rate.[12,13] Turbulence from the aircraft is sufficient to trigger vortex instabilities and subsequent decay.[14] In a very stable and quiescent atmosphere (no atmospheric turbulence but with aircraft-induced fluctuations), WVs may rebound up to the flight level. However, three-dimensional numerical simulations indicate that the circulation decreases rapidly.[14] This situation may be associated with weak winds that occur in conditions where radiative processes are important. Examples of this are the nocturnal boundary layer under clear sky conditions or the typically stable stratified free atmosphere.

Wind shear may cause WVs to stall or rise in a safety corridor without substantial decay.[15,16] The interaction between WVs and a shear layer is complex and very sensitive to the shape of the wind profile, which is the depth and strength of the velocity profile, its vorticity profile.[12,17,18] Two-dimensional simulations of the interaction of WVs with a shear layer show the rise of one vortex. Three-dimensional simulations of the interaction of WVs with laminar and turbulent low-level jets indicate stalling or rebound of one vortex for the laminar case and stalling with turbulent decay of the vortex in the turbulent case. Shear layers can be associated with weak stable stratification and are often a feature of a nocturnal boundary layer. Shear layers potentially result in long-lived stalling or rising WVs. Shear layers are difficult to forecast and, because there is a potential risk associated with this situation, an operational WV prediction system has to consider this phenomenon.

WVs in ground proximity laterally diverge from each other. The secondary vorticity, which is generated due to viscous effects, interacts with the primary vortices.[19–21] This interaction appears to be the main cause of WVs decay and rebound. The trajectories of WVs are observed to be more complex in the presence of background shear.[22]

Advection of WVs out of the glide path is an important mechanism to eliminate WV risk if the crosswind component is strong enough to carry the WV away from the safety corridor. The definition of critical crosswind limits is site specific and dependent on runway operation (e.g., single or parallel runways) and safety corridor dimensions.

WVBC Definition

We now define WVBCs in terms of their ability to cause a characteristic WV behavior. Four WVBCs are defined: rapid decay, moderate decay, weak decay, and transport (lateral). The WVBC concept covers the whole glide path. The key parameters used to define a WVBC are the Bulk–Richardson number Ri_b and the crosswind. Table 1 summarizes the definitions of each WVBC as a function of Ri_b. The shear case is considered as a special situation, often associated with complex temperature and wind profiles, that is not easily amenable to a simple Ri criterion. The classification makes a distinction between weakly, moderately, and strongly stratified classes with corresponding WV decay characteristics. This is motivated by the observation that the decay of WVs in a stably stratified environment is dependent on the strength of stratification.[14] A preliminary threshold of $N^*_{\text{crit}} = 0.3$ has been determined from the Memphis data. This value produced similar-sized sample of WVs in a stable stratified atmosphere.

The Richardson number Ri_b is defined as $Ri_b = N^2/S^2$, where the Brunt–Väisälä frequency is defined by

$$N = [(g/\bar{\theta}_v)(\Delta\bar{\theta}_v/\Delta z)]^{\frac{1}{2}} \tag{1}$$

and the shear number is defined by

$$S = \left(\frac{\Delta\bar{U}^2 + \Delta\bar{V}^2}{\Delta z^2}\right)^{\frac{1}{2}} \tag{2}$$

Memphis Database

The NASA Langley Research Center, in collaboration with the Federal Aviation Administration, carried out measurements at Memphis Airport, Tennessee, during fall 1994 and summer 1995.[6] The resulting data set consists of over 572 WV measurements of landing aircraft together with meteorological data documenting the atmospheric state for each WV measurement. We consider the WVs that were tracked and measured by Lidar. Vortex velocity profiles with a spatial resolution of 1 m are available; the time-dependent circulation for each vortex pair can be estimated with reference to the lateral and vertical position of the vortex and data of the generating aircraft. The latter data include aircraft type, approach speed, weight, and wing span, which are used to calculate the root circulation Γ_0. The database contains atmospheric profiles of wind and temperature that are derived by merging data from various sensors including a meteorological tower, a wind and temperature profiler,

Table 1 Definition and description of WVBC[a] Here we chose N^*_{crit} = 0.3 and $|u_{c,\text{crit}}| > 2$ m/s

Class	Meteorological character	Definition	Flow examples/comments
Transport	Crosswind	$u_c > u_{c,\text{crit}}$	Site specific
Transport (critical)	Shear	Diagnostic	Nocturnal boundary-layer jet
Rapid decay	Turbulence	$Ri < 0.25$	Convective boundary layer
Rapid decay	Strongly stable stratification	$Ri > 1$, $N^* > N^*_{\text{crit}}$	Nocturnal boundary layer
Rapid decay (in-ground effect)	Independent of atmospheric background	$z < 50$ m	Crosswind dependence
Moderate decay	Transition	$0.25 < Ri < 1$	Transition day to nighttime boundary layer
Weak decay	Weakly stable stratification	$Ri > 1$, $N^* < N^*_{\text{crit}}$	Overcasted nocturnal boundary layer

and radio sondes. These profiles are generated every 5 min with a vertical spatial resolution of 5 m. Turbulent kinetic energy and eddy dissipation rates are available at height levels of 5 and 40 m, respectively. These data are computed from sonic anemometer measurements that are based on 30-min samples. We use the reference time scale t_0, the initial theoretical circulation Γ_0, and the initial vortex spacing b_0 to normalize all measurements.[7] The reference time scale is defined as $t_0 = b_0/w_0$.

Data Analysis

The atmospheric state strongly influences WV behavior. Therefore, our starting point is the analysis of weather conditions with a subsequent classification of the weather according to the definition of the WVBC (Table 1) and the selection of corresponding WV measurements. This analysis has been automated to allow for an efficient analysis of the data for a variety of criteria. For a particular meteorological profile the Richardson number is computed at each measurement height. A profile is assigned to a particular class if 66% of the Richardson numbers between 40 and 200 m satisfy the limits shown in Table 1. WVs approximately evolve within this height interval and we require that WVs originate above $5b_0$. The choice of the 66% criterion has been selected after a number of tests. This number provides a sufficiently large number of samples for each class and is at the same time effective in characterizing the atmospheric state. WVs in-ground effect (IGE) are not classified using the Ri criterion because our analysis has shown that there is no systematic dependence on atmospheric background conditions for WVs in-ground effect.

In a next step, the corresponding WV measurements are analyzed. We compute the circulation over radii in the range of 5 to 15 m.[23] This is done individually for the port and starboard vortices. Before computing the circulation it is checked that there are sufficient velocity data available within this radii interval and that the initial vortex spacing b_0 is larger than 22 m. This limit eliminates small aircraft from the data set for which the computation of a 5–15-m circulation value would not be meaningful. No further correction of the circulation data is performed. In principle, the influence of the neighboring vortex on the velocity field of the vortex from which the circulation is computed can lead to an over- or underestimation of the computed circulation value depending on the viewing angle of the Lidar and type of aircraft.[24] Campbell et al.[25] outline an analytical correction for this effect, which is small for scan angles between 60 and 90 deg. This correction has been tested in an analysis of the Memphis data and it is concluded that systematic and random errors in the measurements outweigh the benefit of the correction.[26] The WV in-ground effect considered in this analysis originate below a height of 50 m.

Classification of Wake Vortices for Individual WVBC

We investigate whether there is a distinct WV behavior associated with atmospheric conditions classified according to the Richardson number criteria.

In the following we consider the cumulative distributions of WV detection time t_e based on LIDAR measurements. The detection time t_e is the point in time of the final Lidar measurement. It is assumed that the end of a WV measurement correlates well with the onset of a rapid decay and, therefore, with the lifetime of a WV, which is assumed to be the end of a potential hazard. This assumption is investigated later in more detail.

Figure 1a shows the cumulative distribution of WV detection times for the atmospheric states given in Table 1. Profiles that do not satisfy the 66% criterion are kept in a residual class. The six cumulative distributions are combined into three cumulative distributions according to their characteristic decay features in Fig. 1b. The most rapid decay is found for WVs in ground proximity, in a turbulent environment, and in a strongly stable stratified environment. These three situations are called the rapid decay class. The class with intermediate decay is related to an atmosphere in transition or where the Ri criterion (i.e., the 66% limit) is not fulfilled. The weak decay class comprises atmospheric conditions that are weakly stable stratified.

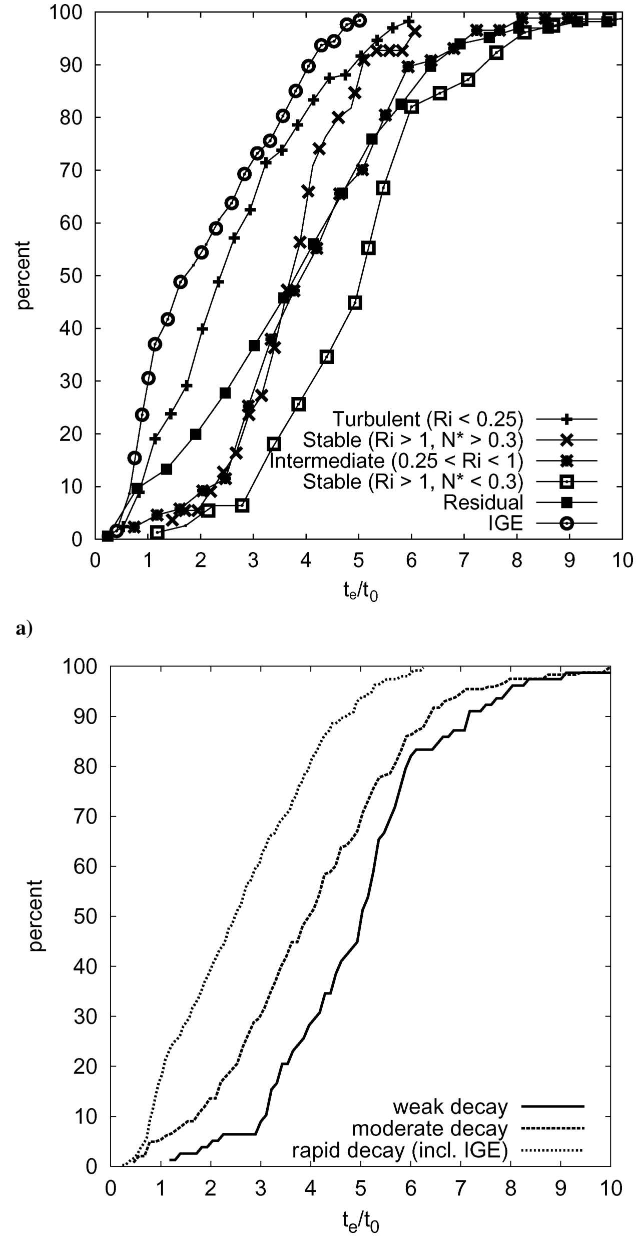
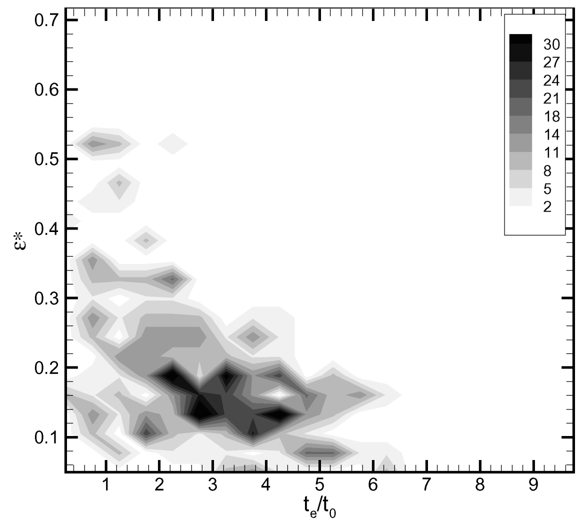


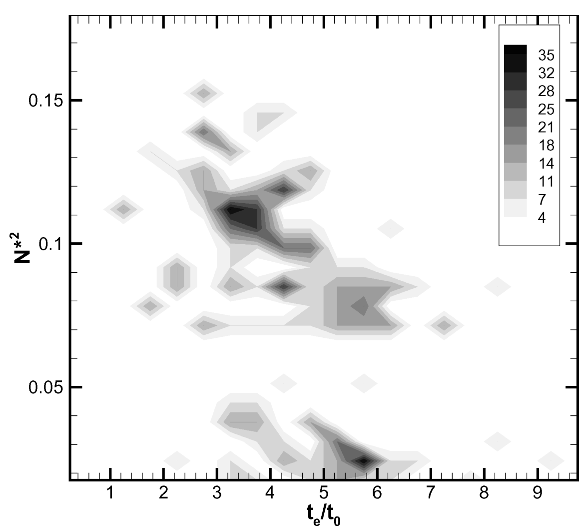
Fig. 1 Cumulative distribution of WV detection time for various meteorological flow characters and WVBC. Sample numbers: rapid decay, 350; moderate decay, 258; weak decay, 83 vortices: a) cumulative distribution of WV detection time for particular meteorological situations. The residual denotes cases where the *Ri* criterion is not fulfilled and b) cumulative distribution of detection time for the WVBC.

For practicable applications, the tails of the cumulative distributions are of prime interest which correspond to the longest living wakes in a particular class. If we consider a 95% threshold, the plots indicate differences of up to three time units for the WVBC rapid decay and weak decay. For a typical medium aircraft this corresponds to approximately 70 s.

As a cross check we consider joint frequency distributions of WV detection time t_e vs ϵ^* and N^{*2} for wakes evolving in a turbulent environment ($Ri < 0.25$, Fig. 2a) and for wakes evolving in a stable stratified environment ($Ri > 1$, Fig. 2b). If we consider the turbulent atmosphere we find that short detection times are on average associated with high ϵ^* levels, whereas decreasing ϵ^* levels seem to correspond to longer living wakes. However, there is no one-to-one relationship between ϵ^* and detection time. Most likely, the scatter reveals the influence of other atmospheric parameters on WV decay and the fact that ϵ^* is measured at a constant height. The scatter is



a) Vortices in turbulent environment ($Ri < 0.25$)



b) Vortices in stable stratified environment ($Ri > 1$)

Fig. 2 Joint frequency distribution of eddy dissipation rate ϵ^* (a) and Brunt–Väisälä frequency N^* (b) versus detection time t_e (in per mil). Only out of ground effect (OGE) cases are considered.

even larger if we consider the wake evolution in a stable stratified atmosphere (not shown). This is expected as turbulence becomes a more intermittent phenomenon in time and space such that a local ϵ measurement does not necessarily relate to the conditions in a region where the wake evolves. The joint frequency distribution of N^* and t_e also indicates scatter, but there seems to be a decrease of WV detection time for increasing N^* for $N^{*2} > 0.07$. Conditions with stable stratification ($Ri > 1$) are associated with weak turbulence levels (mean value is $\epsilon^* = 0.07$). Cases with $Ri < 0.25$ are associated with moderate turbulence levels (mean value is $\epsilon^* = 0.22$) with mostly neutral and unstable stratification. These joint frequency distributions corroborate the dependence of WV detection time, and presumably the vortex life span, on the atmospheric background state.

Comparison to the ICAO Separation Matrix

The cumulative distributions of Fig. 1 are analyzed in terms of the existing ICAO separation standards. Assuming two representative aircraft, from the heavy (B747, $\Gamma_0 = 557$ m^2/s, $t_0 = 29$ s) and medium (A320, $\Gamma_0 = 282$ m^2/s, $t_0 = 16$ s) weight classes, with an approach speed of 70 m/s, we compute the corresponding distances that then can be compared to the existing ICAO separation. The separation for a pair of aircraft heavy behind heavy (H → H) is 4 n

Table 2 Average normalized circulation $\bar{\Gamma}^*$ and the corresponding standard deviation σ_{Γ^*} at the end of a WV measurement for a vortex detection time larger than 60 s

WVBC	$\bar{\Gamma}^*$	σ_{Γ^*}
Rapid decay	0.43	0.2
Moderate decay	0.53	0.18
Weak decay	0.42	0.3

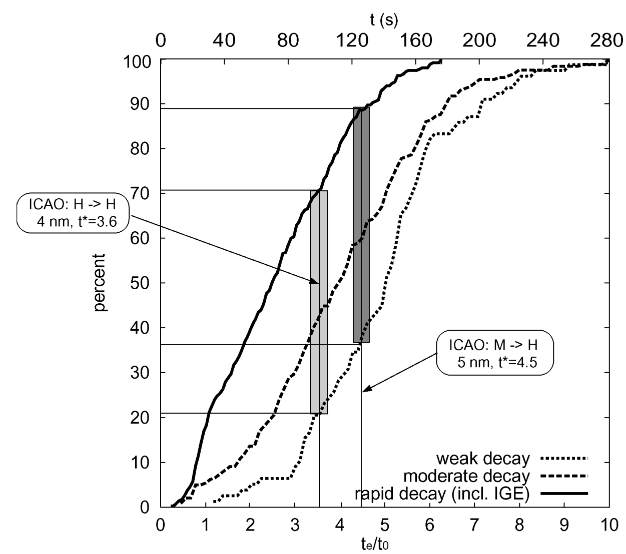


Fig. 3 Cumulative distribution of WV detection time for WVBCs related to ICAO separation M → H and H → H. Also shown is the dimensional time axis using $t_0 = 29$ s.

miles ($t^* = 3.6$). From the cumulative distribution in Fig. 3 we find that only about 70% of the WVs have decayed in the rapid decay class, about 45% in the moderate decay class, and about 20% in the weak decay class. The required separation for a pair of aircraft M → H is 5 n miles ($t^* = 4.5$). For this pairing we find that close to 90% of the WVs of heavy aircraft have decayed in the rapid decay class, about 60% in the moderate decay class, and about 35% in the weak decay class. The gray bars highlight the range of decay times with their corresponding frequency of occurrence linked to atmospheric conditions for a given separation. From this we can conclude that in all cases substantial fractions of the WVs have not decayed, suggesting that decay is not the dominant hazard reduction mechanism. Therefore, WV transport seems to be the prime reason that existing separation standards can be viewed as safe.

The preceding discussion relies on the assumption that the WVs have decayed once the measurements end. The limits of our simplified assumption can be illustrated by the computation of the mean circulation and standard deviation of those vortices living longer than 60 s (approximately $t^* = 3.7$ for each of the classes in Table 2). In addition we compute the average circulation around the separation time corresponding to various separation distances (Table 3).

Table 2 clearly shows that the vortices on average still have significant circulation (on the order of 40–50% of Γ_0 or approximately 100 m^2/s for the Memphis traffic mix) at the end of the measurements, which in turn implies that the fraction of WVs with substantial circulation for a given separation in Fig. 3 is even larger. Presently there is no consensus on an acceptable threshold circulation value.

The fairly large circulation values at the end of a record are presumably related to the automated analysis algorithm that stops once there is no coherent vortex profile found in the lidar signal. The complexity of evaluating WV data from lidar signals is shown in Ref. 24. There, it is demonstrated by means of large eddy simulation (LES)

Table 3 Average normalized circulation and the corresponding standard deviation of vortices at 66 s (2.5 n miles, 233 vortices), 104 s (4 n miles, 44 vortices) and 132 s (5 n miles, 9 vortices)[a]

Separation distance	$\bar{\Gamma}^*$	σ_{Γ^*}
2.5 nm	0.55	0.18
4 nm	0.42	0.15
5 nm	0.34	0.10

[a]Average circulation has been computed in a 10-s window. All wake data have been considered.

and observational data that WVs, which have lost their classical velocity signature due to their interaction with atmospheric boundary-layer turbulence, may still have 50% of their inital circulation.

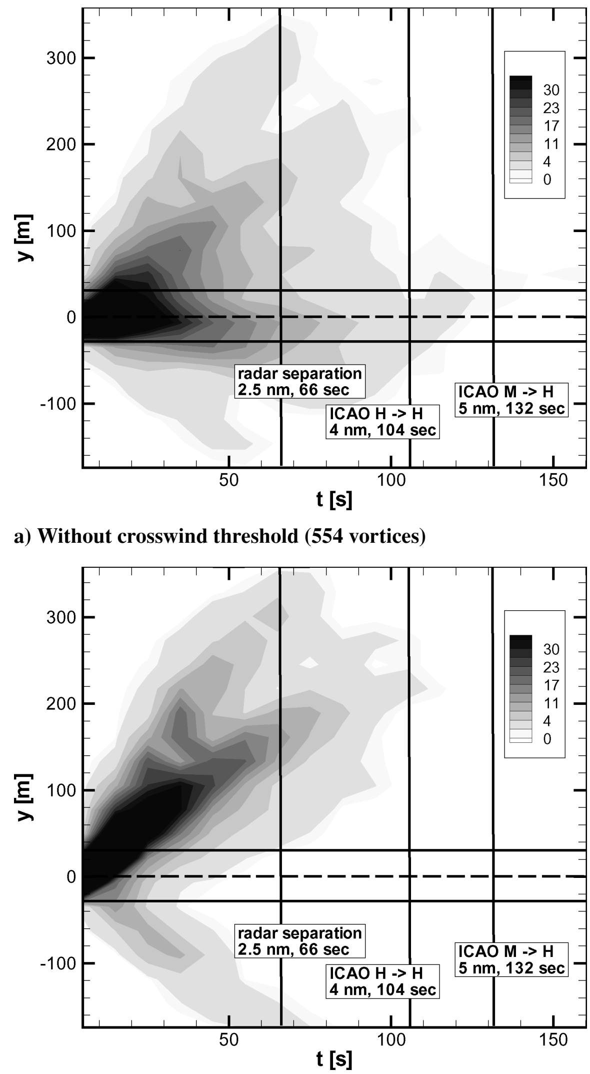
The average circulation at the different separations (2.5–4–5 n miles) indicates a decrease in circulation with increasing separation, but all with nonnegligible circulation values. Here all wake data have been considered without a classification into WVBC. In contrast to the preceding use of normalized quantities, the consideration of dimensional separation distances leads to a substantial reduction of samples with increasing separation because the majority of aircraft belong to the medium class (small t_0 compared to heavy aircraft). Therefore, the average circulation at 5 n miles separation has considerable uncertainty.

Lateral and Vertical WV Transport

The preceding discussion indicates that WV transport appears to be the prime reason that existing separation can be viewed as safe. We therefore investigate the vertical and lateral WV position with respect to the ICAO separation. In the following we assume a corridor dimension of 60 (lateral) $\times$ 40 m (vertical), which corresponds to twice the standard deviation of the distance of approaching aircraft from the instrument landing system (ILS) localizer at a height of approximately 200 m above ground (2 n miles before touchdown) measured recently at Frankfurt airport.[27] This deviation increases with increasing distance from the runway threshold. The corridor dimensions are approximately 100 (lateral) $\times$ 160 m (vertical) at the intercept 12 n miles before the runway threshold. Only out-of-ground data are considered and the mean WV positions from Lidar data are used. The aspects of lateral transport of WV in-ground effect are investigated elsewhere.[3,28] The WV positions are given relative to the initial position of the aircraft when passing through the Lidar scan plane. The area where a vortex is hazardous because of its rolling moment it may impose on a following aircraft is not considered in the definition of the safety corridor that accounts for the navigational error only. The distance of a following aircraft relative to the vortex that eventually causes a hazardous rolling moment is dependent on the aircraft geometry. This distance must be added to the safety corridor dimensions.[29]

Figure 4a shows the joint frequency distribution of lateral position vs time. The vortex trajectories are considered. Also sketched is the safety corridor. For all three separations shown in the graph WVs appear in the safety corridor. If we consider the combination M $\rightarrow$ H, in total 4 (6) out of 554 vortices are found within the lateral dimensions of the safety corridor (the number of wakes for the larger corridor dimension given in parantheses), 18 (24) vortices for the combination H $\rightarrow$ H and 70 (97) vortices for a separation of 66 s, which corresponds to radar separation. For the 70 (97) vortices from the radar separation case, it is illustrated in Fig. 5 that 5 (72) vortices are at the same time within the vertical limits of the safety corridor, and there is 1 (12) vortex (vortices) for the H $\rightarrow$ H combination, and 0 (1) for the M $\rightarrow$ H separation. The consequence of a wake in the safety corridor has to be weighted by the probability that a wake actually is encountered in a hazardous way by a following aircraft. ICAO separation indicates a much lower risk for encountering a wake compared to that for radar separation. But even for ICAO separation, a safety corridor free of wakes cannot be guaranteed without any further restrictions.

If we assume an arbitrary critical crosswind level of 2 m/s, no wakes are found within both lateral safety corridors dimensions



a) Without crosswind threshold (554 vortices)

b) With crosswind threshold $|u_c| > 2$ m/s (251 vortices)

Fig. 4 Joint frequency distribution of lateral vortex positions versus time (in per mil). We consider the lateral vortex position relative to the initial aircraft position; only OGE cases are considered.

for all three separations (Fig. 4b). This crosswind value has been determined from profile data as the median between 40 and 200 m. A crosswind larger than 2 m/s is found for 251 vortices. It is obvious that crosswind proves a very efficient mechanism to guarantee a vortex-free flight corridor. The crosswind threshold has, as expected, no significant influence on the joint frequency distribution of vertical WV position (not shown).

Not taking into account the lateral transport, we consider the effectiveness of vertical WV transport to clear the safety corridor. Initially the observations show large deviations from the reference level, which can be related to uncertainties of the measurements during the early WV roll-up phase (Fig. 5). After that, the vertical WV position at a given time is the result of a combination of self-induced downward WV descent, atmospheric effects, and measurement uncertainties. We find 17 (195) vortices for a separation of 66 s within the vertical dimensions of the safety corridor, 1 (20) vortex (vortices) for H $\rightarrow$ H, and 0 (3) vortices for M $\rightarrow$ H (again, the numbers for the larger corridor dimension are in parentheses). Therefore, only the consideration of the lateral position together with a critical crosswind threshold will guarantee a WV-free corridor.

As a side note, for in-ground-effect vortices, a crosswind threshold of 2 m/s is also sufficient to provide a WV-free corridor for all separations investigated earlier. However, this observation is based on a fairly small sample size of 127 vortices.

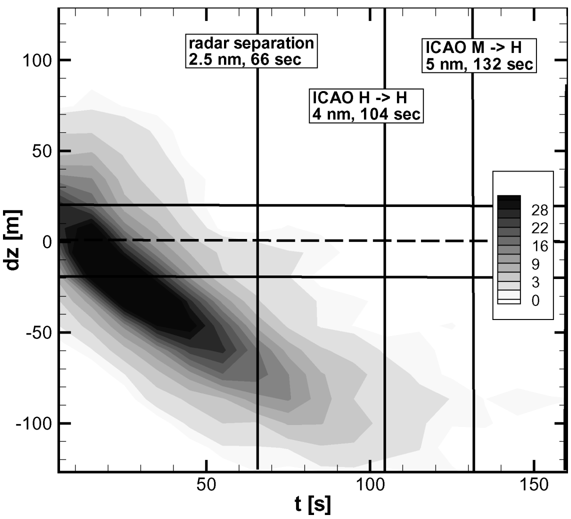


Fig. 5 Joint frequency distribution of vertical vortex positions vs time (in per mil). We consider the vertical vortex position relative to the initial aircraft position. No crosswind threshold is taken into account and only OGE cases are considered.

To extend the preceding analysis, we have estimated the potential of the transport class for Frankfurt Airport using a meteorological database generated for the High Approach Landing System risk assessment. This database, generated with a mesoscale model, provides a climatology of wind, temperature, and turbulent kinetic energy profiles along the glide path including the diurnal variation of those profiles.[30] We have analyzed wind data between 50 and 1200 m for crosswinds larger than 2 m/s, requiring that this threshold has to be exceeded at all levels. This is the case on average for 37% of the profiles analyzed (summer: 35%; winter: 39%). Assuming a more conservative threshold of 3 m/s, the percentage reduces to 25% (summer: 22%; winter: 27%).

A simple estimate of the potential throughput increase for a crosswind threshold of 2 m/s is obtained by using some assumptions. It is assumed that the whole time share of 37% can be used operationally. Furthermore, as an example we assume a sequence of heavy–medium aircraft along the glide path that are staggered with ICAO separation (i.e., 5–3–5–3 n miles), which is compared with the same sequence staggered by radar separation (2.5 n miles). Assuming a glide path of 13 n miles length, we estimate a throughput increase of about 20% for this specific combination of weight categories. If we consider only medium aircraft, an increase of 17% is estimated. It is obvious that these estimates, in reality, will be lower.

These figures indicate the significant potential for reducing separation based on crosswind alone while the percentages are expected to represent a lower bound. One of the next steps is to assess the predictability of those situations that favor the transport of the vortices out of the glide path. A successful example of a crosswind forecast algorithm is implemented in the Frankfurt WVWS.[31] There, a statistical algorithm based on the persistence concept provides forecasts of the crosswind over a prediction horizon of 20 min. The forecast is driven by actual wind measurements near the runway threshold. This algorithm is optimized to satisfy the operational needs of the air traffic controller.

Discussion

We have demonstrated that it is possible to classify WV behavior for specific atmospheric conditions via simple criteria. So far, the WVBC classification is not yet optimized to permit changes in separation solely based on decay. An analysis of the AVOSS performance[32] suggests that WV demise contributes to the expected throughput increase. This may also be concluded from the cumulative distribution (Fig. 3) of the rapid decay class, where about 40% of the WVs have decayed under radar separation (assuming a time separation of $t^* = 2.3$). In particular for cases of weak crosswinds, consideration of WV demise seems to have potential for reduced separations. Therefore, atmospheric situations with weak winds together with a sufficient level of turbulence should be considered in the WVBC concept, which requires a refinement of the rapid decay class. The refined class has to identify those cases and should include the convective boundary layer (CBL) from which it is known that WVs decay rather quickly.[11] Simple robust models of the CBL do exist and an approach to diagnose a CBL has been described recently.[33] The refinement of the rapid decay class will be tested in a follow-on study. In general, the new concept needs to be tested against other WV databases in order to evaluate our conclusions drawn from the analysis of the Memphis data.

Our analysis indicates that a simple crosswind threshold seems to allow approaches with radar separation. Of course, the problem has to be reevaluated if closely spaced runway operations are considered. In addition, it is still a challenge to obtain high-quality wind data along the whole glide path. The wind field uncertainty in time and space due to turbulent fluctuations, surface heterogeneity, and orography needs to be established individually for a given airport.

Furthermore, a validated WVBC approach may simplify a risk assessment for an operational system as the number of free parameters is reduced. With this classification scheme, it is possible to estimate the potential capacity benefit for an individual airport if the climatology of the relevant meteorological parameters in the vicinity of the glide path is known (see, e.g., Ref. 30).

Summary

We have introduced the concept of WVBCs and have provided an initial validation using WV and atmospheric measurements from the Memphis database. We are able to classify WV decay behavior using simple Richardson number criteria. The decay of WVs can be grouped into the three categories: rapid, moderate, and weak decay. There are distinct differences of up to three time units with respect to decay between those WVBCs. So far, the consideration of WV decay alone does not permit the spacing reduction of approaching aircraft even for the rapid decay class; to allow this, a refinement of the rapid decay class is necessary. The cumulative distribution of WV detection time indicates that a substantial number of WVs have not decayed for ICAO separated aircraft. The Memphis data indicates that crosswind is essential to clear the flight corridor. In our investigation a crosswind threshold of 2 m/s is sufficient to provide a WV-free safety corridor even if the aircraft are separated by 66 s. Without this threshold wakes are found within the safety corridor for ICAO separated aircraft. The hazard of a wake in the safety corridor of course must be weighted by the probability of an encounter of a following aircraft. The analysis of a wind climatology representative for Frankfurt Airport indicates the substantial potential of the transport class to allow spacing reduction of approaching aircraft.

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