COMPARISON BETWEEN ARRIVAL AND DEPARTURE WAKE VORTEX STATISTICS NEAR THE GROUND

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OVERVIEW

In-Ground-Effect vortex measurements from arrival and departure aircraft have been made between 2003 and 2007 in a series of pulsed Lidar measurements in St. Louis, USA. These data collections support various objectives outlined in the joint FAA-NASA Wake Turbulence Research Management Plan (Ref. 1).

Wake turbulence data collection traditionally has been focused on arrival aircraft, leaving their departure counterpart less well understood. In response to the renewed interest internationally in studying vortices from departure aircraft, the present paper summarizes the initial results of comparing the vortex statistics near the ground between arrival and departure vortices generated from similar flight altitude to wingspan ratio and crosswind range. The present study also has the advantage that departure and arrival vortex data are collected from the same site, using the same sensor and the same processing technique, such that the relative characteristics can be revealed with simple statistical techniques and minimizing the potential biases from sensor, airport and processing related considerations.

The study to date suggests that departure vortices have similar initial circulations compared to their arrival counterparts, and that the survival probabilities are likewise very similar. There also exists indication that the measured age for wake demise is correlated with environmental turbulence. The overall implication is that statistics compiled and models developed from historical databases based on arrival vortices can be used at least as a first order estimate for examining departure wake mitigation concepts.

1. BACKGROUND AND INTRODUCTION

The Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) are conducting a joint wake turbulence research program (Ref. 1). The FAA-NASA Research Management Plan (RMP), initially released in 2003, envisioned a three-phase incremental approach to evaluating and developing wake solutions.

The near-term phase focuses on developing and implementing procedural changes to current arrival operations for closely-spaced-parallel runways (CSPR) without introducing weather or wake sensors. The near-term phase also distinguishes itself by eliminating the need to predict the wind field. Specifically the effort has been on examining the possibility of reducing the 2500 feet runway centerline separation minimum for dependent approaches to two closely spaced parallel runways (Ref. 2) when only *Large* and *Small* aircraft are involved. The procedure is designed to recover capacity loss under the current IFR conditions when runways separated less than 2500 feet are treated as single runways. St Louis Lambert International Airport (KSTL) in Missouri, US, was selected as the test bed for the near-term CSPR arrival concept, and measurements began in April 2003. The test site eventually evolved to having three pulsed Lidars, two propeller anemometer based Windlines at 12, 6 and 3-foot heights, three vortex Sodars, a 30-foot height three-axes propeller anemometers, laser range finders and pressure based aircraft detectors, as well as a multi-lateration aircraft tracking system.

Currently the joint FAA-NASA RMP is embarking on mid-term solutions that involve the potential application of wind-dependent procedures for improved departure operations from CSPR airports (Ref. 3). The program has entered a data collection phase to support the examination of crosswind based Wake Turbulence Mitigation Departure (WTMD). Because of both the interest expressed by the St Louis operational community and a suite of research sensors are already in place at KSTL, St Louis continues its role as the prime research site supporting the wind based CSPR departure related data collection. Initial short term measurements using a pulsed Lidar to collect departure vortex data at out-of-ground-effect (OGE) altitudes were made between January to April 2006, followed by the current setup of making dedicated wake and crosswind measurements near the ground since April 2006. The KSTL departure test site is recently also complemented by a 106-foot meteorological tower instrumented with high speed sonic anemometers, propeller anemometers, fine wire thermocouples and relative humidity probes.

It should be noted that the vast majority of the recent and historical wake turbulence measurements have been focusing on arrival operations. The literature on field wake vortex data from departure aircraft is therefore comparatively scarce. Of the available measurements on departure vortices (Refs. 4-9), data have mostly been collected in the near-ground-effect (NGE) and in-ground-effect (IGE) altitude range. This is in part motivated by the operational interest, as the region near the ground can be considered as the most safety-critical flight regime. In the data collection at KSTL supporting the near-term and mid-term program objectives, the majority of the measurements likewise have been in the regime near the ground.

Since both arrival and departure wake vortex data have been collected at same airport using the same measurement technique, same processing and at similar altitudes, an unusual opportunity presented itself to permit a statistical comparison between the wake dynamics relevant to the overall CSPR activities. The purpose of the present paper is to document the results of these comparisons.

2. MEASUREMENT SETUP

For the comparison of the arrival and departure data to be presented, measurements were made with two FAA owned WindTracer® pulsed Lidars manufactured by Lockheed Martin Coherent Technologies (formerly Coherent Technologies, Inc.) at two separate time frames. A diagram depicting the two Lidar locations and the associated scan geometries are shown in FIG 1. The FAA3 Lidar collected wake data from landings on Runway 12R, with an 17 degree offset oblique angle scan from the angle perpendicular to the runway. The FAA2 Lidar however, uses a perpendicular scan capturing the departures off Runway 30L. The respective dates of the database periods for the arrival and departures used in the comparison are respectively from March 2005 to June 2006 and from April 2006 to May 2007. The basic specification of the pulsed Lidar is given in Ref. 10, with the processing algorithm described in Refs. 11-12. Some aspects of the performance of the algorithm as of today are characterized in Ref. 13.

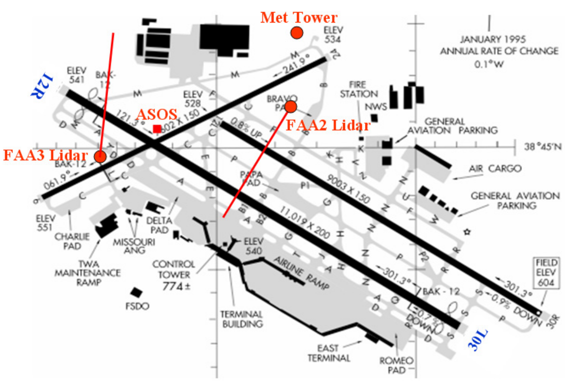

FIG 1. Diagram of the Two Wake Measurement Locations.

Since the arrival dataset uses an oblique scan for which crosswind cannot be obtained, the data comparison involving crosswind therefore utilizes the Automated Surface Observing System (ASOS) wind. The ASOS wind sensor location is also shown in FIG. 1. ASOS measures the horizontal wind at 10 meters height and outputs the data at a rate of once a minute. Also between October 2006 and January 2007, additional wind and turbulence measurements using an instrumented tower were made in a configuration that optimized data quality for Runway 30s departures. The location of the meteorological tower is shown in FIG. 1.

3. RESULTS AND DICSUSSIONS

3.1. Data Selection

The traffic mix at KSTL is mostly *Large*, which has a range of wingspans of about 89 to 108 feet. As such, arrival and departure datasets were first selected for tracks whose initial altitudes are in the range of 20 to 50 feet, which correspond to IGE altitudes for *Large* aircraft. The next filtering of the data involved including data that have only crosswind directions from 12R towards 12L for arrivals, and from 30L towards 30R for departures. After data have been filtered through the wind direction and altitude criteria, the distribution of the initial wake detection altitudes relative to the threshold of 12L is shown in FIG. 2. Note that the figure shows the number of vortex detections, not aircraft counts. The range of the ASOS crosswind component in the respective arrival and departure wake datasets is shown in FIG. 3.

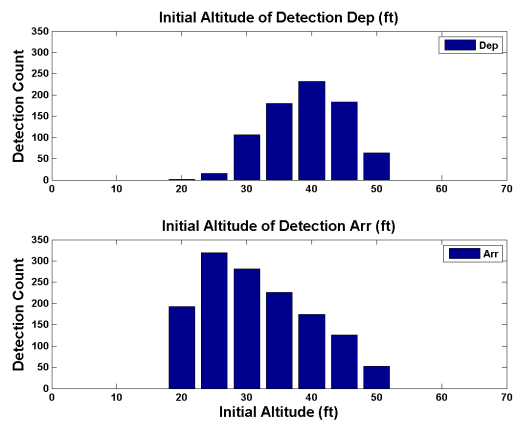

FIG 2. Initial Wake Detection Distribution in the Filtered Dataset Used for Statistical Comparison.

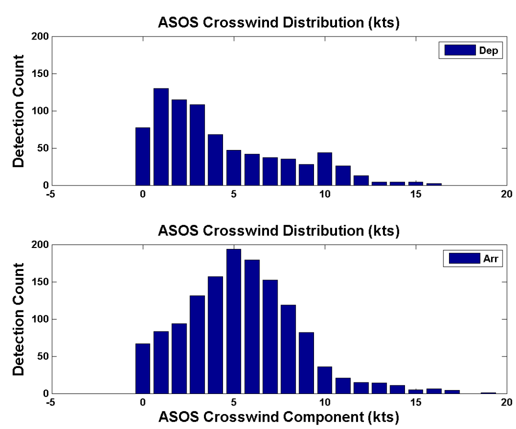

FIG 3. ASOS Crosswind Component Distribution in the Filtered Dataset Used for Statistical Comparison.

The distribution of the aircraft in the dataset that had been filtered through the aforementioned class, altitude range and crosswind direction are shown in FIG. 4. The number of aircraft in the arrival and departure datasets are 1022 and 563, respectively. It is noted that the relative distributions of the aircraft between the arrival and departure datasets are similar. B737s and MD80s are the dominant aircraft in the datasets.

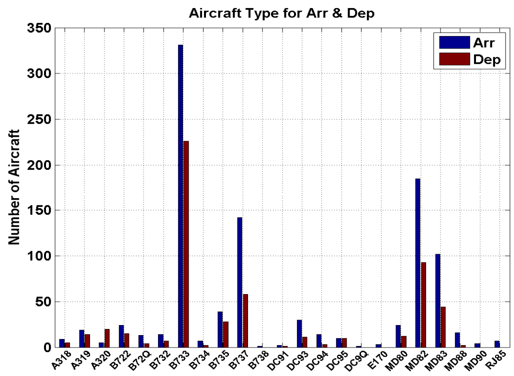

FIG 4. Aircraft Distribution in the Filtered Dataset Used for Statistical Comparison.

3.2. Final Age and Transport Statistics

The correlation between final wake age and crosswind, and that of transport distance and crosswind, are the most essential characteristics for CSPR operations. The comparison is therefore focusing on these two aspects. ASOS crosswind bins 2 knots wide were used, and the 50, 75 and 90 percentile statistics are shown in FIG. 5. The comparison is restricted to 14 knots, for beyond the sample sizes become too few. Also motivated by operational perspective, wake transport distances and the associated wake ages are not separated by upwind and downwind vortices. Similarly, the percentile statistics for both arrival and departure IGE vortex transports are shown in FIG. 6.

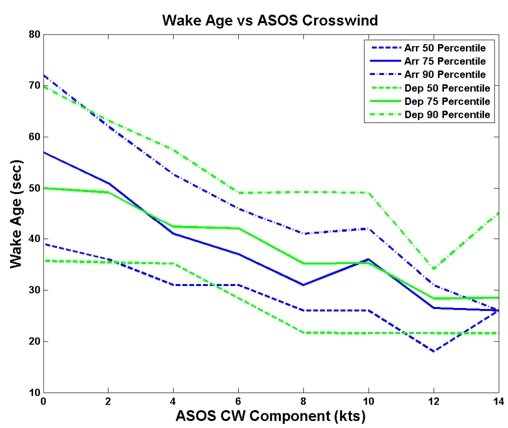

FIG 5. Comparison of Final Wake Age vs. Crosswind Component Statistics.

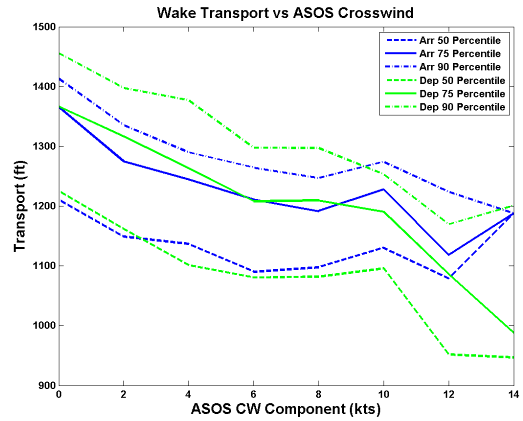

FIG 6. Comparison of Transport Distance vs. Crosswind Component Statistics.

There exists a strong visual similarity between the statistics shown at least at the 50 and 75 percentile levels. In examining the comparison, it is also useful to keep in mind that the scan rate for the arrival dataset is five seconds, whereas the departure data is seven seconds. Therefore, for the 50 and 75 percentile statistics, the difference between arrival and departure data in FIG. 5 is usually within one scan's time.

Both arrival and departure vortices generated near the ground have similar behaviors in that increasing crosswind reduces the age of the vortices, and that vortices under high crosswind do not transport as far as their counterparts in lower crosswinds. These characteristics have been documented, at least for arrival vortices, in prior FAA sponsored measurements as exemplified in Ref. 14.

The T-test was used to further quantify the similarities between the arrival and departure wake statistics shown in FIG. 5 and FIG. 6. Table 1 below details the sample counts contained in each of the crosswind bins. Again, the sample size represents the counts of both upwind and downwind vortices in each bin. Since the T-test requires the sample counts from each bin size to be identical, data were therefore randomly drawn before the test was applied. A common sample count that is 20 fewer than the smaller sample group is used. The data within each group were then scrambled with a random generator and then the amount of common samples were taken out of the random selection. Due to the low sample counts, the T-test was not applied to the data beyond the 8-10 knot range. The randomized process was repeated to ensure consistent outcome. The process repeatedly showed that within 95 percent confidence, the comparisons at the various wind bins considered are not statistically different from each other. Finally, note that the percentile compilation and the T-test examination adjusted for the less than perfect match of the crosswind distributions existed in the two datasets. In addition, within each crosswind bin, the percentile statistics essentially also conveyed the traditional vortex survival probability information.

Crosswind Bins (kts)	Arrival Samples	Departure Samples	Common Samples
0-2	188	211	168
2-4	232	202	182
4-6	338	94	74
6-8	239	74	54
8-10	100	67	47
10-12	19	49	NA
12-14	8	11	NA
14-16	1	7	NA

TAB 1. Summary of the Sample Counts in FIG. 5 and 6.

The shorter wake age of the vortices at high crosswind suggests an accelerated wake decay process compared to that at the low crosswind condition. A universally accepted mechanism to account for the observation does not appear to exist (Refs. 15-19), particularly the role of the turbulence from the environment vs. that of generated by vortex-ground interaction which are contained within the vortex cells. Details of the decay mechanism are beyond the scope of the present paper, however, turbulence data had been collected also at KSTL from October 2006 to January 2007 using three Campbell Scientific CSAT3 sonic anemometers sampling at 20 Hertz. The sonics were placed at three heights on the 106-foot high tower.

FIG. 7 shows the eddy dissipation rate (EDR) vs. surface wind data from the 48-foot height sensor with headwind for Runway 30s operations and with crosswind from 30L towards 30R. (This was selected as a representative height for the IGE regime for the current study, but the trend is generic of the data from all three sensor heights from the tower.) It is apparent that there exists a good correlation between EDR and wind in the IGE wake regime. Although turbulence is generated by the total surface wind, it is the crosswind component that is used to derive operational insight from the wake data for CSPR operation.

EDR is also plotted against runway crosswind, and the results are shown in FIG 8. Overall, there is still a good correlation beyond 5 knots crosswind components, which is operationally significant for CSPR-dependent operations highlighted in Refs 1 and 2. Values of EDR near the ground under high wind can be rather significant, and could have contributed to the demise of vortices during IGE under high wind. For example, an EDR of the order of 1.0E-2 under 15 to 20 knots crosswind component translates to a range between 0.3 and 0.4 in terms of non-dimensional EDR for the aircraft class considered herein. Under these high EDR conditions, it is expected (Ref. 15) that vortices would evolve into a ground linking state at a nominal value of 20 seconds.

As another example, between 4 to 6 knots crosswind, the typical range of non-dimensional EDR for the aircraft types considered herein 0.15 to 0.18, which then translated to an expected time to link of 30 seconds nominally. It is noted that these times are similar to the 50 percentile wake age vs. crosswind component values of FIG. 5, providing circumstantial evidence that the wake demise statistics near the ground are related to the environmental EDR, and that the Lidar is often tracking vortices past Crow linking stage.

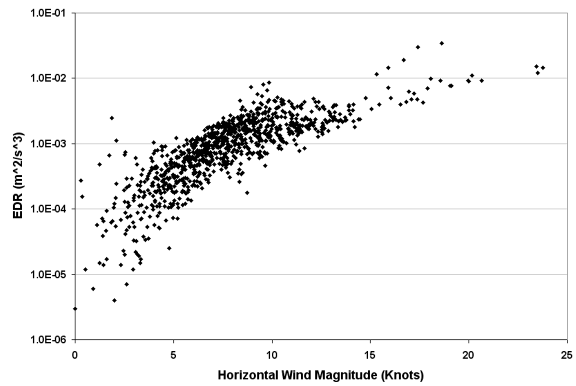

FIG 7. Ambient Turbulence vs. Horizontal Wind at 48 Feet Altitude.

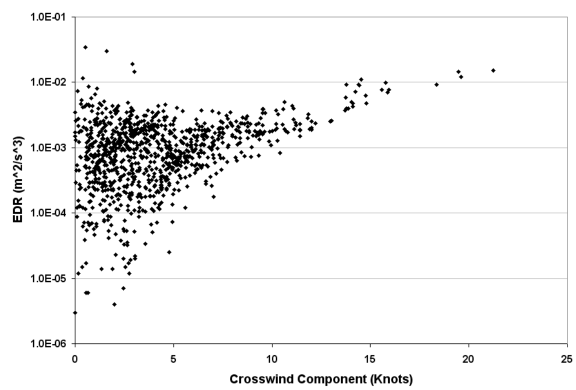

FIG 8. Ambient Turbulence vs. Runway Crosswind at 48 Feet Altitude.

Due to the difficulty that circulation data are often noisy and that the oblique scan used in the arrival data collection represented another complexity in the interpretation, the decay characteristics will be inferred via the following heuristic argument only.

The classical relationship commonly used to assess initial circulation, Γ, for arrival vortices should hold for departure as well.

(1)
$$\Gamma = \frac{W}{\rho_\infty \, U \, b_o}$$

where W, ρ_∞, U and b_o are the standard definitions of weight, air density, aircraft true air speed and initial vortex spacing.

Taking Equation (1) and normalizing the circulation of departure with arrival parameters yields:

(2)
$$\frac{\Gamma_D}{\Gamma_A} = \frac{W_D}{W_A}\frac{U_A}{U_D}\frac{b_{o,A}}{b_{o,D}}$$

A survey of W_D / W_A values indicates that the ratio for transport jets is in the range of 1.1 to 1.2 Ref. 20), and for U_A / U_D the nominal value is around 0.9. Finally, for $b_{o,A} / b_{o,D}$, the theoretical bound is likely to be slightly below unity. The Γ_D / Γ_A initial circulation ratio, in this argument, then is around unity. The final wake age statistics as shown in FIG. 5 reveal that departure and arrival vortices have similar wake ages (i.e., the time needed for the vortex strength to blend into background turbulence). Since circulations for arrival and departure vortices start approximately the same, and they have very similar wake age, the decay, at least in a statistical sense, would likewise be similar.

4. CLOSING REMARKS

The observation of departure vortices at IGE having similar statistics also imply that for the development of operational concepts, in the absence of dedicated departure wake data, historical IGE data collected from arrival traffic can be used. The reduction in wake age and transport distance with increasing crosswind is also observed in the IGE departure wake data, suggesting that the decay of departure vortices near the ground is subjected to a similar if not identical mechanism to that of arrival vortices. Globally, there exists some circumstantial evidence that the wake age statistics may be correlated with environmental turbulence.

ACKNOWLEDGEMENTS

The funding from the Federal Aviation Administration is gratefully acknowledged. We particularly thank Steven Lang and Jeffery Tittsworth of the FAA for their support and encouragement. The authors also thank the following USDOT Volpe Center personnel with great appreciation; Mike Geyer and James Hallock for critical comments, Amir Tabrizi for the overall meteorological data quality control effort, and Timothy Hall for the discussion on statistics.

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