

Measurements of Wake Vortices Interacting with the Ground

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Although wake vortices are known to decay more rapidly near the ground than away from the ground, the details of the ground interaction are not well understood. Propeller anemometer arrays located under the approach path have been used to study vortex transport and provide some information about the vortex interaction with the ground, such as the generation of secondary vortices via boundary-layer detachment. A propeller anemometer array at John F. Kennedy International Airport using 8.5-m poles was augmented with 1) a sonic anemometer measuring three-dimensional wind and temperature at 10 Hz and 2) a vertical array of vertical wind and crosswind anemometers, mounted at four additional levels (4.2, 3.2, 1.05, and 0.5 m). The sonic anemometer gave 1) measurements of turbulence inside the vortex flowfield and 2) indications of vertical variations in the ambient headwind and temperature, which were brought down to the measurement level by the descent of the vortex recirculation oval. In general, under conditions of low to moderate turbulence, the turbulence level inside the wake vortex flowfield is greater than that in the ambient wind. The vertical anemometer array showed that the crosswind profile under a wake vortex in ground effect has a very thin boundary layer, much thinner than that of the ambient wind. It also provided some details concerning the wind profile of the secondary vortex.

I. Introduction

VORTEX decay is known to be enhanced by proximity to the ground. The details of this interaction with the ground are not well understood. For example, how thick is the boundary layer below a wake vortex that has descended into ground effect? The boundary-layer thickness will influence the development of secondary vortices, which cause wake vortices to rise. When the wake vortex recirculation oval descends to the ground, it transports a sample of the atmosphere from the flight-path altitude down to the ground. Can measurements inside the wake vortex oval be used to estimate the potential temperature and headwind at the flight-path altitude? In a stratified atmosphere, the edge of the vortex circulation oval is a critical location for vortex decay. What are the temperature and velocity characteristics of this region of the vortex flowfield? These questions will be addressed in this paper using data collected using in situ sensors located below the final approach path.

In 1994, a wake vortex test site was established¹ near the middle marker on the approach to runway 31R at John F. Kennedy International Airport. An array of propeller anemometers (measuring vertical wind and crosswind) was installed on 8.5-m poles at 15-m spacing on a baseline 1) located 640 m from the runway threshold, 2) oriented perpendicular to the landing flight path, and 3) extending ± 107 m from the extended runway centerline. Propeller anemometer data are sampled at 10 Hz and averaged for 2 s before being recorded. The data collection system operates automatically, triggering the start of a run when a peak in aircraft noise is detected above a suitable detection threshold. Such an array can accurately track² the lateral motion of wake vortices and, using some recently developed algorithms, can also estimate the vortex height and circulation. Anemometer arrays are particularly suited³ for detecting wake vortices stalled on the extended runway centerline, where they

may be encountered by a following aircraft. The data from the array can also be used to determine the ambient wind and turbulence conditions.

II. Array Augmentation

Although the basic anemometer array can provide some information concerning the interactions of wake vortices with the ground, such as the detection¹ of secondary vortices, additional sensors were needed to address all of the issues of this paper. These sensors were installed before a special test in November 1996, which provided most of the data for this paper.

The coordinate system is defined with respect to the pilot of a landing aircraft. The zero lateral position is the extended runway centerline. A positive lateral displacement is to the pilot's right. A positive crosswind blows toward the pilot's right. A positive headwind blows from the runway.

A. Additional Propeller Anemometers

Additional propeller anemometers were installed at heights of 4.2, 2.1, and 1.05 m above ground level (AGL) at a lateral position of +30 m. Both vertical wind and crosswind components were measured. Although separate poles were used for some of these anemometers, all were located close to the main array pole (8.5-m height). Because the November 1996 1.05-m measurements showed almost full crosswind, but little vertical wind, the 1.05-m vertical wind anemometer was moved to measure the crosswind at 0.5 m during a special test in May 1997. Note that, because the grass at the test site can grow taller than 1 m, it was mowed regularly during the two test periods.

B. Sonic Anemometer

A high-speed sonic anemometer, which measures temperature and all three wind components, was installed at lateral position -15 m. Because it was installed on a separate 8.5-m pole, the sonic anemometer was displaced 15-m farther away from the runway threshold, relative to the main propeller anemometer array.

C. Data Collection

Data from these new sensors were recorded for 10 days in November 1996 and included approximately 1800 arrivals. Aircraft types included the full fleet mix at Kennedy Airport, including a large fraction of heavy aircraft. Identification of aircraft types was available

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only during the daytime working hours when the site was staffed. Because conditions of nocturnal inversion provided the most interesting runs for this paper, most the data presented will not include the aircraft type.

D. Data Analysis

Because only one lateral position was augmented with the special sensors, the data analysis process had to identify runs where the wake vortices either stalled at the sensor location or passed over the sensor location. The runs where the vortex transited the sensor location gave the best indication of how the temperature and turbulence level varied within the vortex recirculation region. Because the lateral vortex transport is dominated by the ambient crosswind, the selected runs will have very limited variation in ambient crosswind.

E. Data Accuracy

The anemometer lateral locations are accurate to 1 m and the vertical locations to 0.3 m. The single-axis propeller anemometers have a distance constant of 2.1 m and a starting threshold of 0.4 m/s (which increases with bearing wear). They were sampled at 10 Hz and averaged for 2 s before being recorded. The sonic anemometer has a sound path of 175 mm and was set to measure at 10 Hz; all measurements were recorded. Anemometer resolution was 0.01 m/s.

III. Vortex Model

The classical model for the interaction of a wake vortex pair with the ground satisfies the boundary condition of no vertical wind at the ground by pairing each vortex of circulation Γ and height h with an image vortex of circulation $-\Gamma$ and height $-h$. This model ignores that a real boundary layer will also have zero horizontal wind at the ground. Nevertheless, the image model gives a first-order approximation to the dynamics of a vortex pair interacting with the ground, particularly if the boundary layer under the vortex is very thin and, hence, difficult to detach.

The image model of vortex dynamics was used to estimate how the vortex pair from a Boeing 747 stirs up the atmosphere, under the assumption of no vortex decay and no crosswind. The aircraft height was assumed to be 50 m, the vortex spacing 48 m, and the vortex circulation $600 \text{ m}^2/\text{s}$. There were 14 evenly spaced atmospheric layers (7–100 m AGL) tracked. Two parameters of the atmospheric layers are expected to be more or less unaffected by the wake vortex flowfield, namely, the headwind and the potential temperature. The layers are modeled as discrete points, which become mixed up in the strong wind gradients near the vortex locations and serve to indicate the extent of the recirculation oval. Figure 1 shows the locations of the layers at times of 12, 50, and 100 s after aircraft passage. The two vortex locations are marked with small squares.

The first observation from the model is that the vortex recirculation oval actually consists of two separate recirculation regions, one associated with each vortex. When the vortices reach the ground and separate, the two regions of recirculation become quite distinct. The recirculation regions remain distinct from the local environment and push the original ambient atmosphere out of their way.

At 12 s, the vortex pair has already significantly disturbed the atmosphere. As the vortex recirculation oval descends, it pushes the layers near the ground out to the side and pulls layers from higher in the atmosphere down closer to the ground.

At 50 s, the two vortices have separated and have been pushed under the lowest layer, which is now wrapped over the top of each vortex. Between the vortices, the layer originally located at 86 m is now at the ground.

At 100 s, the vortices have traveled out of view, and the atmosphere has reached its final configuration. The wake vortices have caused a large portion of the atmosphere to descend toward the ground. In principle, ground-based sensors could then make estimates of the headwind and temperature profiles up to 80-m AGL. However, the height of the original layer varies rapidly across the final distribution, and it may be difficult to reconstruct the original profiles from the measured variation with lateral position. In the real atmosphere, the final distribution of the layers will be complicated by wind shear, buoyancy, vortex decay, and boundary-layer effects.

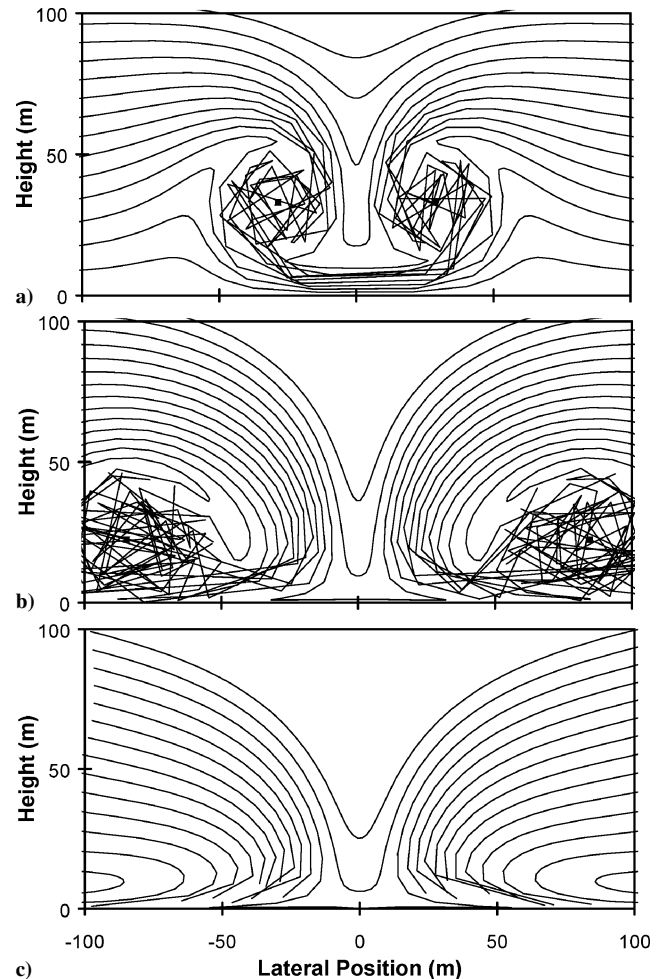


Fig. 1 Atmospheric layers at a) 12 s, b) 50 s, and c) 100 s.

IV. Sonic Anemometer Measurements

Data will be presented first for moderate turbulent conditions, where some of the aircraft types were known. Subsequently, low-turbulence data will be presented.

A. Moderate Turbulent Conditions

Figure 2 shows sample data for a B-747-400 arrival; Fig. 2 shows the conditions that will be provided for most subsequent runs. There are five conditions included.

First, the locations of the maximum crosswind across the array at a given time (MaxCw) and minimum crosswind across the array at a given time (MinCw) vortices are shown (vortex lateral position) in Fig. 2a. At age 65 s, the MaxCw vortex passed the -15 m location of the sonic anemometer.

Second, the sonic (fine line) and propeller (square) anemometer crosswind values at 8.5 m on pole 7, located at lateral position -15 m (CW7) are compared (Fig. 2b). Because the time synchronization for the two separate data files was uncertain, the timing of the sonic data was adjusted to give the best early age agreement. The subsequent disagreement is presumably due to the 15-m longitudinal separation between the sonic anemometer pole and pole 7 of the anemometer array. Two additional crosswind values are plotted as heavy lines: MaxCW and MinCW values observed across the array. When the MaxCW value equals the CW7 value, the MaxCW vortex is located above pole 7. The difference between MaxCW and MinCW (about 2 m/s) before the aircraft arrived is an indication of the atmospheric turbulence level. The vortex-induced crosswind appears abruptly at age 10 s. The crosswind turbulence inside the vortex is not notably different from the ambient crosswind turbulence observed before aircraft arrival. The ambient crosswind is about -2 m/s and results in the MaxCW vortex remaining near the extended runway centerline for a considerable time.

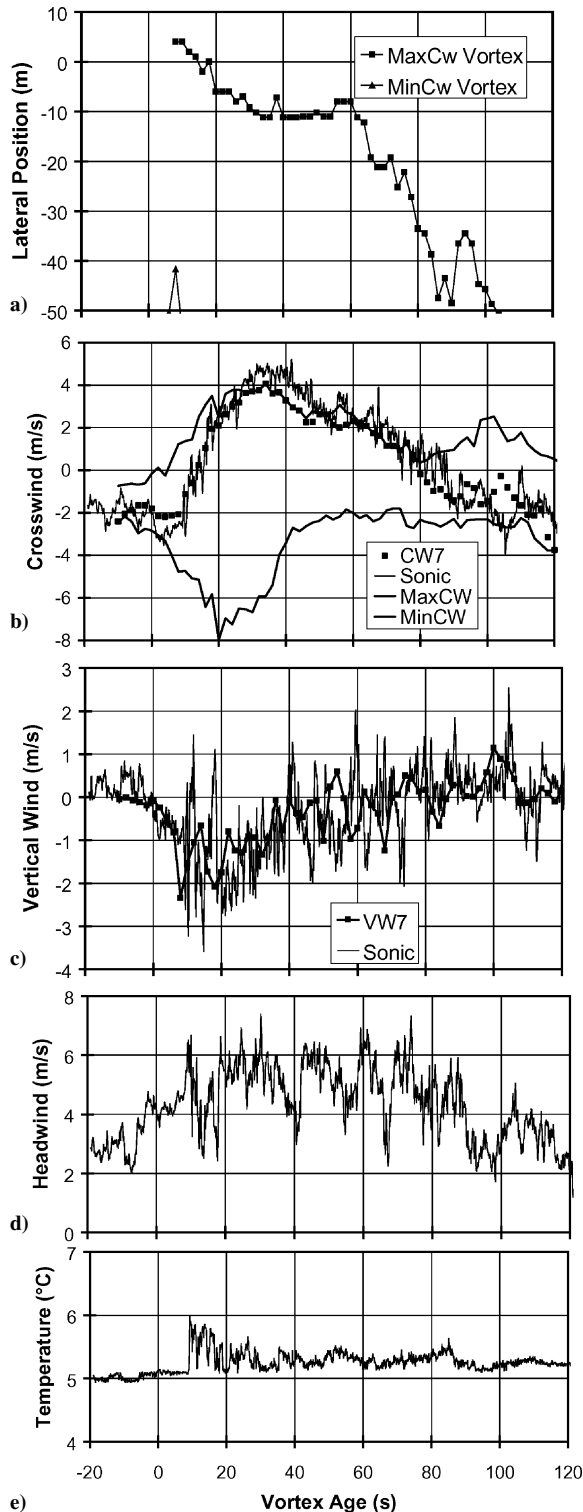


Fig. 2 B-747-400 run, 20 November 1996, 1531 hrs eastern standard time (EST).

Third, the sonic (fine line) and propeller (square) anemometer vertical wind values at 8.5 m on pole 7, located at lateral position -15 m (VW7), are compared (Fig. 2c). The vertical wind is negative (the downdraft between the two vortices) before the vortex reaches -15 m and more or less positive after it passes -15 m. The turbulence level is greatly increased (2–3 m/s peak-to-peak) above ambient when the vortex flowfield begins to affect the vertical wind at age 10 s. The vertical wind turbulence is greater than the crosswind turbulence.

Fourth, the headwind is shown in Fig. 2d. The headwind inside the vortex is significantly greater than the headwind before and after

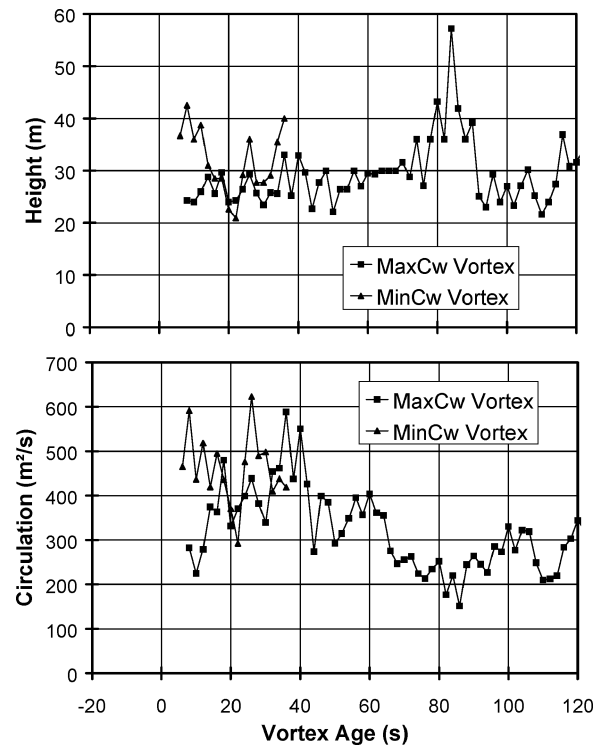


Fig. 3 B-747-400 run, 20 November 1996, 1531 hrs EST.

the time the sonic anemometer is within the vortex flowfield. The peak-to-peak headwind turbulence level is also greater inside the vortex and is about the same as observed for the vertical wind.

Last, the temperature is shown Fig. 2e. The temperature inside the vortex is higher than ambient by perhaps 0.2 – 0.7 °C, with the greatest difference observed just after the vortex flowfield reaches the sonic anemometer at vortex age 10 s.

Figure 3 shows the two additional parameters that are available from the least-square-fit processing of the anemometer array data: 1) height and 2) circulation.

1) The vortex descends to roughly half the aircraft wingspan, as would be expected from the classical vortex motion theory (Sec. II).

2) The initial circulation for a B-747 is expected to be roughly 600 m^2/s . The measurements are more or less consistent with such a value. The circulation decays with increasing vortex age.

In contrast to the lateral position shown in Fig. 2, the least-square-fit algorithm does not give a robust determination of height and circulation, which tend to vary together. The values for early ages are often low, and considerable variation is noted.

Figures 4 and 5 show the data from an aircraft much smaller than the B-747-400. The afternoon meteorological conditions were similar for the two runs, which occurred on successive days. The unique feature of the run shown in Figs. 4 and 5 is that the MaxCW vortex core came very close to the sonic anemometer at age 44 s. The vertical wind (Fig. 4c) shows the classic vortex profile of a downdraft (negative peak of 11 m/s) followed by an updraft (positive peak of 5 m/s). The crosswind (Fig. 4b) shows a peak value of about 12 m/s. The headwind (Fig. 4d) shows a sharp dip near the vortex core, which presumably represents axial flow (in the direction of flight).

In Fig. 4, the vortex influence arrived at the sonic anemometer at 14 s, which is somewhat later than noted in Fig. 2 for the B-747. This difference is not surprising because the descent rate and the wake field of influence are both smaller for the smaller aircraft. Vortex turbulence characteristics in Fig. 4 are generally similar to those noted for the B-747 in Fig. 2. The one difference is more crosswind turbulence for the smaller aircraft. The smaller aircraft showed comparable initial jumps in temperature, but the temperature increase was not as durable as for the B-747. This difference is as one might expect for a smaller wake field of influence.⁴

Figure 5 shows that the vortex height is very well determined at about 11–12 m for the vortex passing close to the height of the

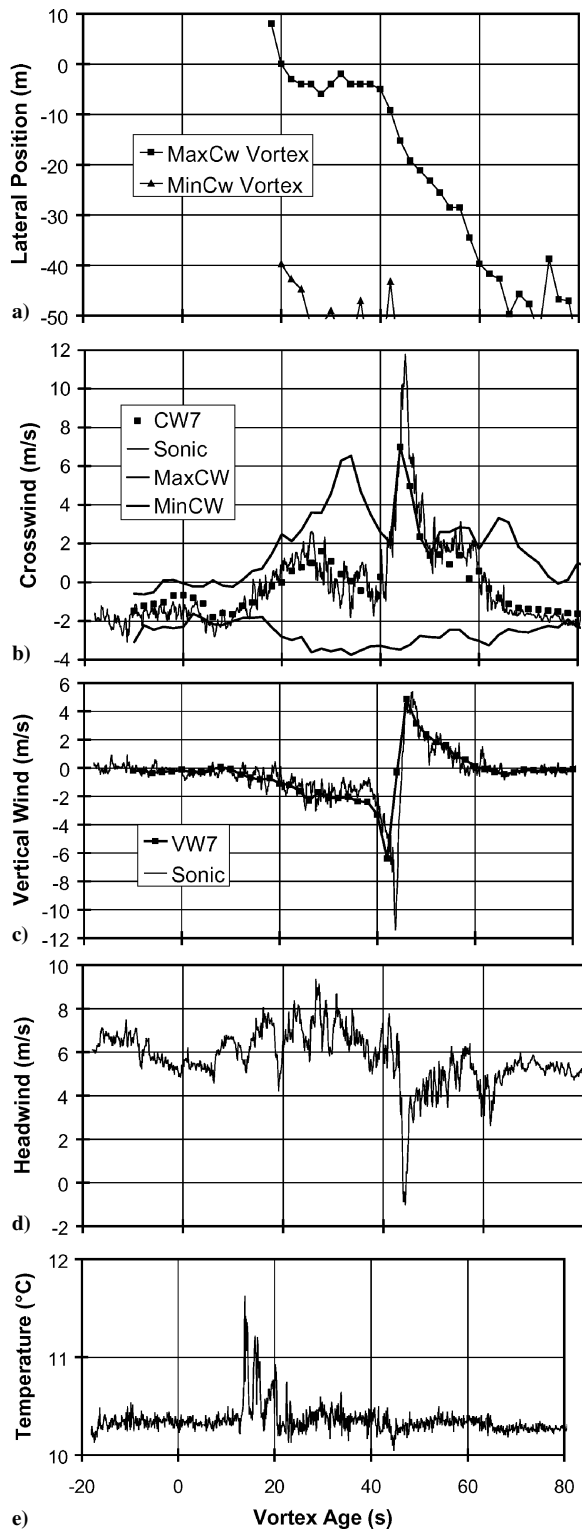


Fig. 4 Run 19 November 1996, 1430 hrs EST.

anemometer array. The circulation is much less well defined for that vortex. Both height and circulation are poorly defined for the other vortex.

Figure 6 shows a midmorning run that has somewhat different characteristics than the runs shown in Figs. 2 and 4.

1) The most notable difference is the behavior of the temperature (Fig. 6e). In this case, the temperature varies up and down by about 1°C before the wake reaches the sensor. The temperature then drops to a low and roughly steady value, apart from a spike at age 74 s. In this case, the atmosphere near the ground may be experiencing thermal activity, whereas the vortex-generation level may have a fixed, slightly cooler fixed temperature.

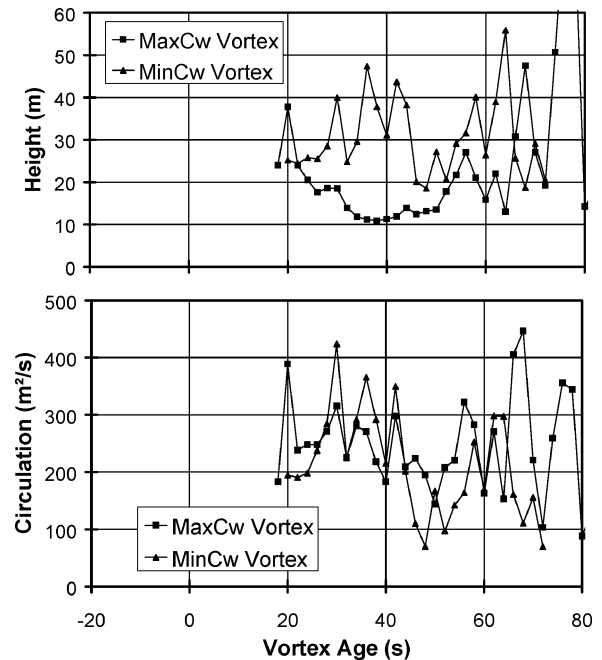


Fig. 5 Run 19 November 1996, 1430 hrs EST.

2) Another difference is the headwind, which is only 1 m/s and increases only slightly inside the wake vortex.

3) The vertical wind is very erratic, probably because of rapid changes in the lateral position close to the position of the sonic anemometer (-15 m).

4) Although the vortex turbulence characteristics are generally similar to the run shown in Fig. 4, an alternation between quiet and turbulent regions appears before the peak crosswind is reached. The first quiet region (15–19 s) appears in all three wind components. Additional quiet regions appear in the crosswind.

B. Low-Turbulence Conditions

Under low-turbulence conditions, B-747 vortices typically did not move slowly across the sonic anemometer location. Consequently, the data presented are for smaller, unidentified aircraft. Figures 7–10 show four typical low-turbulence runs, where the MaxCw vortex was slowly transported past the sonic anemometer. The low turbulence can be noted as the narrow spread (0.3 m/s for Fig. 7) between the MaxCW and MinCW values before aircraft arrival.

Figure 7 shows the following features.

1) The influence of the aircraft and wake begin at the time of arrival. All of the wind components begin to change immediately. The sonic headwind shows a 1 m/s dip as the aircraft passed. The headwind and temperature gradually increase as the wake pushes the atmosphere down toward the ground (Sec. II).

2) All three wind components show very low turbulence until age 13 s, when the turbulence levels abruptly increase. The headwind and temperature also abruptly increase at age 13 s. These changes likely signal the arrival of the vortex oval at the anemometer height. The total increase in temperature is almost 2°C , which is about twice the change noted in the moderate-turbulence cases.

3) In addition to the initial burst of turbulence noted for ages 13–20 s, subsequent bursts of headwind and three-dimensional turbulence are noted for ages 29–32 and 40–44 s. The crosswind turbulence is generally higher after the peak crosswind is observed. Then, all three wind components have similar turbulence levels.

4) The vertical wind changes sign at age 50 s, which is close to the time (55 s) the vortex passed over the measurement location.

5) At approximately age 80 s, the wind and temperature return more or less to their ambient values, observed before aircraft arrival. At this age, the MaxCw vortex is about 15 m from the sonic anemometer. The first indication of the vortex recirculation region (age 13 s) occurred when the MaxCw vortex was about 15 m on

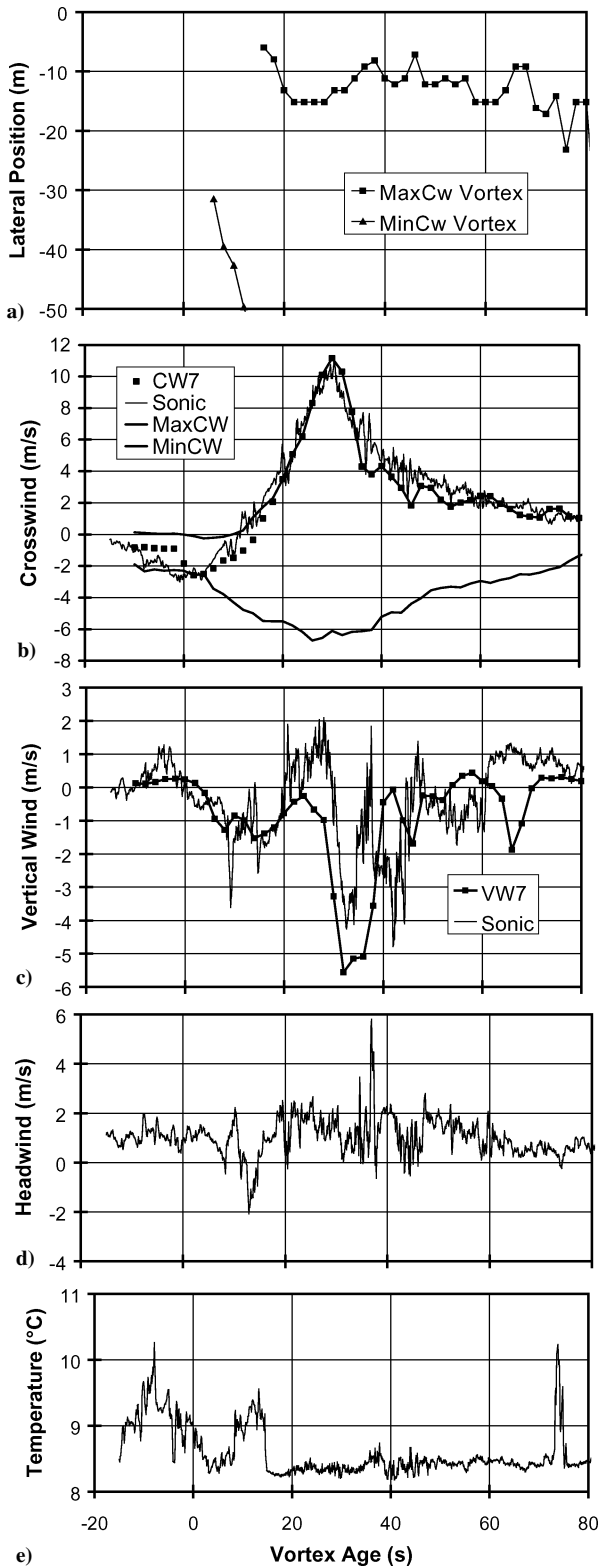


Fig. 6 Run 17 November 1996, 1017 hrs EST.

the other side of the sensor. Thus, Fig. 7 shows a scan across the 30-m-wide recirculation region of the MaxCw vortex.

Because the dip in the sonic anemometer headwind provides more precision in determining the aircraft arrival time, it was used to synchronize the sonic and propeller anemometer data for Figs. 8–10 instead of matching the crosswind measurements.

In several ways, the runs on 16 November 1996 (Figs. 7 and 8) differ systematically from those on 19 November 1996 (Figs. 9 and 10).

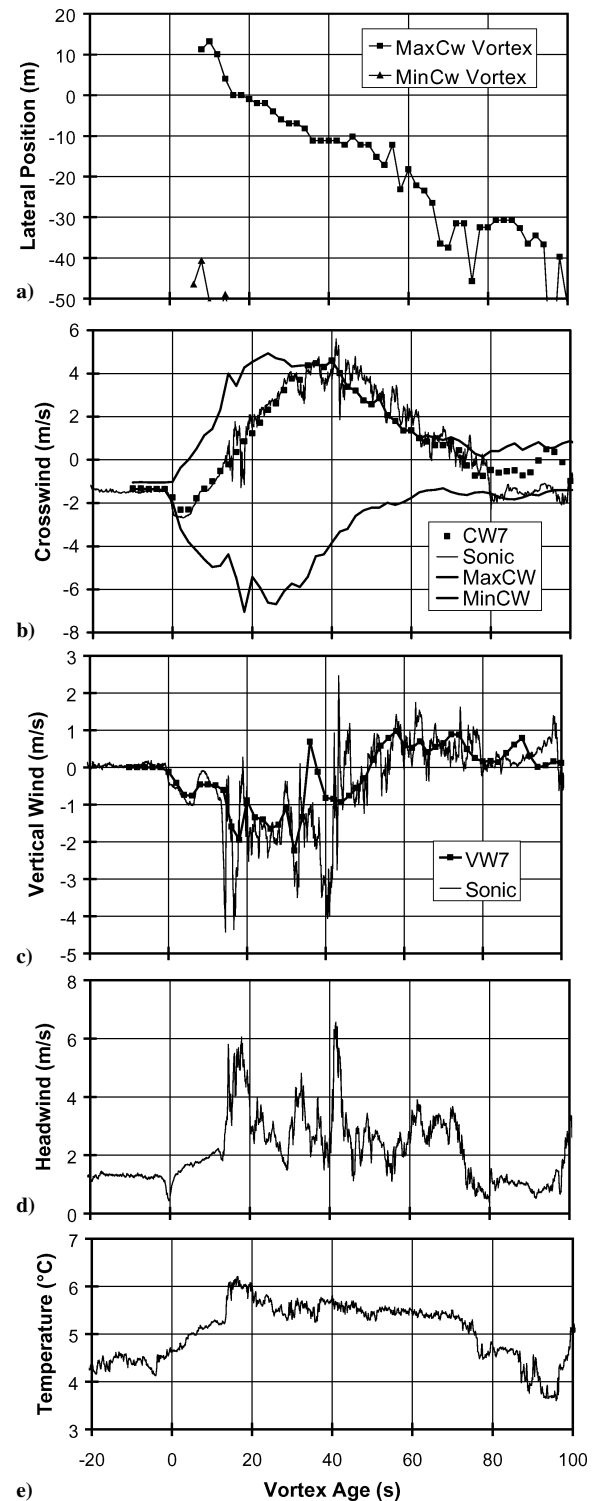


Fig. 7 Run 16 November 1996, 2108 hrs EST.

1) The turbulence level was less.

2) The temperature measurements suggest that there was more stratification. The temperature increases before the vortex recirculation oval arrives in Figs. 7 and 8, but is constant in Figs. 9 and 10.

3) The headwind at the vortex generation height appears to be lower on 19 November 1996 (perhaps 1–3 m/s) than on 16 November 1996 (perhaps 3–5 m/s).

The crosswind data in Figs. 7–10 suggest the existence of secondary vortex at the final edge of the recirculation region, which is where one would expect a secondary vortex. A secondary vortex is characterized by an opposite sign crosswind.

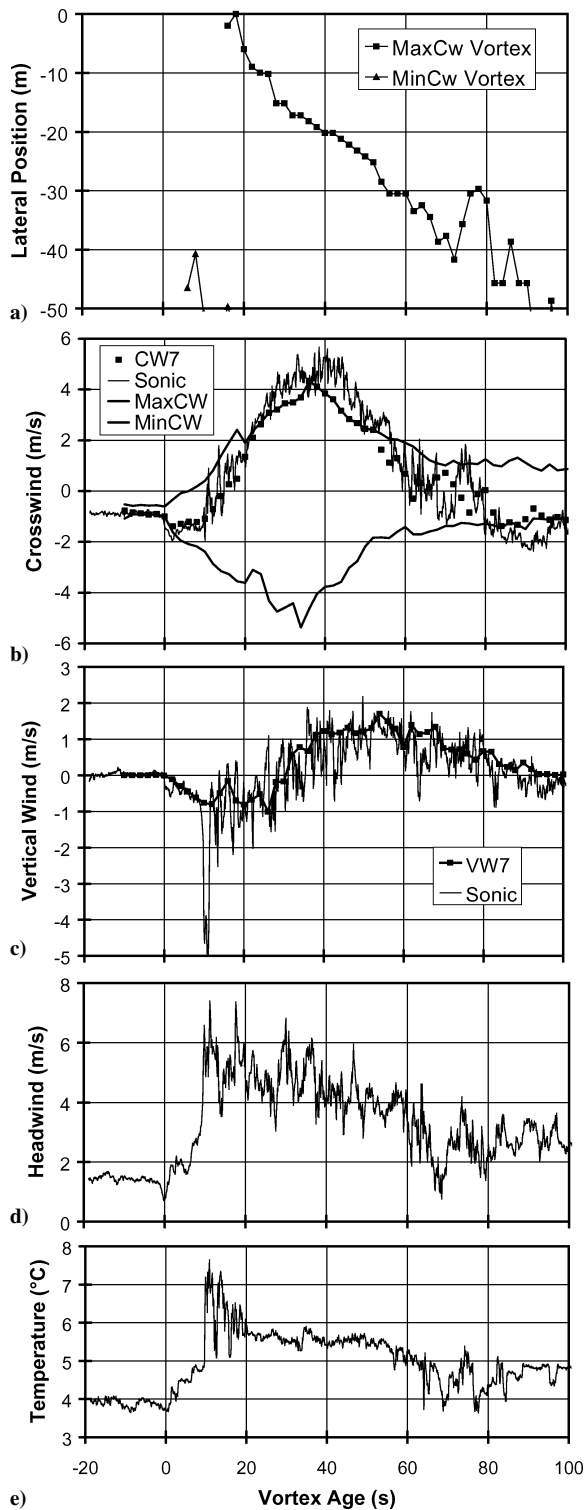


Fig. 8 Run 16 November 1996, 2142 hrs EST.

V. Boundary-Layer Thickness

A. Wake Vortex

Figures 11–13 show the vortex lateral positions and wind profiles (measured at +30 m from the runway centerline) for two B-747s and one smaller aircraft, all of which arrived under low-turbulence conditions. The following data are included in Fig. 11.

- 1) The fitted vortex heights are between 20 and 30 m (Fig. 11a).
- 2) The MaxCw vortex is first detected at +20 m and passes the +30-m measurement location at about age 15 s (Fig. 11b).
- 3) Figure 11c shows crosswind at four levels. The three higher anemometers give equal crosswinds for all ages. The lowest

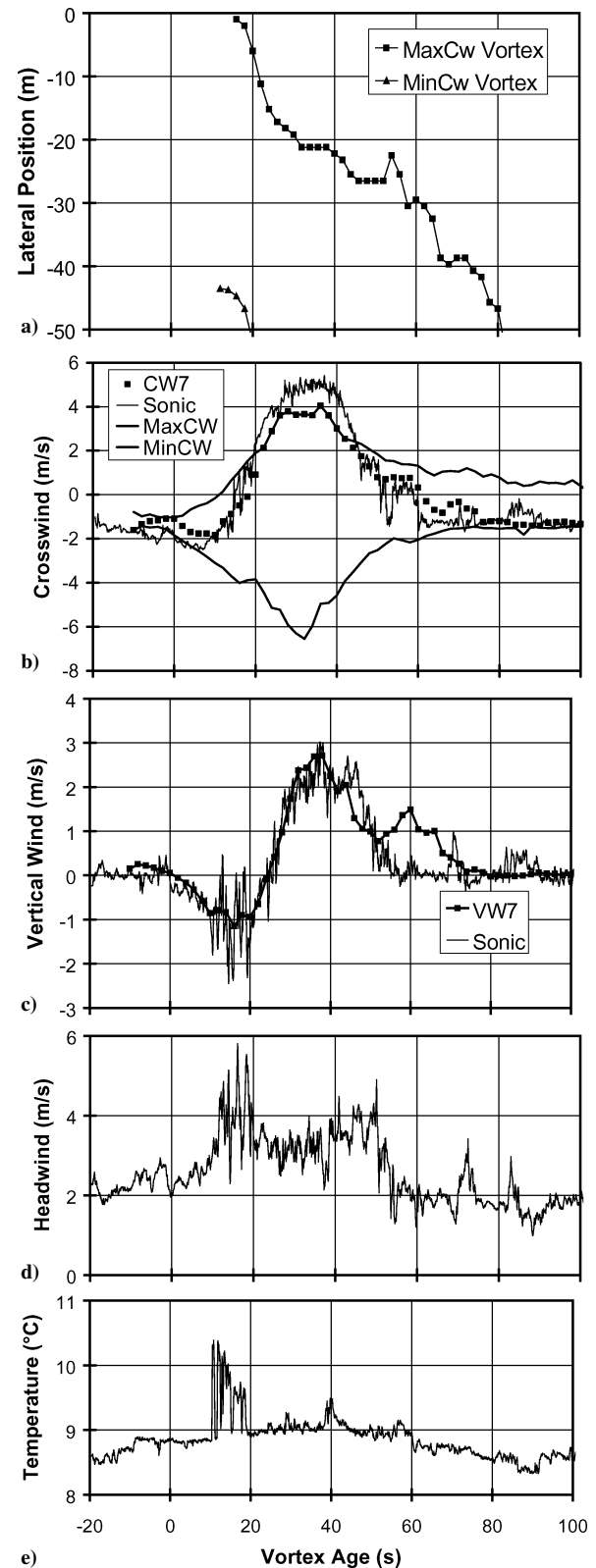


Fig. 9 Run 19 November 1996, 0727 hrs EST.

anemometer starts to read lower but jumps to match the other sensors at age 14 s, when the vortex core passes overhead.

4) The crosswinds of the lower anemometers are divided by the measurement of the 8.5-m anemometer to provide crosswind ratio (Fig. 11d).

5) Figure 11e shows vertical wind at four levels. As expected, the vertical wind generally changes sign when the vortex passes over the measurement location. However, the results are not as simple as

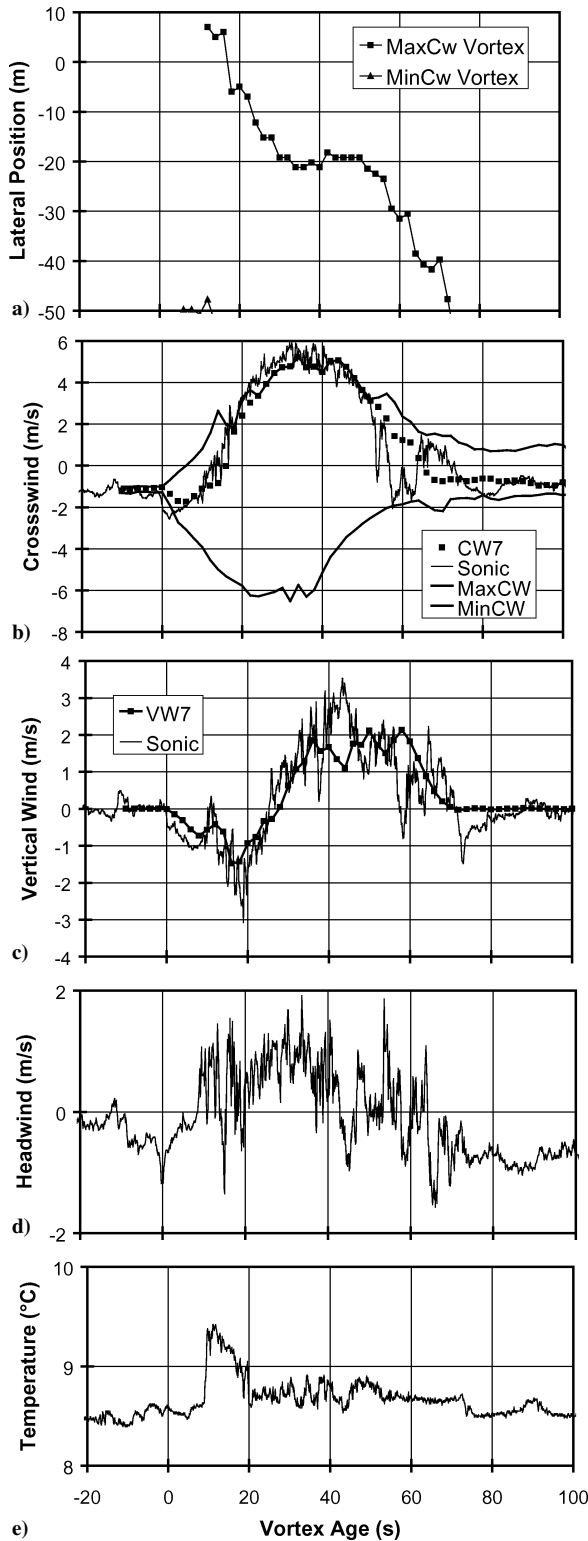


Fig. 10 Run 19 November 1996, 0909 hrs EST.

for the horizontal winds. After the reversal, the 4.2-m anemometer shows a larger vertical wind than the 8.5-m anemometer until vortex age 24 s. This difference may be the result of a boundary-layer interaction. The vertical wind at the two lowest anemometers is very small and shows little correlation with the vertical wind at higher levels.

The B-747 arrival shown in Fig. 12 was taken from the May 1997 test, when crosswind anemometers were located at five levels and vertical wind anemometers at only three. The MaxCw vortex crosses the +30 m sensor location at age 39 s. As in Fig. 11, the crosswind is

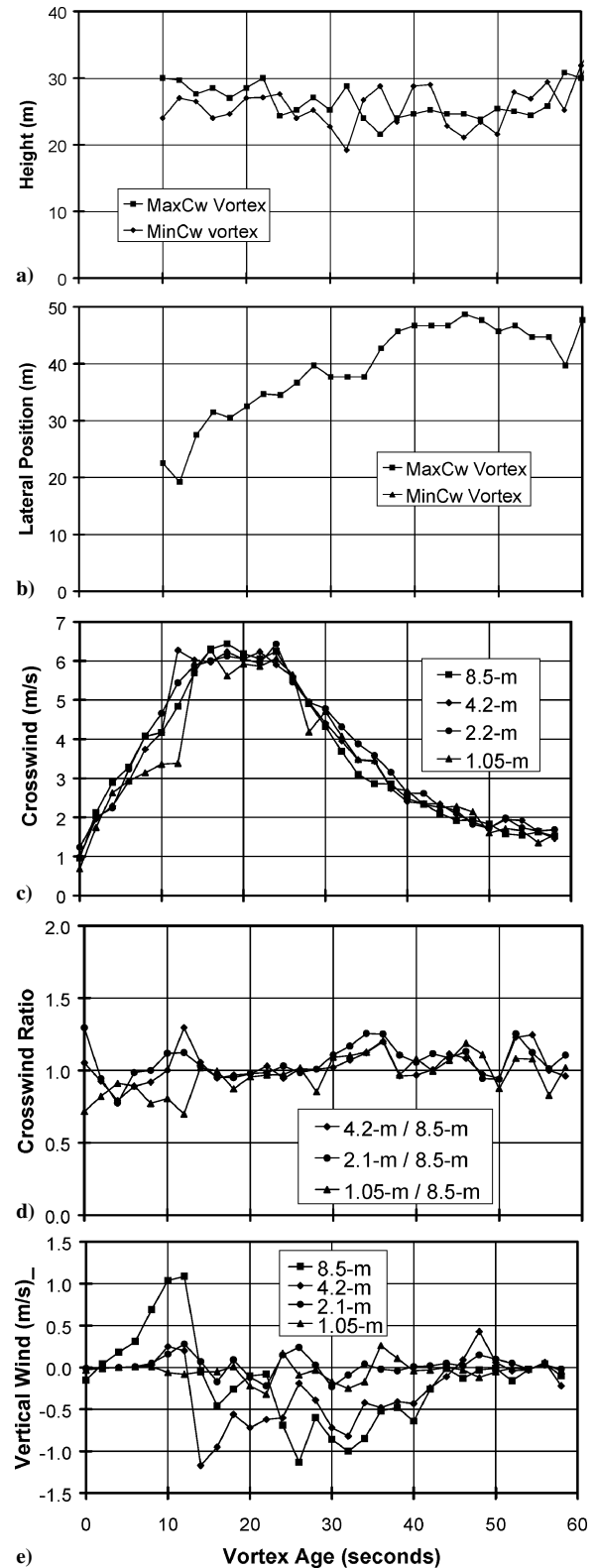


Fig. 11 B-747 run, 17 November 1997, 1628 hrs EST.

remarkably uniform with height AGL under the B-747 vortex. The ratio in Fig. 12d shows that, when the 8.5-m anemometer is reading near its maximum value, the 0.5-m anemometer reads about 70% of the maximum value. The boundary layer is indeed very thin. The vertical wind in Fig. 12 shows the same anomaly noted in Fig. 11; after the vortex passes the sensor location, some time elapses before the 8.5-m anemometer reads the greatest vertical wind.

Figure 13 shows data from a smaller aircraft arriving immediately after the B-747 in Fig. 12. The heights are somewhat lower,

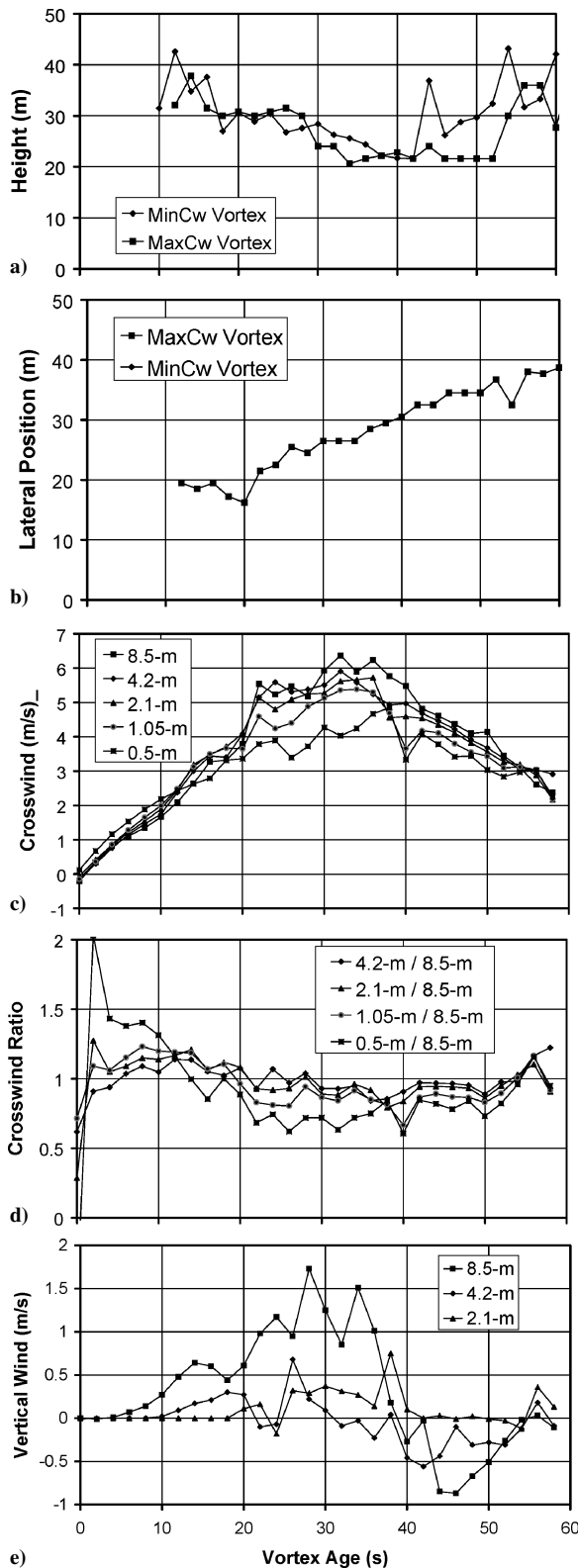


Fig. 12 B-747 run, 28 May 1997, 0442 hrs EST.

as would be expected. The vortex is first detected closer to the runway and reaches the +30 m measurement location at age 32 s. The crosswind profile shows an unexpected dip for ages 22–30 s, before the MaxCw vortex reaches the measurement location. The dip propagates to lower levels at slightly later times. The most likely cause for this dip is a secondary vortex detached from the boundary layer; it has the correct location (outside the main vortex) and the correct sign (opposite that of the main vortex). The vertical wind profile in Fig. 13 shows no signs of either 1) the secondary vortex appearing

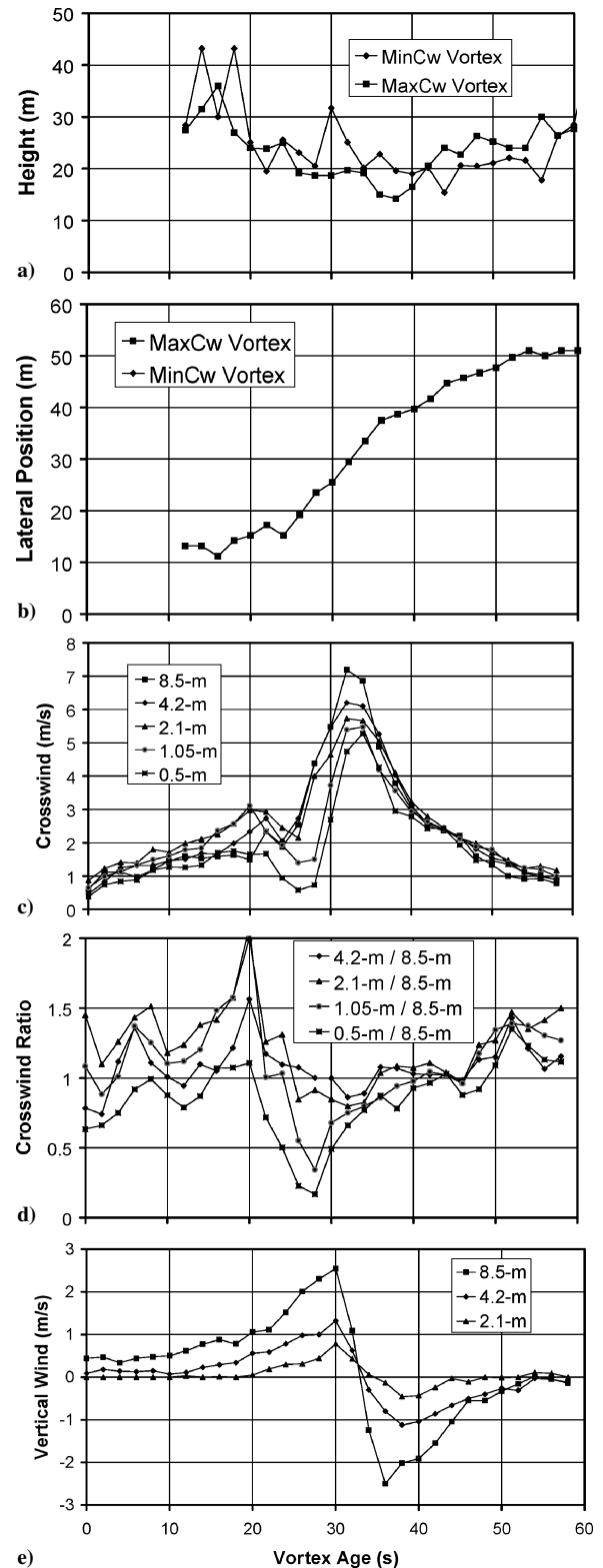


Fig. 13 Run 28 May 1997, 0444 hrs EST.

in the crosswind or 2) the delay in the 8.5-m anemometer reading the maximum vertical wind after the B-747 vortices pass the measurement location. The observed vertical winds are stronger for the smaller aircraft run than for the B-747 runs, presumably because of the lower vortex height.

The secondary vortex in Fig. 13 confuses the interpretation of boundary-layer thickness for the smaller aircraft. When the peak crosswinds were noted at 8.5 m, the 0.5-m crosswind was 70–80% of the 8.5-m value.

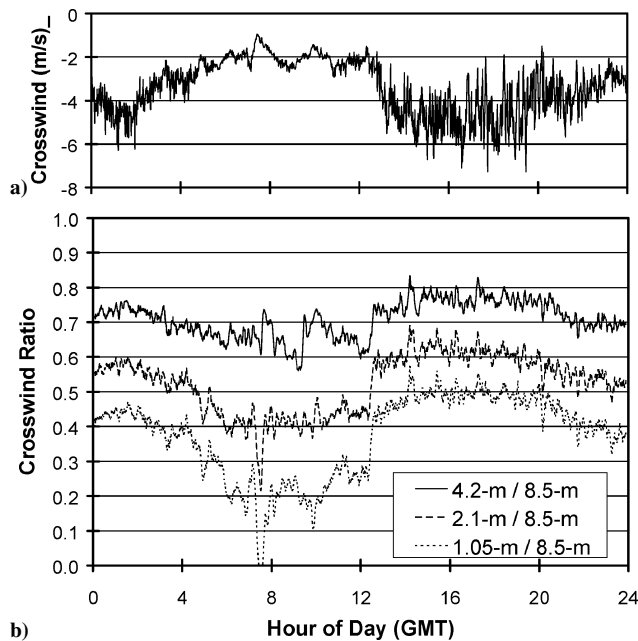


Fig. 14 Ambient crosswind 15 November 1996: a) 8.5 m and b) ratios.

B. Ambient Wind Profile

The same crosswind anemometers used to measure the boundary thickness can be used to estimate the ambient wind boundary-layer thickness. Figure 14a shows the crosswind at 8.5-m height for 15 November 1996. The values plotted are 1-min averages. Note the large amount of turbulence in the middle of the daylight period [1300–2200 hrs Greenwich mean time (GMT)].

Figure 14b shows the ratios of the crosswind at 4.2, 2.1, and 1.05 m to the crosswind at 8.5 m. To keep the plots from overlapping, the ratios have been smoothed with a 7-min running average. The thickness of the ambient wind boundary layer is much greater than the vortex boundary-layer thickness (Sec. V.A).

Under some conditions, the wind is expected to vary logarithmically with height above the ground. Because the heights of the four anemometers varied by factors of two, a logarithmic profile would give equal wind increments between the readings of the four anemometers. The ratio values in Fig. 14b should vary the same way, with the top ratio being one. At some times of the day, roughly equal wind increments are noted between the sensors at 1.05, 2.1, and 4.2 m; however, a larger increment is always noted for the wind difference between 4.2 and 8.5 m. Thus, the ambient crosswind profile is not logarithmic.

VI. Conclusions

A. Atmospheric Profiling

The test results suggest that, in a stratified atmosphere, the headwind and temperature profiles below the vortex recirculation oval can be measured by a sonic anemometer located near the extended runway centerline. Measurements within the recirculation oval are less clear cut because they may include specific vortex effects and generally gave less consistent results. Conclusive results for this measurement technique would require an independent measurement of headwind and temperature profiles.

B. Vortex Turbulence, Temperature

The edge of the vortex recirculation region generally showed a sharp increase in turbulence and frequently also showed a significant jump in temperature, even under moderate-turbulence conditions, where one would not expect a stratified atmosphere. Entrained engine exhaust is a possible explanation for such a temperature jump. Note that temperature changes of similar magnitude were observed for a light twin-engine aircraft. The turbulence inside the vortex often appeared patchy, with varying turbulence levels in different portions of the vortex. In some cases, the crosswind component had lower turbulence levels than the headwind or vertical wind components.

The high turbulence levels inside the vortex 1) act as noise for the anemometer array and, hence, reduce the consistency of the least-square-fit values for vortex height and circulation and 2) are likely part of the decay mechanism that makes wake vortices decay more rapidly near the ground than away from the ground.

C. Vortex Boundary Layer

The vortex-induced crosswind was observed to have a very thin boundary layer at the ground. The measurement at 0.5-m AGL was typically three-quarters of the value at 8.5-m AGL. The vortex boundary layer is much thinner than that of the ambient wind.

D. Secondary Vortex

The test results suggest that the capabilities of an anemometer array for detecting secondary vortices detached from the boundary layer could be enhanced by installing anemometers at different heights. More definitive results could be obtained by specifically examining runs where secondary vortices were located near the vertical anemometer array.

E. Aircraft Detection

Under low-turbulence conditions, the sonic anemometer headwind measurement detected the aircraft arrival with a signature of about 1 m/s. Because no similar signature was noted for the two other wind components or the temperature, it is difficult to interpret the signature as a sensor anomaly, such as aircraft noise affecting the sensor response. On the other hand, although the aircraft passage is known to generate a similar looking² pressure pulse, it is hard to see how a headwind pulse could be generated.

Acknowledgments

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