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Acoustic Characterization of Wake Vortices in Ground Effect

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The experience and findings of an exploratory effort to characterize the sound emitted by aircraft wake vortices near the ground are presented. A line array of four directional microphones was deployed and recorded the wakes of several commercial aircraft in the approach phase with particular attention being paid to the characterization of background noise. It is found that vortices near the ground emit broadband sound with frequency contents ranging from below 100 Hz to near 2000 Hz and possibly beyond. However, addressing the degree of consistency of the vortex sound would require deployment of a larger array. The mechanism of vortex sound generation and suggestions on future studies are discussed.

I. Introduction

Wake-vortex turbulence has become an increasing factor in constraining airport capacity as larger aircraft enter the fleets and as air traffic surges. While all flying vehicles produce wake vortices as the consequence of lift generation, large commercial aircraft create the most significant wake turbulence as the magnitude of a vortex is proportional to aircraft weight. To address the potential hazard imposed by wake turbulence, a set of minimum separation distances for aircraft en-route and terminal operations has been issued by the FAA. These separation distances were derived by examining statistical wake vortex data with a worst-case scenario in mind, not considering meteorological conditions and fleet mix. The separation standards derived this way can be overly conservative at times, thereby limiting aircraft arrival and departure rates. If the meteorological conditions can be reliably forecasted and wake vortex behaviors could likewise be predicted and monitored, air traffic controllers could deploy dynamic separation standards to both optimize airport capacity and enhance safety.

Currently there are various international initiatives to develop such a wake vortex prediction and monitoring system.[1] In the United States, activities of this type are exemplified by NASA's AVOSS[2,3] (Aircraft VOrtex Spacing System) technology demonstration program at Dallas/Fort Worth International Airport (DFW) in 2000. A central part of the AVOSS concept is having an array of meteorological and wake vortex sensors actively predict and monitor/validate wake behavior. Since the DFW proof-of-concept test, AVOSS has evolved into a more comprehensive system design termed WakeVAS[4] (Wake Vortex Avoidance System). To further mature WakeVAS, there is an interest to explore additional technologies to supplement existing wake sensor candidates.

There are efforts underway to examine the concept of passively detecting and tracking aircraft vortices using the sound they generate. Examples of these activities are highlighted in Refs. 5-8 where emphases are on characterizing wake noise in the out-of-ground effect region (loosely defined here as the wake vortex altitude larger than one aircraft wingspan). By comparison, studies on the acoustic characteristics of vortices when they are near the ground, known as the in-ground-effect region (IGE ; defined herein as the wake vortex altitude being less than one aircraft wingspan), have been more ad-hoc and not as well documented[9-12]. As a consequence, the spectral shape of the IGE wake noise, the degree of its consistency, and signal excess above ambient noise background are not known. The present paper represents an exploratory but carefully planned and executed effort to investigate the aforementioned issues. The study distinguishes itself from previous IGE works in two significant areas. Firstly, an array of four

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directional/shotgun microphones was used to study IGE wake sound. Secondly, a careful treatment of the background noise characterization has been made in addition to wake acoustics measurements.

II. Description of Experiment

For the experiment, a microphone array-based acoustic system was designed to collect and analyze acoustic data from wake vortices generated by aircraft on final approach to runway 27 at Logan International Airport in Boston, Massachusetts. Aircraft type, weather information including wind speed, and any other significant observations were recorded as well.

Fig. 1 is a high-level block diagram describing the system's architecture. As seen from the diagram, an array of four microphones was used to collect acoustic signals from the environment. These signals were then conditioned by a preamplifier and low-pass filter (LPF) circuit before they were digitized with a data acquisition card in a laptop. The raw data was subsequently analyzed using custom developed Matlab code.

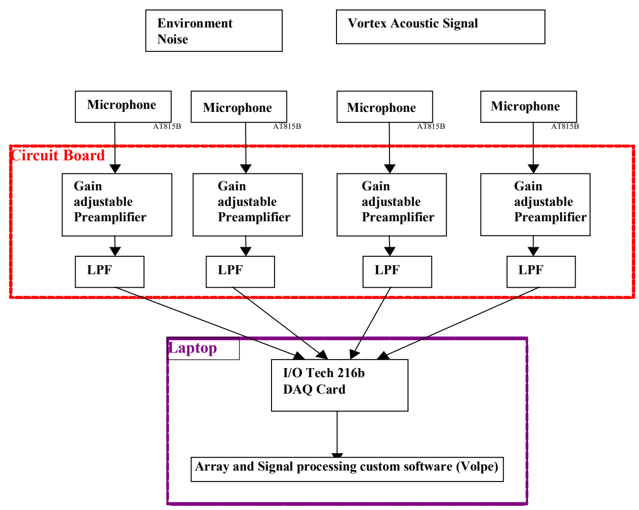

Figure 1. Detailed Experimental Design Overview.

A. Microphones

The experiment used four Audio-Technica 815b shotgun microphones. These microphones were chosen for their high directionality, flat frequency response to 30 Hz, and adaptability for use in the field since they can operate on batteries.

Each microphone was connected to a pre-amplifier via a standard microphone XLR cable. A Lightwave Audio Systems Equalizer windscreen was outfitted to each microphone to minimize the noise caused by wind effects. Without substantial windscreen protection, the background noise from wind gusts would have been too high to record the vortices.

B. Signal Conditioning Circuit

A preamplifier and LPF circuit was designed and built for each microphone. The purpose of this circuit was to condition the signals before they were inputted into the A/D card. The circuit was divided into two main stages: the amplification stage and the filtering stage.

The amplification stage was built using the Analog Devices 620BN Instrument Amplifier. This amplifier was chosen because of its low noise characteristics and its adjustable gain of up to 1000. This stage took in the differential signal and ground from the three-wire, XLR microphone cable and converted that signal to a single-ended output that was referenced to ground. This was then fed into the LPF portion of the circuit.

The filter was a second-order LPF with a cutoff frequency of 2 kHz and a roll-off of -40 dB/decade above the cutoff frequency. The main purpose of the LPF was to prevent aliasing of the signal when sampled by the data acquisition (DAQ) card. The DAQ card used multiplexing sampling at 100 kHz over four channels, resulting in a sampling rate of 12.5 kS/s per channel. The experimental arrangement was in-part driven by the interest to verify the low frequency tones predicted in Ref. 13 so the cutoff frequency was conservatively set at 2 kHz.

C. DAQ Card and Laptop

The DAQ card used in this experiment was the IOtech Daq/216b. A combination of simulations and field tests suggested that the 16-bit resolution of the card was crucial to significantly reduce quantization noise while maintaining a large enough dynamic range so not to saturate the output signal during the course of measurements. This was the deciding factor in choosing the card. The card uses the IOtech-provided DaqView as the software interface. The LPFs' single-ended outputs were interfaced with the 216b card using a BNC to D-connector cable. Careful filtering was done to separate the clean common signal ground from the power ground.

D. Signal Processing

The signal processing consisted of two main parts: time-domain beamforming and spectral analysis. The beamforming is an array processing technique used to amplify signals emanating from a region of interest in space (referred to in this paper as the region of focus (ROF)) while attenuating the signals from sources elsewhere. This in essence will increase the signal-to-noise ratio (SNR) of signals emanating from the ROF. This beamforming process uses the microphones' positions and the coordinates of the intended focus point to determine the lag time of the signal for each microphone. This time lag for a microphone is an estimate of the time needed for the sound to travel from the point of focus to the microphone. When the microphone signals are delayed with respect to a reference microphone according to these time lags, all signals emanating from the focus point are guaranteed to add constructively while others are not. The summation of the delayed signals will result in a spatial array response having a main lobe and side lobes. The maximum of the main lobe is the focus point, and its width defines the ROF. This technique allows focusing the microphone array on a given spatial region by means of post-processing. In this case the ROF is right above the microphone array where the wake is expected. It is also worthy to note that this technique is powerful in terms of knowing if a broadband source is in the main lobe or a side lobe even with this low number of microphones. Because the array pattern is a function of frequency, all frequencies in the main lobe will add constructively while the ones in the side lobe will exhibit a fringe-like pattern. This was a very helpful signal discrimination tool in the analysis. The spectral analysis was subsequently performed on the beamformed data using Short Time Fourier Transform (STFT) techniques to generate time-frequency distribution maps (or spectrograms) from which conclusions about spectral characteristics were derived. All the processing software was developed using Matlab.

E. Observations and Methods

On the day of the test, the microphones were positioned abeam of the approach end of runway 27. During the time of the tests, aircraft were arriving on 27 and 22L and departing on 22R. The winds were nominally from 290 deg. magnetic at 08 knots.

The microphones were put in a line array configuration. The array was designed so that the vortices would pass through the array's region of focus, rejecting the maximum amount of noise from the airport background. The microphones were spaced 5.74 ft apart from each other and directed towards a point 42 ft high and 11 ft in front of the right-most microphone shown in Fig. 3. The array was parallel to and offset 270 ft from the runway centerline on the downwind side. The aircraft altitude was about 50 ft as it passed by the array. Fig. 2 shows the array position circled on a map of Logan while Fig. 3 is a photograph of the line array and aircraft position. Not shown are the nearby propeller anemometer taking wind speed measurements perpendicular to the runway and the laptop-based A/D system.

Field observations were logged to supplement the acoustic data. These observations included aircraft type, weather conditions, the timing of the aircraft flyovers, thrust reverser deployment (when applicable), as well as if vortex sound had been heard by field personnel. The timing of the aircraft flyovers as well as crosswind measurements were used to estimate the time when the vortex enters the region of focus of the array. The correlation between spectral data and visual observations was a useful sanity check of the data analysis and signal processing. The wind anemometer was also present to detect changes in local air velocity that would indicate that a vortex is passing by the ROF. The sequence of each test would begin with the start of data recording a few seconds before the aircraft flew over. The time that data collection began, the time of aircraft flyover, the time of touchdown, the time of thrust reverser deployment, and the time of any wake observations were all recorded during a given test. The DAQ system time-stamped the data relative to the recording start time.

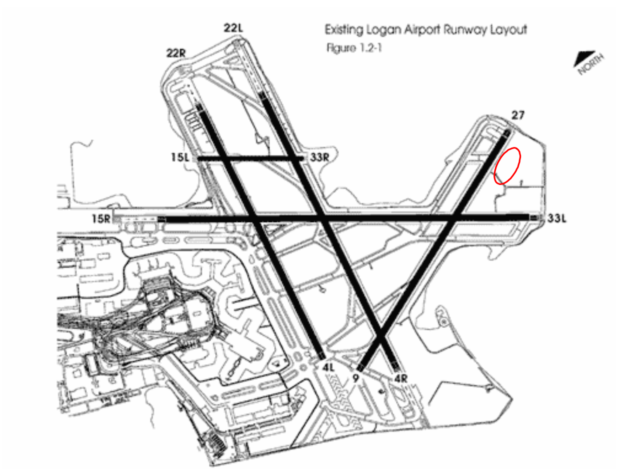

Figure 2. Runway configuration at Logan Airport.
Array located at red oval. Image courtesy of Massport.

Figure 3. Array setup at runway 27.

III. Results and Discussion

A total of 26 aircraft landings were recorded on the test day, ranging in type from several DC-9s to an A330 with the majority being B737s and MD-80s. From the 26 aircraft that were recorded, aircraft flybys 9, 10, and 23 had the most audible wakes that manifested clearly in the spectrogram analysis. While not as discernable as the previous three, data from Aircraft 11, 13, and 19 show evidence of wakes as well. Results from aircraft 10 and 19 are highlighted subsequently to show important trends and conclusions.

Aircraft 10, a Boeing 737-400, had the strongest wake noise of the experiment. Its loud crackling sound seemed to completely envelope the observation area. Fig. 4 shows the spectrogram of the recording made of Aircraft 10. The raw data was run through the Matlab based beamforming and the STFT programs discussed previously.

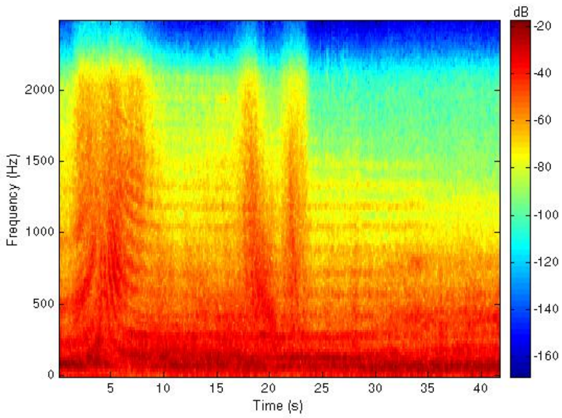

Figure 4. Spectrogram for Aircraft 10, a B737-400.

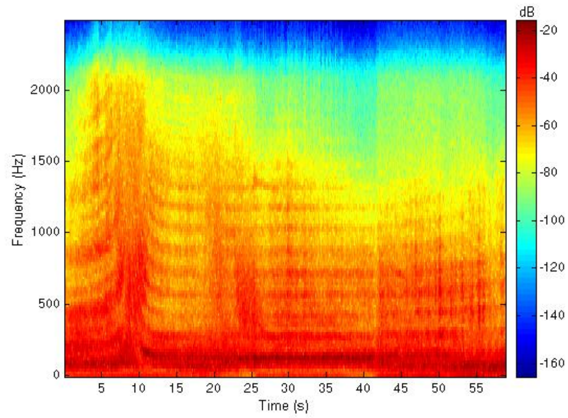

Figure 5. Spectrogram for Aircraft 19, an MD-80.

Aircraft 10 flew past the microphone array at 4 s into the recording. About 15 s of background noise is followed by two strong wake signals that pass through the region of focus of the microphone array, the strongest wake sound occurring at approximately 17.5 s and the weakest wake sound ending at 23.5 s. Note the horizontal lines of constant frequency that occur between the aircraft and the wake signal and also after the wake signal. These lines, a result of the beamforming process, are from noise recorded by the rear and side lobes of the microphone array. Acoustic signals directly in the array's region of focus add constructively while signals that are to the side of or behind the array have constructive and destructive interference during beamforming. Therefore, the portions of the spectrogram with constant frequency lines in the spectrum represent a signal that is not directly over the array. It is apparent that the wake signal in Fig. 4 is in the array's focus area because that signal is smooth with no lines or fringes through it. Another interesting observation is that Aircraft 10 produced two very distinct signals after flyby. The aforementioned discussion and notes from field logbook assure that the appearance of a second acoustic signature is not from thrust reverse. This may have been caused by different portions of the wake passing over the array. The combination of low runway crosswind component and the close proximity of the two successive acoustic signatures (i.e., five seconds apart, which corresponds to a distance of 30 ft between the two vortical structures according to the classical image model) preclude the possibility that the recording is the manifestation of the port and starboard vortices passing over the array. A candidate explanation would be that the array is detecting the sound emitted from the port vortex and the associated secondary vorticity passing over the ROF.

A more detailed Power Spectral Density (PSD) graph is constructed from the recorded Aircraft 10 data, as shown in Fig. 6, by comparing time samples from Fig. 4 of the potential wake signal to the background noise immediately before and after it. In this case, the time sample of the potential wake signal is from 17.5 to 20 s, the initial background noise is from 10 to 16 s, and the final background noise is 24 to 30 s. These two sections of background were used to interpolate the expected background at the time of the wake signal. This method of background estimation will be discussed in further detail next.

In Fig. 6, the red line is the wake signal, the blue scatter is the background, and the magenta lines are the 90% confidence bounds for a signal that is not a part of the background. Demarcating the wake from the background in the lower frequencies is not straightforward with the current four-microphone setup and data analysis approach, but the wake becomes more apparent at about 400 Hz. There is high confidence above 400 Hz that the observed wake signal is not a part of the background. The signal-to-noise ratio (SNR) of the wake signal and the background upper confidence bound are compared together in Fig. 8, the red line being the wake signal and the magenta line being the confidence bound. The bandwidth of the wake signal becomes very apparent, stretching on average 10 dB above the confidence bound from 500 to 2300 Hz.

Figs. 5, 7, and 9 show that Aircraft 19, a DC-9-40, has a wake that is quite distinguishable from the background with 90% confidence from 200Hz to 400 Hz and 500 to 2500 Hz. The plots for Aircraft 19 are shown as an example of the results from an aircraft trial in which wake noise was not heard by the experiment team. Table 1 summarizes the results from the six analyzed aircraft that had the most distinguishable wakes.

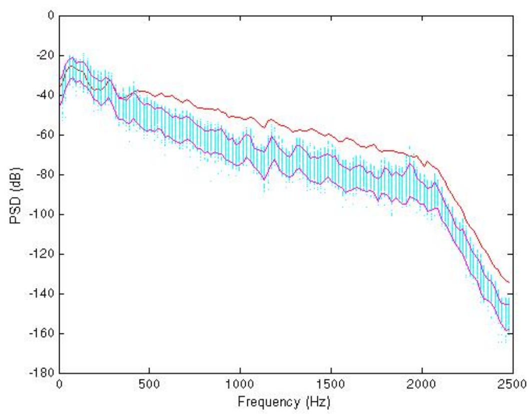

Figure 6. PSD for Aircraft 10.

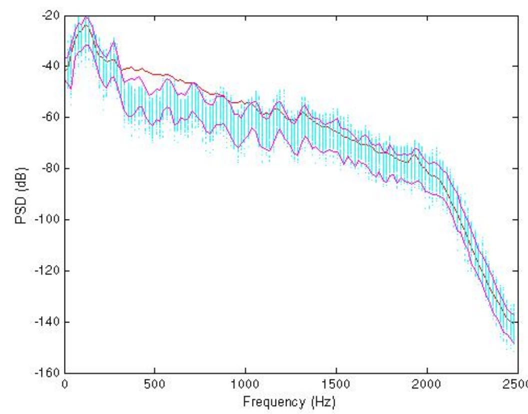

Figure 7. PSD for Aircraft 19.

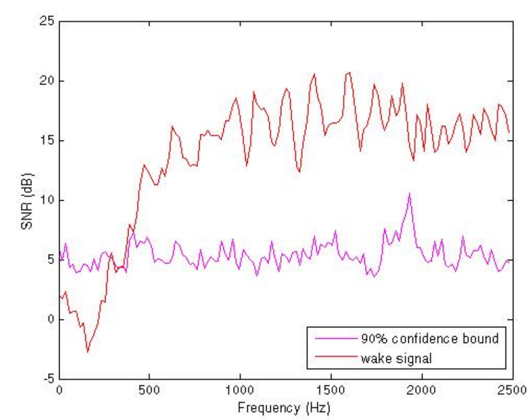

Figure 8. Wake SNR for Aircraft 10.

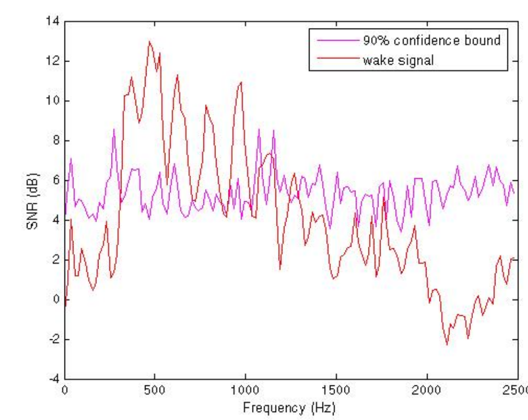

Figure 9. Wake SNR for Aircraft 19.

Table 1. Results for the six aircraft with the most distinguishable wakes.

Aircraft No.	Aircraft Type	Time of vortex after flyover (s)	Approx. frequency range of strongest probable vortex signal with 90% confidence (Hz)	Wake heard?
09	DC-9-40	7	<100, 500-1200, 1400-1900	Yes
10	B737-400	13	500 – 2500	Yes
11	A330-200	10	950-1000	No
13	MD-82	15	<200, 600-1000, 1200-2200	No
19	MD-80	10	300 - 1000	No
23	B757-200	5	750-1800	Yes

A. Signal Analysis

It is clear from Table 1 that the higher frequency signals are more abundant in the data, at least for the IGE region. This is either because IGE wake is louder at higher frequencies or because the background noise at Logan is too high at lower frequencies to distinguish a clear signal. Therefore, the results are inconclusive as to what type of low-frequency signal may exist in IGE wakes, such as those related to the rotational velocities of the vortex cores[13], is produced. It can, however, be said that if a consistent signal is produced at low frequencies, it is weak enough to be drowned out by the background noise recorded by this equipment setup. On the other hand, the vortex signal produced at higher frequencies (above 500 Hz) is quite clear for the IGE region. The region of about 700 to 2500 Hz appears to be the most active as far as acoustic signals are concerned, but these are results for only six of the 26 aircraft recorded, suggesting that there is a large variability either in the noise generating mechanisms of the vortices or in the ability to detect these signals with a varied background environment. Nevertheless, the high-frequency acoustic contents in IGE vortices in the kilohertz range appears to be a distinguishing feature not found in the at altitude wake acoustics studies[7,8].

The signals were also correlated with other information in the following fashions. The first way that the signals seen above can be correlated to the wake is by revisiting the classical image model of wake vortices as discussed in Ref. 13 to estimate the time after flyover that wake observation is expected. Using this model and assuming a Boeing 727, it is found that the vortex lateral transport rate in ground effect is about 9.8 ft/s. Additionally, the vortex starts out about 43 ft away from the centerline along the wing and travels at an altitude of 42 ft (top of ground effect). On the day of the test, the crosswind component was on average steady at 2.7 mph across the runway toward the microphones, and the microphones were 270 ft from the centerline with a region of focus that formed about a 30 degree cone. Using these numbers, it is estimated that the wake must travel about 202 ft and will pass over the microphone array 14 s after flyover. The average time from flyover to wake signal for Aircraft 9, 10, 11, 13, 19, and 23 was 10 s. This shows that, to the first-order, the signal appears at about the same time that the wake is expected. Variability between this measurement and the model is due mostly to wind fluctuations, variation in aircraft type, variation in aircraft position, uncertainty in the model, and uncertainty in the measurement.

The second way that the signal can be correlated to the wake vortex is from its appearance on the spectrograms in Figs. 4 and 5. Signals behind the microphone array tend to have lobes that interfere destructively, imposing lines on the spectrum plot that are maxima and minima from these side or rear lobes. The portion of the spectrogram that has been time-correlated to be associated with the wake does not have these fringes, indicating that they are within the region of focus of the array as expected from microphone positioning and wake trajectory modeling. The signals before and after the wake on most of the spectrograms have lines in them, indicating that they are to the side of or behind the array. These signals are the aircraft engine on flyover and the thrust reversers on landing.

The third method for verifying that the observed signal is from the wake is by field observations. However, the obvious drawbacks in this method are the subjectivity of field personnel and the frequency response characteristics of human being different from those of the microphones. As shown previously, wake sound was recorded from Aircraft 19 but not heard in field observation.

B. Uncertainty Analysis

The first and most important type of uncertainty to consider in this experiment is random variations in the PSD of the background and signal. These are not measurement uncertainties due to primary measurements from instrumentation characteristics, but rather they are random fluctuations in the acoustic signals being recorded. These fluctuations come from the random background noise at the airport. This analysis led to the uncertainty bounds seen on the PSD plots in Figs. 8 and 9. The bounds have been constructed such that it can be said with 90% certainty that anything above those uncertainty bounds is a distinct signal and not random background fluctuations. An alternative method would be to treat the noise as a Gaussian distribution and model uncertainty with respect to that distribution. It is clear from the PSD plots that there is far more low-frequency noise energy and, therefore, it is significantly harder to detect a low-frequency signal with certainty.

The second uncertainty is associated with internal circuit noise in the electronics, that being the uncertainty or error in measurement. The bulk of the electronics noise came from the microphones and the amplifier circuit. The microphones had a professional quality SNR of 70 dB. The sensitivity of the microphones was such that for a 94 dB SPL signal the microphone had an output of 12.5 mV +/- 0.00395 mV. During equipment testing it became apparent that the electronics noise was not a significant factor when compared to background fluctuations.

The final type of uncertainty associated with this experiment is bias uncertainty from operations at the airfield. Low-frequency tones associated with aircraft

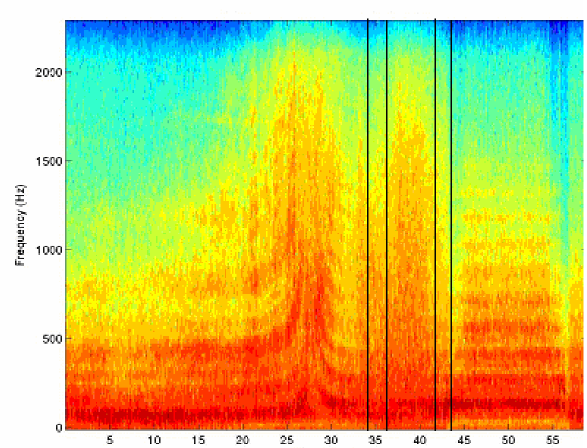

Figure 10. Two potential time periods used for interpolation of the wake background reference.

engines, airport vehicles, and other aircraft components contribute to the background spectral density. Since the output of these sources are constantly changing (such as the engine noise of an aircraft decreasing while it moves down the runway), the background during one portion of the test period may have been significantly different than the background during another portion. Contributing factors also include deployment of thrust reversers and aircraft departures on other runways.

An improper choice of background (used for generating the PSD and SNR plots at a given time) could lead to improper conclusions by confusing background noise for wake signal or vice versa. The background choice is simply a reference point and must be chosen with care to accurately reflect the wake SNR. Fig. 10 is one example of a possible background choice around the wake signal of Aircraft 9. The background spectrum during the time that the wake appeared could be interpolated from the spectra before and after the wake signal. This is the only method for determining the background at the time of the wake signal since the two cannot be separated.

C. Comparison to Theory

The theory of aerodynamically generated sound stipulates that acoustic signatures are created as a consequence of unsteady vorticity. Ref. 13 represents an attempt to model the wake noise by considering a range of IGE vortex dynamics. By considering the sound generation due to the motion and dynamics of the vortex cores only, each of the mechanisms identified is theorized to produce different tones, or a narrow band, ranging from 150 to 200 Hz as the upper bound and down to infrasound region. As multiple mechanisms could coexist in the wake, the resulting composite spectra are then continuous and disguisable below the 150 to 200 Hz upper frequency limits. Only aircraft flybys 9 and 13 support evidence of IGE wake sound in the range near and below 200 Hz. The present experience indicates that there is also abundance of acoustic energy in the kilohertz range which were not predicted by the theoretical study of Ref. 13, and not found in the OGE studies to date in Refs. 7 and 8. The modeling study of Ref. 13, again, only considers the core flow dynamics in its laminar state, and deviation of the theoretical results from field observation therefore suggests that the recorded spectra is most likely stemmed from the turbulent flow field from the vortex-ground interaction. For example, the recorded spectra of over 400 Hz suggest that there exists a fluid mechanics mechanism whose vorticity fluctuation occur at the same 400 Hz or beyond. Moreover, it is conceived that these high-frequency vorticity sources are more likely to be small scale eddies. Such mechanisms cannot, as inferred by Ref. 13, originate from the pure laminar core dynamics. Therefore, the spectra is fundamentally composed of two parts: those related to the core dynamics manifesting in frequencies below the 200 Hz range which the current array may not have enough gain to unambiguously resolve; and those dominated by a turbulent process which occurred at higher frequencies due to the smaller eddies generated from the interaction of vortices in ground effect. The source of these eddies may be the secondary vorticity sheet generated as the result of vortex-ground interaction and/or unsteady advection of turbulence around the vortex cores.

IV. Summary

An exploratory study using a line array of four directional shotgun microphones to quantify the acoustic signature of wake vortices IGE has been presented. The configuration of the array was such that a relatively young wake (30 seconds into a wake's life or less) would pass by a fixed focusing volume formed by the microphones in the runway threshold area. The results suggest that wake vortices do produce a distinct acoustic signature of broadband nature; however, as determined by four microphones, this signature is not necessarily consistent and its determination is sensitive to the choice of background selection. The tests revealed a distinct wake signature of varying intensity at higher frequencies while the low-frequency results are less discernable. Overall, the high-frequency component of the wake sound is more readily detected in the array configuration and processing technique experimented so far.

Despite certain limitations, this experiment showed that it is possible to detect the acoustic signature of wake vortices in an airport environment with relatively simple equipment. It is premature to conclude whether the wake signals possess common and consistent characteristics that could be used for reliable tracking. More studies of wake vortices IGE are necessary and believed to be warranted to determine the detailed characteristics of the wake acoustic signature. Future investigations should use microphone arrays with at least sixteen microphones to better suppress the low-frequency background of the noisy airport environment or should explore other array configurations such as multiple small clusters of microphones spread over a corridor. A larger number of microphones will also allow for more detailed analysis of wake characteristics and better address the question of the consistency of IGE wake signatures. Additionally, future studies can also greatly benefit from having a more established and independent wake vortex sensor (such as a LIDAR or an array of crosswind propeller anemometers) making concurrent measurements to track the vortices so that vortex activity could be better correlated to the observed acoustic signature. Future tests involving sampling the velocity field in the kilohertz range near the ground and at the beamformed location and checking their correlation with the acoustic signal can offer additional insight on the link between aerodynamics and acoustics.

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