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WAKE TURBULENCE RE-CATEGORISATION ON APPROACH AND DEPARTURE FOR SAFE AND MORE EFFICIENT AIR TRAFFIC MANAGEMENT

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Abstract

Current wake turbulence separation minima between successive arrival or departure air traffic are usually based on ICAO 3-category scheme (with specific minima for A380), using maximum gross weight as criterion. Possible significant efficiency optimization can be achieved from increased number of categories or establishment of aircraft pair-wise separation minima, enabling a reduction of over-conservatism for some aircraft pairs, while maintaining an acceptable safety level.

1 Introduction

The demand is high for increasing airport capacity and efficiency at some European airports, in particular for increasing runway throughput from an air traffic management perspective. Runway capacity and efficiency is often directly linked with the minimum longitudinal separation between traffic on approach phase and on final approach, or between departure traffic. The separation minima are based on surveillance capabilities and on wake turbulence (WT) in order to mitigate respectively collision risk and wake turbulence encounter(WTE)-induced accidents.

During recent years, knowledge about wake vortex (WV) behaviour in the operational environment has increased thanks to measured data and improved understanding of physical processes. It is mainly for this reason that it has been possible to revise wake turbulence categorization and corresponding separation minima, enabling the optimization of airport/runway throughput and efficiency whilst maintaining acceptable levels of safety.

2 Wake Turbulence

Every lift-generating, hence flying, aircraft trails wake vortices. The trailing vortices roll-up into a pair of coherent, counter-rotating vortices that can persist for several minutes after the the generating aircraft has flown by, potentially causing a hazard to any following aircraft that may encounter these vortices. The trailing vortices' rate and time to dissipate depend on the weight, size, wing configuration and speed of the aircraft as well as atmospheric conditions.

ICAO Doc 9426 Air Traffic Services Planning Manual presents considerations about WT and WTE effect on aircraft: "The three basic effects of wake turbulence on a following aircraft are induced roll, loss of height or rate of climb, and possible structural stress. The greatest danger is the roll induced on the penetrating aircraft to the degree that it exceeds the counter control capability of the aircraft concerned. Should the wake turbulence encounter occur in the approach area, its effect is greater because the following aircraft is in a critical state with regard to speed, thrust, altitude and reaction time. The vortices are most dangerous to following aircraft during the take-off, initial climb, final approach and landing phases of flight, as recovery time for temporary loss of control is less close to ground."

In order to mitigate WTE inducing unrecoverable situation in the approach and departure phases of flight, wake separation provisions have been set in ICAO Doc 4444 PANS-ATM since decades, based on a grouping of aircraft types into three categories according to the maximum certificated take-off mass (MTOM) as follows:

- HEAVY: 136000 kg or more;

- MEDIUM: less than 136000 kg but more than 7000 kg;
- LIGHT: 7000 kg or less.

The Airbus A380-800 has specific provisions defined in an ICAO State guidance released in 2008 with safety case [1].

Table 1 presents a combined view of the distance separation minima between preceding (leader) and succeeding (follower) aircraft.

		FOLLOWER			
		A388	**HEAVY**	**MEDIUM**	**LIGHT**
LEADER	A388		6 Nm	7 Nm	8 Nm
	HEAVY		4 Nm	5 Nm	6 Nm
	MEDIUM				5 Nm
	LIGHT				

Table 1: ICAO PANS-ATM wake turbulence distance-based separation minima on approach and departure

It must be noted that these provisions do not completely prevent adverse wake encounters (WE) occasionally occurring.

3 Wake Re-Categorisation Principles

An optimization of ICAO provisions can be achieved either by increasing the number of categories, still based on the maximum take-off mass, and by taking into account the aircraft type resistance to a wake turbulence encounter, using aircraft wingspan as additional parameter or by defining pair-wise separation (PWS) minima.

The increased number of categories or the PWS minima enables to remove some over-conservatism from the ICAO provisions, with a separation minima reduction for followers behind weaker wake generator types, and/or for followers with higher wake resistance, and additional reduction when both are combined, see **Figure 1**.

The ICAO separation minima between strongest wake generators and least resistant followers are considered as reference design case and are not modified.

Safety benefits are also provided for most vulnerable aircraft types, by increasing some separation minima and/or change of category grouping.

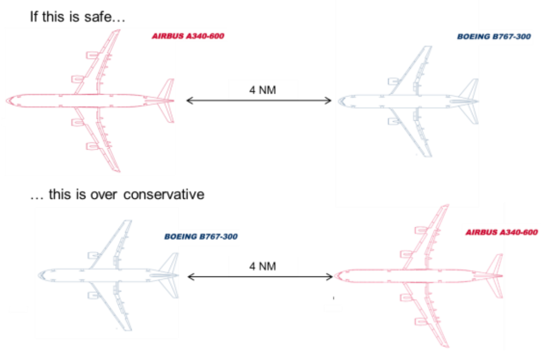

Figure 1: Over-conservatism in wake turbulence separation minima between aircraft types from ICAO Heavy Category

4 Safety Principles

For all proposed changes to WT separation minima, safety assurance needs to be provided that the WT risk will remain acceptably safe, by applying established safety criteria.

Since no absolute target level of safety is agreed for wake turbulence, an acceptable reference scenario must be defined and proven to be acceptably safe from an accident risk viewpoint.

For the aircraft types impacted by a reduction of the wake separation minima, the WT risk will increase, so the wake separation reduction must be such that each aircraft type will not be exposed to a greater maximum wake encounter severity than a reference level which can be considered as acceptable based on that currently experienced with the ICAO wake separation provisions.

For the most WT-‘vulnerable’ aircraft pairs, i.e. more exposed in terms of maximum WE severity than the acceptable reference level, safety is also enhanced by increasing their separation minima, hence reducing risk of WT-induced accident.

The risk must also be shown to remain acceptable in all operating conditions, and in particular for the ones considered as “reasonable worst case”.

The following safety criterion has been established:

For an aircraft type pair at revised separation minima, the pair-wise wake turbulence risk (severity) shall not be higher than the risk (severity) of reference aircraft type *pair selected as acceptable baseline with proven extensive operations at ICAO minima and in reasonable worst-case conditions.*

This approach was previously followed to develop the safety cases supporting the ICAO provisions of wake turbulence separation minima applicable to A380 [1] and B747-8[2].

The reasonable worst case (RWC) situation for an arrival aircraft to encounter a WV can be defined by the following parameters for WV generation and evolution, and encountering aircraft recovery capabilities:

- weather conditions are such that the WV is not transported by the wind out of the flight corridor of the follower aircraft in case of in-trail arrivals to single runway;
- weather conditions affecting decay of wake vortex circulation, i.e., atmospheric turbulence and temperature stratification, are such that there is minimum decay of the wake vortex circulation (low wind, low turbulence, low stratification);
- the follower aircraft encounters the wake vortex while flying close to the ground during its approach to landing. It is acknowledged that wake turbulence encounters can also occur on the glide slope and especially at glide slope intercept during approach operations. Due to the missing interaction with the ground the vortex strength is typically larger for identical separation distances under these circumstances. Nevertheless, these operational scenarios are regarded as less hazardous compared to encounters close to ground because more height above ground remains for counteracting the adverse effects of an encounter.
- the wake vortex potentially encountered close to the ground consists of a single vortex since the two rolled-up WV are known to separate laterally when entering into interaction with the ground boundary layer;
- the encountering aircraft passes through or close to the WV centre with a shallow horizontal encounter angle.

The demonstration of satisfaction of the safety criterion has been established by carrying a comparative WT risk assessment between aircraft types. This has been quantified based on aircraft characteristics and WV data, through applying relevant WT severity metrics to characterize wake generation and resistance. This has also included both comparison between aircraft types and relative to a reference acceptable baseline.

The safety assessment has primarily been conducted for the reasonable worst-case conditions on approach phase of flight. This is considered as wake separation design case.

5 Safety Risk Metrics and Data

To quantify the WT risk, a metric has been selected to characterize the WTE severity.

For wake encounters during final approach and departure (typically with small encounter angles) the predominant impact of wake vortices on the encountering aircraft is the rolling motion. For this reason it is logical to choose a severity criterion which takes the wake-induced rolling moment into account.

The rolling moment is, however, a dimensional quantity which makes it difficult to use for a global comparative analysis using various types of followers. The primary metric eventually selected for the safety assessment is the Roll Moment Coefficient (RMC). It allows evaluation of the wake impact on an aircraft, and comparison between aircraft types of the impact of a same wake vortex encounter.

The RMC is a dimensionless rolling moment-based severity metric, accounting for the aircraft ability to recover. It is the rolling moment M_v normalized using the air density ρ, the aircraft flight speed V_f, span b_f and wing area S_f:

$$RMC = \frac{M_v}{\frac{1}{2}\,\rho V_f^2\, S_f\, b_f} \tag{1}$$

Various simplifying assumptions are used to compute the RMC from the WV, leader and follower characteristics, allowing ones to calculate, a priori, the RMC related to a wake vortex encounter (WVE) for any given leader-follower aircraft type pair. The metric itself and its parameters have been chosen based on dimensional and physics-based analyses. The RMC metric has been shown to properly reproduce WE flight test results conducted by AIRBUS with two leader aircraft types (A388 and A346) and two follower aircraft types (A343 and A320). Details of the metric and its validation are provided in [3].

The quantification of an RMC for an aircraft type pair in RWC necessitates, as input:

- for leader (wake-generating) aircraft types:
  - wake strength (circulation) at the age and altitude of WVE
  - wingspan
- for follower (wake-encountering) aircraft types:
  - wingspan and wing aspect ratio
  - final approach speed profile to determine the time-to-fly the separation distance
  - stabilized approach speed

To characterize the wake circulation required for RMC computation, a large dataset of measurements collected by LiDAR technology at London Heathrow has been used, called EGLL-1 campaign. In total, the database contains 121,636 tracks (among which 54,516 HEAVY- generated WV).

The dataset has been used for deriving wake decay curves in RWC (corresponding to top 2% long-lasting wakes of the dataset) for aircraft types in ICAO HEAVY category.

The dimensional decay curves are obtained from a generic and dimensionless decay curve obtained when combining all WV tracks measured in RWC, see **Figure 2**, and made dimensional using, for each aircraft type:

- the measured initial wake circulation Γ_0
- the measured lateral WV spacing b_0

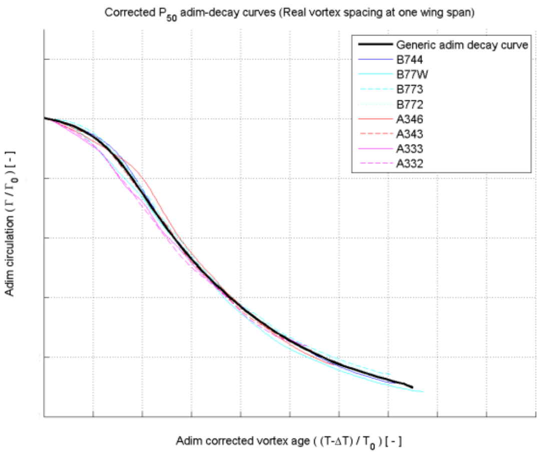

Figure 2: Dimensionless 50th percentile curves derived for large Heavy generator aircraft type compared to RECAT 50th percentile decay curves

The RWC decay characterization based on the EGLL-1 data analysis is further detailed in [4].

Some recent HEAVY aircraft types were, at the time of EGLL-1 campaign, very rare (A380-800 started operational service in end 2008) or not yet in operational service (like B747-8 and A350). However, they have been subject to a specific wake turbulence safety assessment supported by specific wake measurements [1], [2] [6].

The wake decay profile for ICAO MEDIUM aircraft types is also obtained from the generic dimensionless decay curve.

The observed decay rate in RWC has been confirmed applying the same methodology for wake decay characterisation to another wake dataset collected at Dubai.

The WT separation minima are all expressed in distances. However, the characterisation of a WVE depends on the wake evolution (transport and decay) and is always a function of time. It therefore requires converting properly the distance separation in time for the following aircraft to cover that distance. The final approach speed profile has hence to be characterized for each aircraft type to be able to compute the time separation corresponding to a distance separation.

A database of RADAR measurements, collected at various European airports, is used to determine typical final approach speed profile and final approach speed per aircraft type. The database provides between 3 months and 2 years approach measurement at each place.

When available, approach speeds as provided or suggested by the manufacturer, are also considered to assess consistency.

Finally, the aircraft data have been collected for a list of aircraft types covering the most frequent aircraft observed at busiest European Airports. The aircraft type characteristics are extracted from the information contained in *Airplane Manufacturer Manuals for Airport Planning* documentation.

6 Wake Encounter Flight Simulation Campaign

Evidence for acceptability of WT severity alignment between aircraft types of various sizes and under dynamic conditions have been obtained during a WVE flight simulation campaign, named Wake Impact Severity Assessment ('WISA').

This campaign consisted in comparing the acceptability levels by Pilots flying aircraft on final approach and exposed to various severity levels (expressed by RMC). The objective was to show that a RMC value being judged as acceptable on a given follower aircraft type is still acceptable on a larger aircraft type.

The campaign made use of a research flight simulator. The experiment was set-up considering six aircraft types (B744, A332, A320, F100, "F65", C550), distinguishing encounter at level flight (3000ft) and in approach (200 and 100ft), and for various RMC values. The "F65" is a scaled version of the F100 model in order to obtain an aircraft with a wingspan of 20 m, representative for the Embraer 145 which is used as reference aircraft in the safety assessment and separation design. In total, 768 simulation runs were performed.

The severity was rated by both the Pilot Flying and Pilot Not Flying for each run, using an eight-point rating scale. In addition, the pilots were asked to indicate whether or not a go-around would have been initiated in an operational environment.

The analysis shows that the data on severity metrics are well correlated: RMC appears to be a good metric for WVE severity, as it strongly correlates with the pilot severity rating.

These results support the wake severity alignment for Medium and Light aircraft onto the references pivot pairs. The results furthermore show that this alignment can only be partially applied for Heavy aircraft.

7 RECAT-EU Scheme with 6 Categories

Based on the principles, safety risk metrics and data described above, a new wake turbulence categorization on approach and departure, called "RECAT-EU", has been developed by EUROCONTROL, in close consultation with Stakeholders.

RECAT-EU wake turbulence scheme consists in a split of ICAO HEAVY and MEDIUM categories into 'Upper' and 'Lower' parts leading to 6 categories (indicated here as CAT-A to CAT-F). The RECAT-EU WT separation minima are provided in Table 2.

Leader / Follower		*"Super Heavy"*	*"Upper Heavy"*	*"Lower Heavy"*	*"Upper Medium"*	*"Lower Medium"*	*"Light"*
		"A"	"B"	"C"	"D"	"E"	"F"
"Super Heavy"	"A"	3 Nm	4 Nm	5 Nm	5 Nm	6 Nm	8 Nm
"Upper Heavy"	"B"		3 Nm	4 Nm	4 Nm	5 Nm	7 Nm
"Lower Heavy"	"C"		(2.5NM)	3 Nm	3 Nm	4 Nm	6 Nm
"Upper Medium"	"D"						5 Nm
"Lower Medium"	"E"						4 Nm
"Light"	"F"						3 Nm

Table 2: RECAT-EU WT distanced-based separation minima on approach

This split has been based on an initial clustering and grouping based on aircraft characteristics, i.e. weight and wingspan, then subject to refinement and validation by a quantitative wake turbulence risk assessment.

The clustering has been conducted on a sub-set sample of aircraft types representative of the European traffic. The clustering and categorisation is not based on any optimisation process related to traffic mix and capacity. This allows the resulting proposal to be adapted to any airport and related traffic.

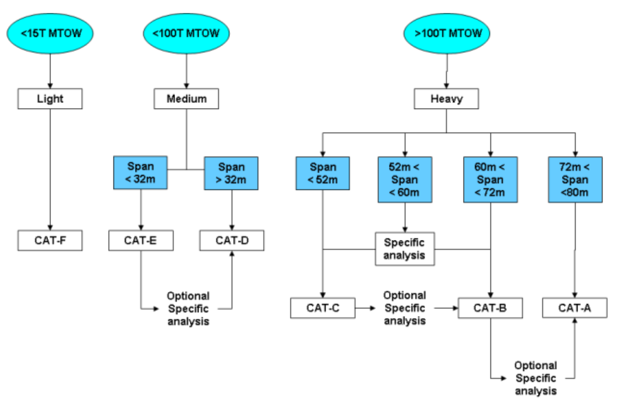

Figure 3: Categorisation process and criteria for assigning an existing aircraft type into RECAT-EU scheme

For historical reasons and considering its characteristics as categorisation metrics, the MTOM has been kept and used for defining the new categories. In a second step these categories are further refined based on wingspan criterion. The categorisation process of existing aircraft types in these CAT-A to CAT-F is presented in

Figure 3. It is firstly based on the wake generation characteristics as leader using the aircraft type MTOM as the criterion, and then on the wake resistance characteristics as follower using the wing span as the criterion. Following this logic, the categorisation of 2000+ aircraft types with ICAO designator has been established, based on the list of aircraft types identified in ICAO Doc 8643. Some examples of the most common aircraft types at European airports are provided in Table 3.

The principles used for RECAT-EU on approach phase are also used to revise WT time separation minima for some pairs on departure phase, in a proportional way.

'Super Heavy'	'Upper Heavy'	'Lower Heavy'	'Upper Medium'	'Lower Medium'	'Light'
'CAT-A'	'CAT-B'	'CAT-C'	'CAT-D'	'CAT-E'	'CAT-F'
A388 A124 (…)	A332 A333 A343 A345 A346 AN22 B744 B748 B772 B773 B77L B77W B788 IL96 (…)	A306 A30B A310 B703 B752 B753 B762 B763 B764 B783 C135 DC10 DC85 IL76 L101 MD11 TU22 TU95 (…)	A318 A319 A320 A321 AN12 B736 B737 B738 B739 C130 IL18 MD81 MD82 MD83 MD88 T204 TU16 (…)	AT43 AT72 B712 B733 B734 B735 CL60 CRJ2 CRJ7 CRJ9 DH8D E145 E170 E190 F70 F100 GLF4 RJ85 RJ1H (…)	FA10 FA20 D328 E120 BE40 BE45 H25B JS32 JS41 LJ35 LJ60 SF34 P180 C650 C525 C180 C152 (…)

Table 3: Example list of aircraft types assigned to RECAT-EU proposed categories

8 Wake Turbulence Risk Assessment

Using the data and computing the WT severity metric (i.e. RMC) at RECAT-EU separation minima in the defined RWC situation, the risk distribution is obtained for the core list of aircraft types. The WT risk is assessed on a pair-wise basis, comparing the reference ICAO WT separation scheme to the RECAT-EU separation scheme for assessing the satisfaction of the safety criterion formulated above.

The aircraft pairs used as acceptable baseline for severity comparison, are composed of a group of aircraft types (in the Lower Heavy and Lower Medium categories), for which the separation minima behind Heavies is considered as acceptable today in reference WT scheme (and not modified in RECAT-EU scheme). For consistency reason, a given pair with RECAT-EU separation will always be compared to a baseline pair of the same ICAO category. The baseline aircraft pairs are also frequent (i.e., on average 17% of all Heavy-Medium pairs in peak period at top 9 busiest European airports and reaching 24% at one airport).

Applied to all pairs of aircraft types from the core list, RECAT-EU scheme has been validated with a detailed WT risk assessment, consisting of different comparisons:

- evolution of the maximum severity encountered per follower or per pair in RWC ('Level 1').
- overall pair-wise WT risk comparison between followers within the same reference ICAO WT category ('Level 2').
- overall effect of RECAT on the wake turbulence risk distribution for all weather conditions (not only RWC) ('Level 3').
- pair-wise WT risk assessment detailed per separation minima applicable between WT categories considering the full distribution of circulation observed in RWC at specific separation. ('Level 4').

Figure 4 presents the 'Level 1' comparison between reference ICAO and RECAT-EU WT schemes for all followers. This plot shows that RECAT-EU scheme, compared to ICAO:

- increases the individual severities for the CAT-B types but remaining below 75% of a maximum observed severity for Medium excluding the lightest Medium < 15T);
- keeps constant individual severity for CAT-C types;
- increases the individual severity for the CAT-D, but remaining below the maximum individual severity observed in the Medium category (excluding the lightest Medium < 15T) that defines the maximum observed severity for Medium. It is also observed that the range of maximum individual severity in CAT-D with RECAT-EU corresponds to the range of maximum individual severity observed with ICAO reference scheme for the reference pairs (range defined by blue dash lines);

- keeps constant maximum individual severity encountered by CAT-E types;
- reduces the maximum severity encountered by the lightest Mediums (moved to CAT-F) compared to ICAO constant the maximum severity encountered by the Light (CAT-F);

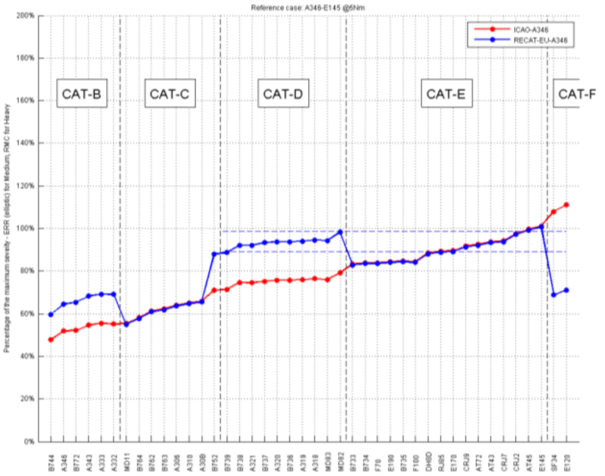

Figure 4: Overall comparison between ICAO and RECAT-EU schemes of WT severity for worst-case pairs (with Heavy leader) at separation minima in RWC (percentage of maximum observed severity for E145 behind A340-600)

An example of ‘Level 4’ WT risk assessment is illustrated in Figure 5. It shows that the resulting WT risk distribution in RWC at RECAT-EU separation minima for two selected CAT-B – CAT-B pairs ([A346 – B744] and [A346 – A332]) remains lower for high severity values than for CAT-B – CAT-C pairs at separation minima in acceptable reference WT scheme.

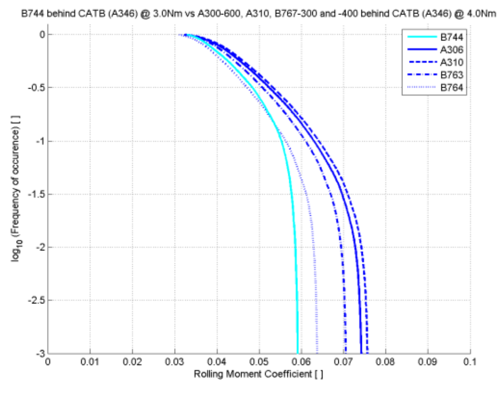

Figure 5: ‘Level 4’ risk distribution for CAT-B – CAT-B RECAT-EU test pairs and CAT-B – CAT-C pairs in reference WT scheme

For the aircraft types outside the core list used for validation, generalization criteria are defined for categorization into the RECAT-EU scheme. They are only based on aircraft primary characteristics of wake generation and WVE resistance (weight and wing span), while preserving the satisfaction of the safety criterion.

A first case of categorisation of a new Heavy aircraft type took place with the AIRBUS A350 family, where the variants were analysed in terms of wake generation, (characterized based on wake roll-up numerical simulation and wind tunnel measurements) and wake encounter resistance, being compared to the A346 as reference Upper Heavy aircraft. This resulted in categorization of A350 types as Upper Heavy (CAT-B).

9 Endorsement, Implementation, and Operational Benefits

Following extensive consultation of European Stakeholders, the RECAT-EU safety case has then been reviewed and endorsed by the European Aviation Safety Agency (EASA), and can be used as basis to update current schemes.

The scheme is not mandatory for deployment across all European States, but made available for local deployment based on Airport Stakeholders’ needs and benefits.

Any local deployment and operations based on RECAT-EU scheme needs to be supported by a safety assessment, complementary to the RECAT-EU ‘generic’ safety case, to address changes to the local ATM functional system enabling RECAT-EU operations.

First European ATC operations based on RECAT-EU have started on March 22nd 2016 at Paris Charles De Gaulle (CDG), with other major airports having expressed an interest in deployment.

RECAT-EU delivers significant benefits on separation management flexibility, as well on operational resilience with reduction in delay recovery and in cumulative delays

Capacity benefits are also predicted to be achieved, with an average arrival throughput increase of 5% to 8% in peak traffic period, depending on the traffic type mix and density. This represents for an airport like Paris CDG, up to 20 additional movements per day available in peak times when traffic is constrained.

10 Pair-Wise Separation (RECAT-EU-PWS)

Following RECAT-EU scheme with 6 categories as initial step of re-categorisation of ICAO wake provisions, a second step consists in the determination of a static “Pair-Wise” regime, where each aircraft type pair has its appropriate WT separation minima. The work takes place in the framework of Single European Sky ATM Research (SESAR) Programme, in Project 06.08.01. The PWS minima design is conducted on the basis of the RECAT-EU safety case methodology and metrics, with refinements to provide adequate assurance for use in a pair-wise analysis.

The distance-based PWS minima are initially determined for 96 aircraft types, frequent at European major airports and for which data are available to characterize the wake generation and wake encounter resistance.

Based on the observed obtained PWS minima, as well as on similarities in wingspan and MTOM, 14 categories of aircraft types are defined as leader and follower, as generalisation. The resulting 14-category scheme, based on a sub-division of the RECAT-EU 6 categories, covers most of the landplane aircraft types (about 90 %). The aircraft are assigned to one of the 14 categories, based on their MTOM, span and wing aspect ratio.

A third product is also developed: a 20-category scheme that combines the 14-category scheme with the RECAT-EU 6 category scheme, in order to cover all landplane aircraft types.

There are two ways to operate the RECAT-EU PWS distance-based solutions. First, for “Pair-Wise application” for arrivals and departure, the PWS minima can be applied as such, completed by another category-based separation matrix for other landplane aircraft ICAO types. This complementary separation standard can be either:

- the 20-category separation matrix,
- the 14-category separation matrix complemented by another regulated standard (e.g. ICAO), or
- another regulated standard (e.g. ICAO).

The pair-wise application requires an ATC separation support tool.

The RECAT-EU-PWS solutions can also be used to establish a customized N-category scheme, defined to be an optimum for a given traffic mix at an aerodrome, and built using a grouping of categories of:

- the 20-category scheme; or
- the 14-category scheme complemented by another regulated standard.

Such N-category scheme, applicable both on approach and departure, may need an ATC separation support tool, or not, depending on the number of categories and associated complexity of separation combination to be managed by ATC. The customized N-category separation scheme solution can correspond to RECAT-EU 6-CAT grouping (since RECAT-EU-PWS minima are inclusive of it), but also allows further local optimization considering local traffic mix.

The WT PWS minima are directly determined from the WT pair-wise risk assessment. The minima indeed results from relative comparison of pair-wise WTE severity in RWC with reference baseline aircraft type pairs at ICAO separation minima defining acceptable level for alignment of other pairs.

Although the PWS design logic is to align most of the pairs to a higher WT severity exposure, some margins are kept by the selection of the reference pairs with corresponding WT severity level and by applying conservatism on the determination of some parameters for the WT severity metric which cannot be characterized with sufficient precision.

Because it was found difficult to "fairly discriminate" different aircraft types of similar size as generator, the leader aircraft types are clustered in 9 groups depending on their similarities in span and MTOM. The dimensional wake decay curves are compared between reference generators in a given cluster, and the slowest decay profile is used as bounding wake decay for the cluster. The PWS minima are determined for the 9 reference leader aircraft types and applied (copied) to the other aircraft types of the cluster. This introduces some conservatism and safety margins to the resulting PWS minima. This also allows easiest association of other types with those with available LiDAR data.

Using the available datasets previously described, the Pair-Wise WT severity distribution are calculated for 96 follower aircraft types and the 9 reference leaders in RWC at ICAO separation minima.

Reference baseline pairs are selected to determine acceptable RMC values for PWS design by alignment of other pairs to that WT severity level. The reference leader-follower pair could theoretically be a "worst-case" (most exposed) pair in ICAO scheme. However, the selected pairs should provide the assurance that

- the corresponding severity exposure level has been frequently experienced (i.e. aircraft type pair frequent in peak time at busiest European airports),
- it does not lead to an increase of the risk of WT-induced accident and decreases this risk for the most exposed pairs, and
- it will provide an acceptable evolution in terms of overall risk.

The selected pivot pairs have, as leader, the AIRBUS A340-600 (A346) and cover three follower types, to accommodate different aircraft type configuration designs influencing WVE impact, for acceptable severity alignment:

- the EMBRAER 145 (E145) for MEDIUM and LIGHT category jets
- the ATR 42-500 (AT45) for MEDIUM and LIGHT category turbo-propellers
- the AIRBUS A310 (A310) for Heavies.

A specific reference type is selected for HEAVY followers considering the difference in RMC level compared to Medium types in RWC at ICAO minima and the limited assurance in full WT severity alignment acceptability.

The PWS minima are determined by aligning the calculated RMC on that of the reference aircraft type pairs, see Figure 6. The PWS minima are initially specified down to 0 NM without consideration or limitation of minimum radar separation (MRS) minima, even for pairs for which no wake separation minima are specified in ICAO PANS-ATM.

This leads to an increase of exposure for some follower aircraft types to levels considered as acceptable for baseline types. The justification for this alignment is based on analytical comparison of normalized (dimensionless) roll inertia and similarity in aircraft type configuration design influencing roll inertia. It has also been further confirmed through the wake encounter flight simulation campaign as described in Section 6.

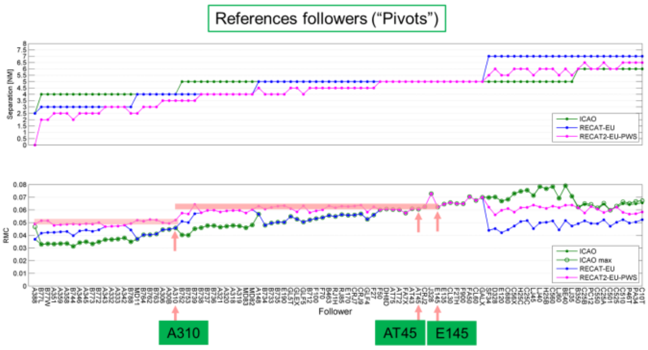

Figure 6: Comparison of pair-wise WT severity distribution in RWC between ICAO, RECAT-EU and RECAT-EU-PWS separation minima

Sensitivity analyses to several parameters (time-to-fly, flight speed, initial circulation and vortex spacing) of the RMC are performed in order to assess their effects on the obtained PWS minima. The analyses showed that the global behaviour of the risk curves in RWC remains the same, while in some cases, some pairs have a RMC slightly above the reference RMC, yet very close to that of the reference or to what is accepted at ICAO separation for similar pairs.

PWS minima are then revised following additional considerations. First, an assessment for out-of-ground effect (OGE) situation has been performed with decay model for OGE long lasting wakes based on LiDAR data. The analysis confirmed that for the large majority of the pairs, the PWS minima also meet the safety criterion for OGE case. Some pairs are however above the defined acceptability criteria, and for those pairs, safety margins are added. PWS minima, for which no ICAO wake separation minima are prescribed are aligned on ICAO. PWS minima are capped at 2NM behind HEAVY leaders to mitigate the risk of significant increase in WVE probability of occurrence. Finally, a consistency check of the obtained separations allows removal of some conservatism for minima behind MEDIUM leaders.

Comparing PWS and ICAO minima, the WT risk in RWC is increased for the lowest severity levels, while the highest severity levels are reduced, leading to a more aligned distribution. In all wind conditions, the risk distribution profiles with RECAT-EU-PWS and with ICAO are close, shifting towards higher probability of low severity encounter events.

11 Conclusions

The European solution for WT re-categorisation and PWS minima is based on a set of principles, comparing the wake generation and wake resistance between aircraft types.

RECAT-EU 6 CAT scheme splits ICAO Heavy and Medium categories into 'Upper' and 'Lower' part. This split starts from on an initial clustering and grouping based on aircraft characteristics, and results in a reduction of separation minima by 1 to 2 NM for followers behind weaker wake generator types, and/or for followers with higher wake resistance.

The static PWS minima design is developed for 96 frequent aircraft types on the basis of the RECAT-EU safety case methodology and metrics, endorsed by EASA. A derived 20-CAT scheme is also specified covering all aircraft types. Both PWS and 20-CAT minima are inclusive of RECAT-EU 6 CAT.

To cover all certificated aircraft types with ICAO designator, generalization criteria are defined based on aircraft primary relevant characteristics of wake generation and wake resistance (MTOM, wing span and aspect ratio) for categorization.

Both RECAT-EU and RECAT-EU-PWS are validated by a comparative WT risk assessment, quantified based on aircraft characteristics and wake data. It uses relevant WT metrics to characterize wake generation and WE resistance. For some aircraft pairs, the WT risk increases while keeping the maximum range not higher than currently observed for the most exposed pairs, considered as acceptable. On the other hand, safety benefits are also proposed for some aircraft types, by increasing some separation minima and/or change of category grouping, hence reducing their exposure to WT risk.

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