EXPERIMENTAL STUDY OF PROPELLER-AIRCRAFT RUN-UP NOISE

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ABSTRACT

Measurements were made of the characteristics of the noise radiated by a Beechcraft 1900D twin-propeller aircraft during engine run-up. The objective was to determine the feasibility of controlling this noise using active noise control. Total noise levels varied with aircraft heading from 103 to 112 dB (100 to 109 dBA) at 73 m from the aircraft. Noise directivity plots were generated. Levels at the nearest community 3 km away varied from 74 to 77 dB (62 to 66 dBA). Near the aircraft the noise spectra comprised a series of equally-high peaks at the 112-Hz fundamental frequency and its multiples. In the community, the three lowest peaks dominated the A-weighted spectrum, with higher-frequency peaks being progressively attenuated. A coherence analysis was performed on the noises measured at 73 m and 98 m from the aircraft. The insertion loss of a blast fence near the run-up area was estimated from run-up noise measurements made on both sides of the fence. The insertion loss varied from 4 to 13 dB and was greatest at mid frequencies.

SOMMAIRE

Des mesures ont été faites des caractéristiques du bruit rayonné par un avion à deux hélices – un Beechcraft 1900D - durant des tests d'accélération des moteurs ('run-up'). L'objectif a été de déterminer s'il serait faisable de controller ce bruit par un système de contrôle actif. Les niveaux totals du bruit ont variés avec la direction de 103 à 112 dB (de 100 à 109 dBA) à 73 m de l'avion. La directivité du bruit rayonné a été déterminée. Dans la communauté voisine la plus proche, à environ 3 km de l'avion, les niveaux ont variés entre 62 et 66 dBA. Proche de l'avion, le spectre du bruit a consisté d'une série d'arrêts d'amplitudes semblables correspondant à la fréquence fondamentale de 112 Hz et de ses harmoniques. Dans la communauté voisine, les trois arrêts les plus bas ont dominés le spectre; les arrêts de plus hautes fréquences ont étés de plus en plus attenués. Un analyse de cohérence a été faite sur les bruits mesurés à 73 m et à 98 m de l'avion. La perte par insertion d'une clôture acoustique proche du site de test, estimée à l'aide de mesures prises des deux côtés de la clôture, a variée de 4 à 13 dB et a étée le plus élévée à moyenne fréquence.

1 INTRODUCTION

The work reported here was part of an investigation of the feasibility of controlling propeller-aircraft run-up noise using active noise control [1]. For active control to be feasible, the noise to be controlled must have appropriate characteristics. Furthermore, simulations of the effectiveness of an active-control system require a knowledge of the directional radiation characteristics of the propeller noise source. Thus, it is crucial to characterize the source and the noise radiated. Finally, run-up areas often have blast-fences, providing some noise attenuation, next to them. Active technology can be used alone, or in combination with the blast fence. Thus, it is of interest to determine the insertion loss of a typical blast fence.

Measurements of propeller-aircraft run-up noise were carried out in July 1999. First, noise levels generated by run-ups were measured near the aircraft, and in the nearest community, to determine levels generated and their frequency contents. Measurements were made in different directions, in order to estimate the radiation directivity of the propeller-aircraft noise source. A coherence analysis of the noise was performed. Finally, the insertion loss of an existing blast fence located near the run-up area was determined.

2. METHODOLOGY

A Beechcraft 1900D twin-engined turboprop aircraft (shown in Figure 1) was provided by Central Mountain Air for the noise measurements. It is a 19-passenger aircraft, with length of 17.7 m, wingspan of 16.6 m, and a cruising speed of 533 km/s. The aircraft has two, four-bladed propellers of 1.6-m diameter, centred 2 m above the ground. It performed full-power engine run-ups, during which both propellers

Figure 1. Beechcraft 1900D twin-engine propeller aircraft.

rotated at approximately 1700 rpm. Four microphone positions were used to measure the resulting sound-pressure levels (see Figure 2). Two Bruel & Kjaer 2230 free-field microphones, positioned at approximately 73 m (Position 1) and 98 m (Position 2) away from the aircraft, captured the near-field run-up noise. A Bruel & Kjaer 4165 free-field microphone was positioned in a community north of the airport, approximately 3 km (Position 3) from the aircraft (see Figure 3). A fourth microphone (Bruel & Kjaer 2230) was positioned on the opposite side of the blast fence (shown in Figure 4) to the aircraft, again at a distance of 73 m (Position 4). The aircraft performed 12 full-power run-ups, each for a duration of one minute, rotating by 30° in between run-ups. The headings shown in Figure 2 refer to the direction of the aircraft relative to geographic north.

Run-up noise signals, along with the ambient noise, the idle-engine noise and calibration tones, were recorded on portable Teac DAT recorders. The recordings were analyzed using a Larson Davis 2800 Real-Time Analyzer. Unweighted and A-weighted total levels were determined. Narrow-band and third-octave spectra were generated.

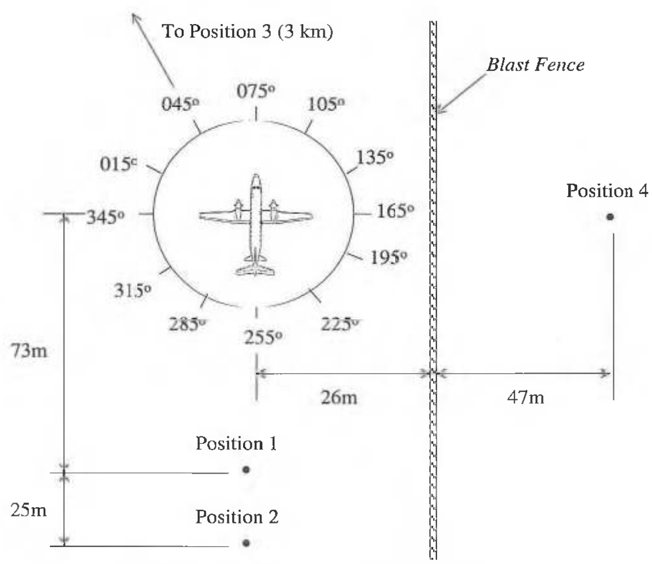

Figure 2. Noise measurement set-up.

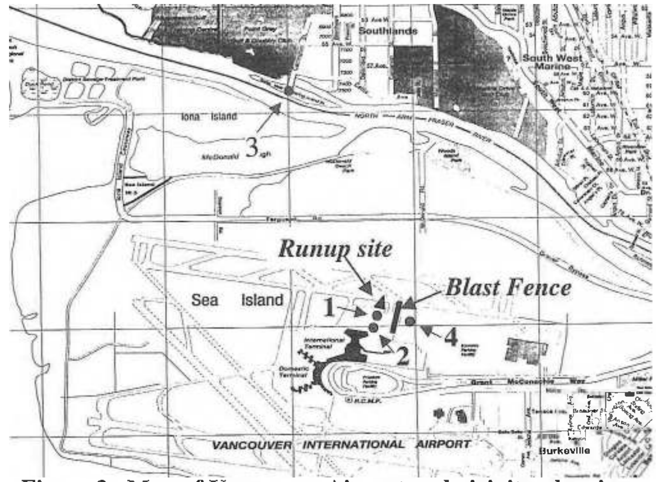

Figure 3. Map of Vancouver Airport and vicinity, showing microphone positions and blast fence. (aircraft denoted by triangle)

3. NOISE LEVELS AND SPECTRA

Figure 5 shows a typical run-up noise spectrum measured at Position 1 (heading 255°) near the aircraft where an active-control system would likely be located. Figure 5a shows the third-octave-band spectrum over the range 12.5 to 20000 Hz, without and with A-weighting. Total noise levels varied with heading from about 103 to 112 dB (100 to 109 dBA). Propeller-noise levels were significantly higher than the ambient-noise and idle-engine levels of 62 and 83 dBA, respectively. Figure 5b shows the A-weighted narrow-band spectrum over the range 0 to 1250 Hz. It can be seen that the spectra consisted of sharp peaks at multiples of the fundamental frequency of 112.5 Hz - *i.e.,* at 225, 337.5, 450 Hz, and so on. The fundamental frequency corresponds to the blade-passing frequency (BPF) of the propellers.

Figures 6a and b show similar results for Position 3. Levels varied from about 74 to 77 dB (62 to 66 dBA) at Position 3

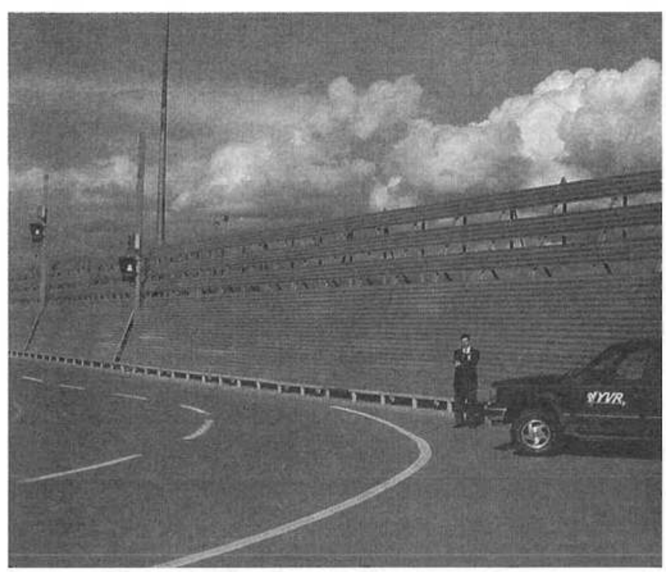

Figure 4. Blast fence at Vancouver Airport.

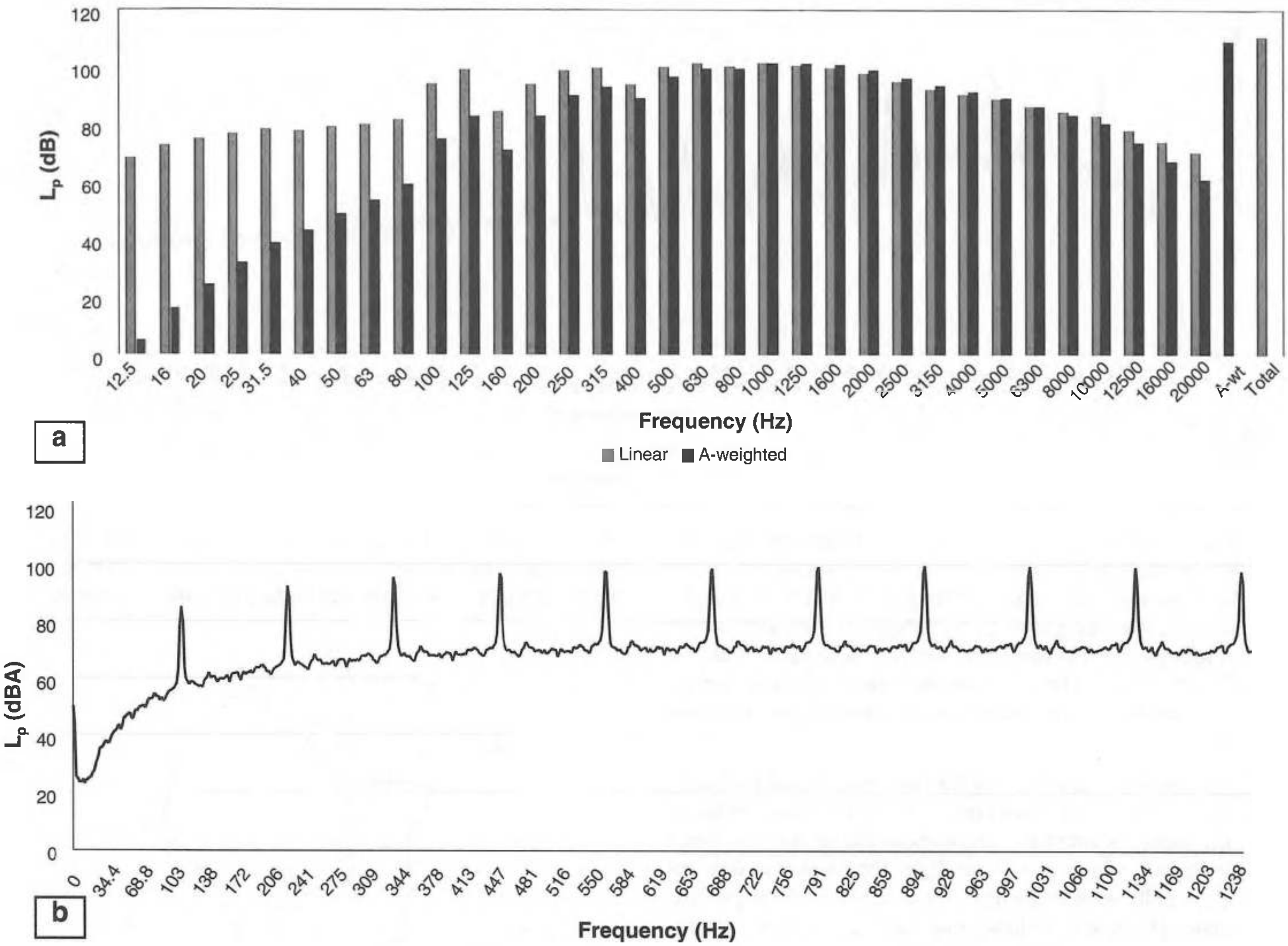

Figure 5. Typical run-up noise spectra measured at P1 (heading 255°) near the aircraft.

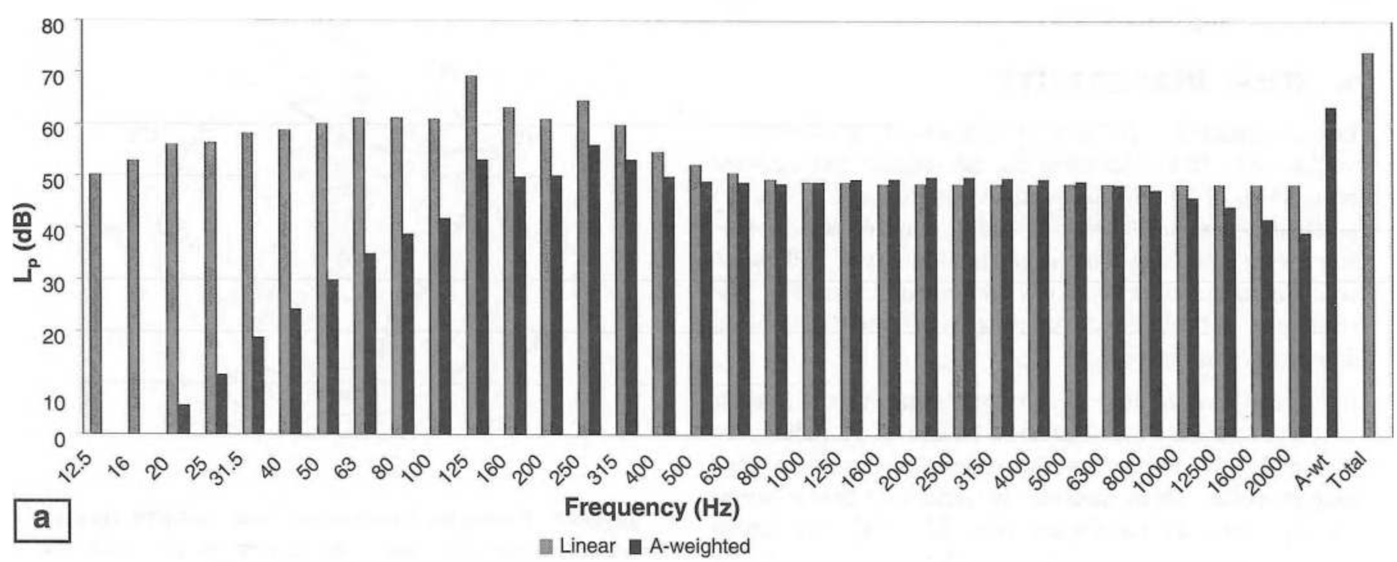

Figure 6. Typical run-up noise spectra measured at P3 in the community 3 km from the aircraft.

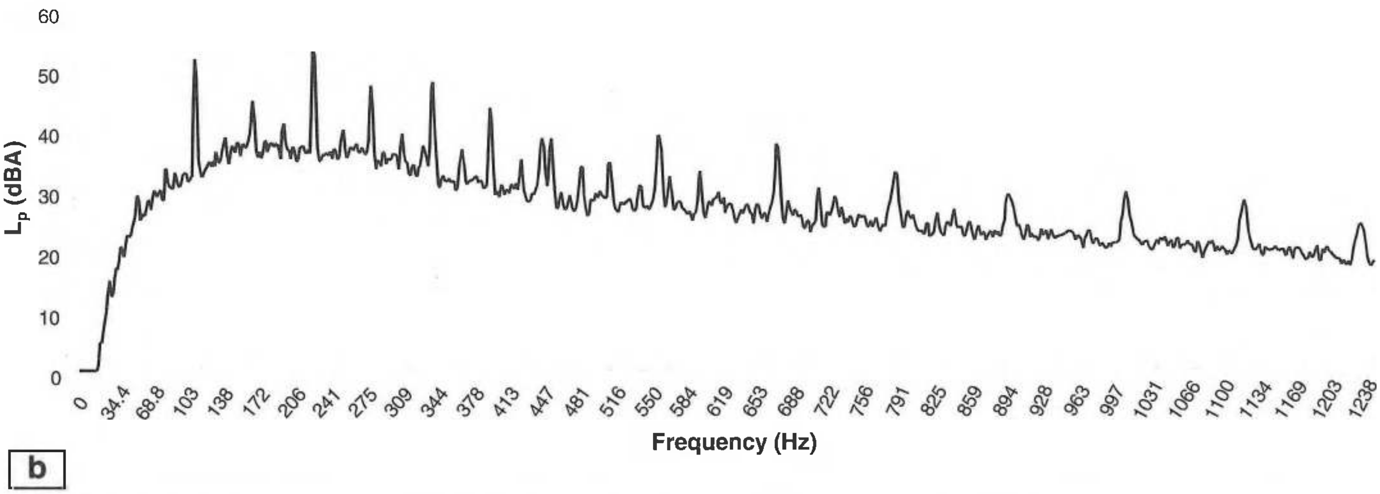

Figure 6. concluded.

in the community. Higher-frequency levels are relatively low and the fundamental and first two harmonics dominate the noise spectrum. The high-frequency components of the noise clearly suffer progressively higher attenuation due to air and ground absorption. A series of secondary peaks (at 170, 280, 390,...Hz) is evident in between the main peaks. These are believed to be due to non-linear effects, discussed below.

Harmonics with levels as high as the fundamental BPF are a characteristic of propellers operating under static conditions - *i.e.,* when the aircraft is stationary, as during run-ups. When the aircraft is in motion, or in flight, the harmonics drop off very rapidly with frequency - by as much as 8 dB per harmonic. This results in lower total noise levels when the aircraft is in motion. The high levels of the harmonics during a run-up (static conditions) are created by non-uniform inflow to the propellers, including naturally occurring turbulence in the atmosphere, ground vortices, as well as by wakes from fuselages, wings, nacelles or test stands [2].

4. NOISE DIRECTIVITY

Levels measured at Position 2 (98 m away) varied between 94 and 108 dBA, exceeding the idle-engine and ambient noise levels of 79 dBA and 62 dBA, respectively. Using the levels measured at Positions 1 and 2, noise directivity patterns were generated. The unweighted-total and BPF noise contours measured at Position 1 are shown in Figure 7. The total noise and BPF directivity patterns measured at Position 2 are shown in Figure 8.

In order to analyze these directivity patterns, it is of interest to try to understand the radiation pattern of propellers, by considering the mechanisms that generate noise from a spinning propeller. These mechanisms include thickness noise, loading noise and quadrupole noise [2, 3, 4]. Thickness noise arises from the transverse periodic displacement of the air by the volume of a passing blade element. This mechanism creates linear noise characteristics, meaning that it is the mechanism responsible for creating harmonics at integer

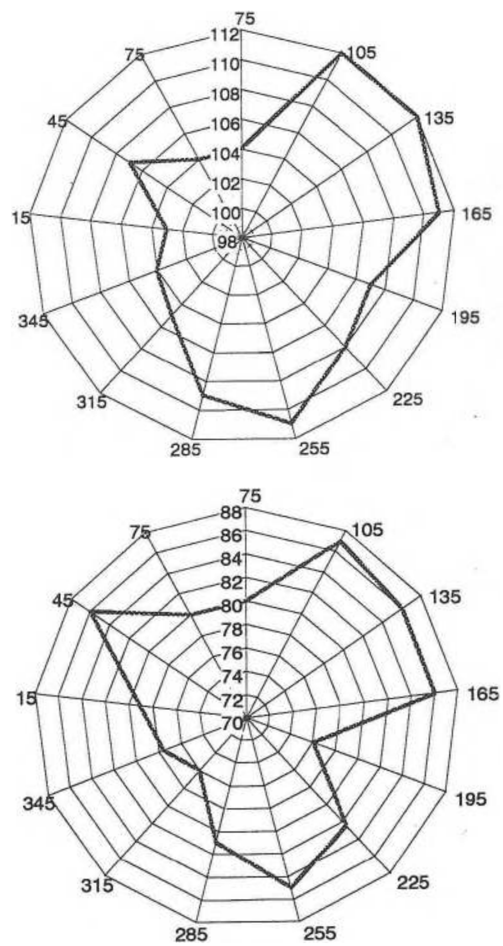

Figure 7. Unweighted-total (upper plot) and BPF (lower) sound-pressure-level directivity patterns of the Beechcraft 1900D at P1.

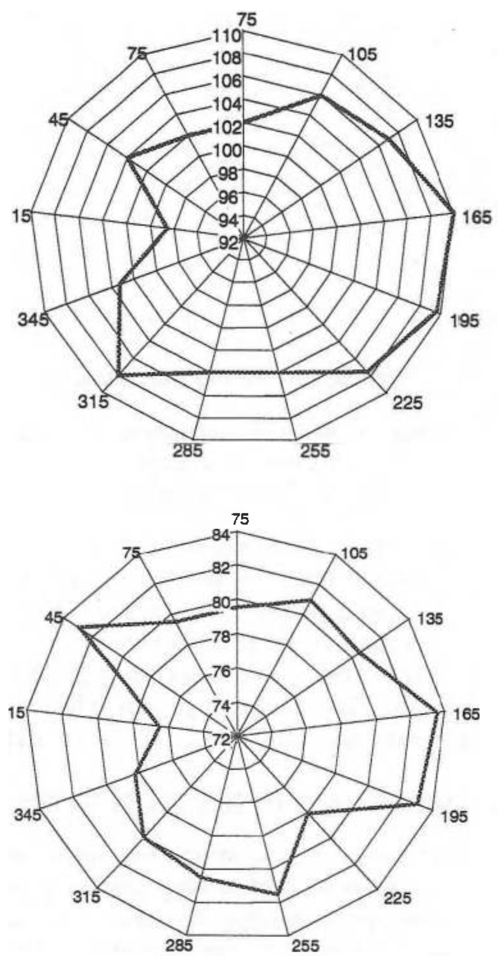

Figure 8. Unweighted-total (upper plot) and BPF (lower) sound-pressure-level directivity patterns of the Beechcraft 1900D at P2.

multiples of the fundamental BPF. Thickness noise can be represented by a monopole source distribution and becomes important at high rotational speeds. Loading noise is a combination of thrust and torque (or lift and drag) components which result from the pressure field that surrounds each blade as a consequence of its motion. This type of noise can be represented as a dipole and is an important mechanism at low to moderate speeds. Quadrupole noise arises from turbulent airflow over the blade sections, and can be used to account for all of the viscous and propagation effects not represented by thickness and loading sources. This creates nonlinear radiation characteristics, meaning that it will generate tones which are not at integer multiples of the BPF (as seen in Figure 6, for example) [2]. Quadrupole noise is the main component of aerodynamic noise arising from turbulent airflow.

A propeller operating during a run-up encounters a great deal of non-uniform inflow, including naturally occurring turbulence from the atmosphere and ground vortices, and wakes from various parts of the aircraft [2]. Since run-up propeller speeds vary from one aircraft to another, it is not possible to draw general conclusions as to which mechanism will govern the generated run-up noise.

By observing Figures 7 and 8, it can be seen that at Position 1 (73 m away) there is a strong directionality towards the right of the aircraft for the 105° to 165° headings, and towards the 45° and 255° headings in both cases. At Position 2, the directionality towards the right of the aircraft is still prevalent, as is the directionality towards the 45° heading. At Position 2 there is also a stronger directionality towards the 315° heading than at Position 1. None of these radiation patterns is symmetrical; this could be due to ground reflection, reflection from the blast fence, or the two propellers' spinning out-of-phase with one another – detrimental factors which could not be controlled. A dipole from the left propeller appears to be present at Position 2, but not at Position 1. This could indicate that radiation patterns are sensitive to distance from the aircraft, probably due to the turbulent nature of the wind blast generated by the propellers during a run-up. An inclined dipole appears to be present for the two BPF contours, with the null shifting from the 195° heading at Position 1 to the 225° heading at Position 2. The directivity appears to rotate as the receiver position moves further away from the aircraft.

From these results, it is difficult to pinpoint exactly which noise mechanism is governing the radiation patterns, since no clear monopole, dipole or quadrupole radiation patterns can be seen. It is important to note that such patterns are generally associated with in-flight noise, making the analysis more difficult when attempting to study run-up noise directivity. In addition, the turbulent airflow over the blades, and reflections from the ground and blast fence, distort the directivity, further increasing the complexity of the analysis. Clearly, a more detailed investigation of propeller noise radiation and how to model it is required.

5. COHERENCE ANALYSIS

If an ANC system is to attenuate noise effectively, the error signal must continuously send 'correction' signals to the controller, to account for fluctuations in the sound field. A way to quantify how much fluctuation occurs is to perform a coherence analysis. If the reference signal is strongly correlated with the control signal sent to the control source, it is deemed 'coherent', and the need for an error signal is minimized. A coherence analysis was therefore performed, in order to quantify the randomness of the recorded run-up noise and determine if a qualified reference signal is available [5].

Coherence is a statistical measure that determines how similar the sound pressures at different positions in space are to each other. In acoustics, it is the direct measure of to what extent two functions (*e.g.*, X and Y) are linearly related, the functions being two random sound-pressure fluctuations [6]. The degree of coherence is represented by values between 0 and 1 (1 representing perfect coherence) that indicate to what extent function X corresponds to function Y at each frequency. For this run-up noise study, the functions are the noise signals measured at two different points in space; this is called the 'auto-correlation'- the degree to which the noise correlates with itself at the two points. The noise data recorded at Positions 1 and 2 were used for this analysis. Positions near the aircraft were chosen since a local active-control system would likely have to be located in this region if it is to create a large quiet zone.

The noise data measured at Positions 1 and 2 were recorded simultaneously on the left and right channels of the DAT recorder. These were input to a computer, and digitized into functions X and Y. The method used for the coherence analysis was Welch's averaged periodogram method [7]. The functions X and Y were divided into overlapping sections, then windowed to a given length. The squared magnitude of the Discrete Fourier Transforms (DFTs) of the sections of X and the sections of Y were averaged to form P_{xx} and P_{yy}, the Power Spectral Densities of X and Y, respectively. The products of the DFTs of the sections of X and Y were then averaged to form P_{xy}, the Cross Spectral Density of X and Y. The coherence C_{xy} is given by,

$$C_{xy} = \frac{|P_{xy}|^2}{P_{xx}P_{yy}}$$

This analysis was performed for various headings, and similar results were obtained at all headings. The coherence for the 105^o heading is shown in Figure 9. The results in Figure 9 show a coherence of 0.7 to 1.0, indicating a very good correlation between the two positions. The 0 to 350 Hz range was chosen in order to display the fundamental frequency

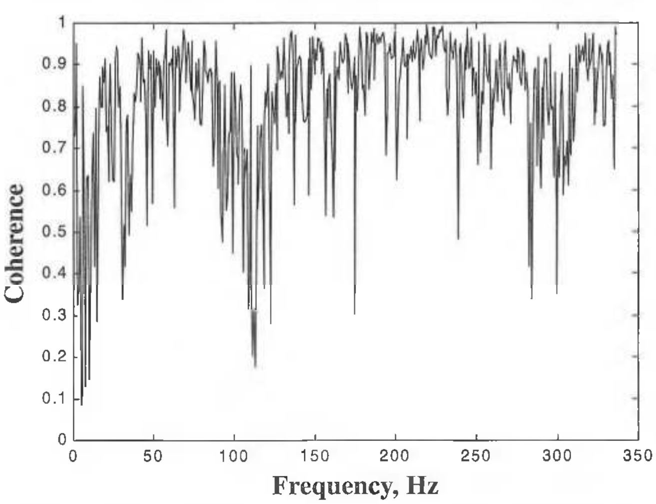

Figure 9. Coherence-analysis results for the 105o heading, for the 0-350 Hz range.

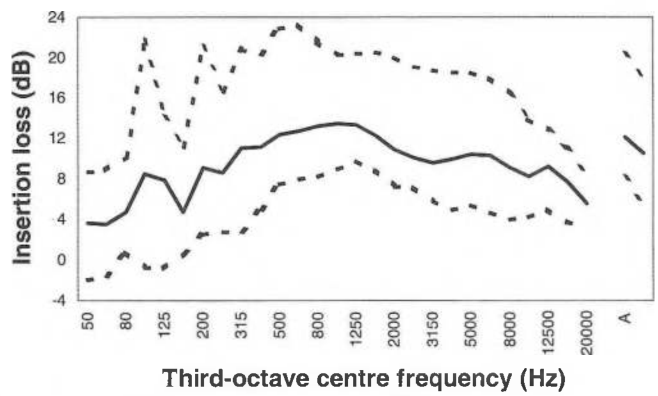

Figure 10. Range (dashed lines) and average (solid line) of the apparent insertion loss of the blast fence for all aircraft headings.

(112 Hz) and the first harmonic (224 Hz), which are the frequencies that would likely be selected for active control. The coherence graph shows a dip in the 112-Hz region, while the coherence appears to be stronger (close to 1.0) in the 224-Hz region. This would indicate that an ANC system optimized for the 224-Hz wavelength might be more effective than a system optimized for the 112-Hz wavelength.

6. BLAST-FENCE INSERTION LOSS

The blast fence next to the run-up area was approximately 4-m high. It was made of steel decking, the lower half being solid, the upper half consisting of metal slats with gaps between them (see Figure 4). The microphone at Position 4 was positioned 73 m away from the aircraft, on the other side of the blast fence, so that the levels could be compared with those measured at Position 1, thus estimating the blast-fence insertion loss. Since Positions 1 and 4 were at 90 ^{o} to one another relative to the aircraft, the spectrum at Position 4 had to be compared with that at Position 1 for a 90^o difference in headings. Figure 10 shows the range and average of the apparent third-octave-band insertion losses provided by the blast fence for all headings, over the frequency range 50-20000 Hz.

A similar pattern emerged at every heading. The blast fence appeared to provide an average insertion loss of 4 to 14 dB, with the average being around 10 dB. Most of the attenuation appears in the 500 to 8000 Hz range, with an attenuation of at least 8 dB for all headings, and as much as 24 dB in the case of the heading of 225 ^{o}. A small dip at 400 Hz, where less attenuation occurs, can be seen for most headings. A more noticeable dip, at which little or no insertion loss occurs, exists at 160 Hz for all headings.

If more attenuation is required, an active-noise system could be integrated into the blast fence, creating an active-noise barrier, in order to increase the low-frequency insertion loss of the blast fence [8].

7. CONCLUSION

Measurements have been made of the characteristics of the noise radiated by a twin-propeller aircraft during engine run-up, in order to characterize the noise source and its radiation for possible active noise control. Results show that the A-weighted noise in the nearest community is dominated by fundamental and harmonic peaks with frequencies in the range 100 to 400 Hz, making active control an interesting option. The insertion loss of the run-up area blast fence was shown to be low at low frequencies, suggesting that incorporating active technology to create an active noise barrier with better low-frequency performance could be an interesting option.

8. ACKNOWLEDGEMENTS

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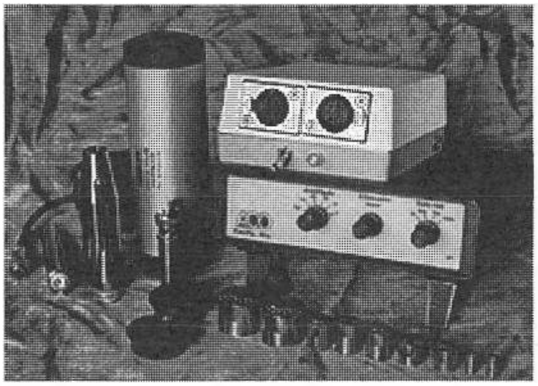

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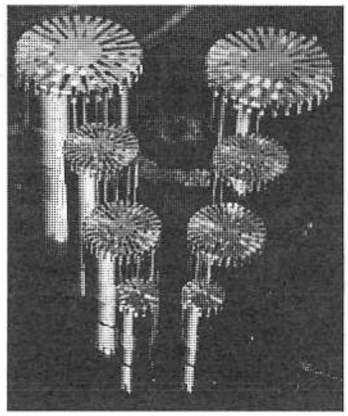

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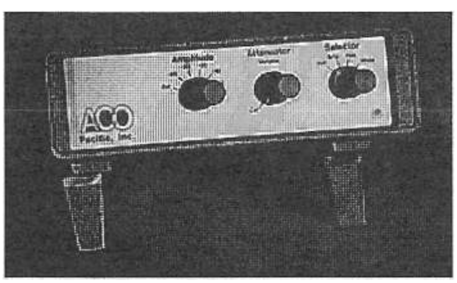

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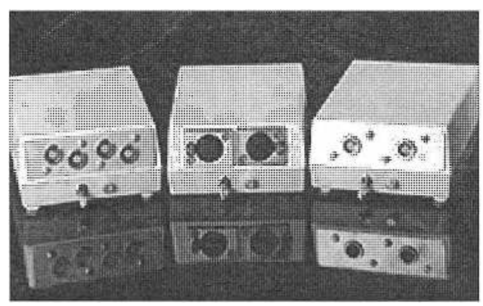

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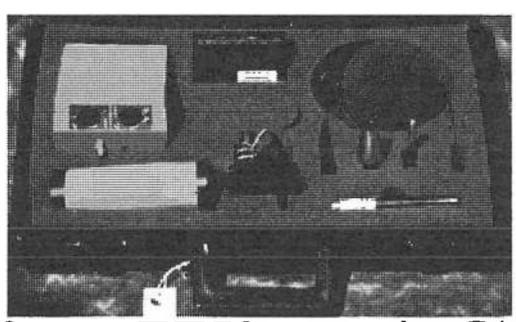

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