Ground Effects on Aircraft Noise for a Wide-Body Commercial Airplane

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A flight experiment was conducted to investigate ground effects on noise from an airplane with a high-bypass-ratio engine. A Boeing 747 was flown at altitudes of 30-960 m past a 20 microphone array. Ground effects are calculated in terms of one-third-octave band spectra and in terms of EPNL units. The 747 experimental results are compared with previous results for a turbojet-powered T-38 airplane and with the SAE recommended empirical lateral attenuation prediction procedure. Theoretical predictions are compared with the 747 and T-38 results. Good agreement was found between the predictions and measured results. However, there was a consistent underprediction of the peak measured attenuation. Less lateral attenuation in effective perceived noise was measured for the 747 than for the T-38.

Introduction

WHEN aircraft are close to the ground during takeoff and landing, noise propagates at shallow grazing angles to the sideline. The signal received is less, by as much as 20 dB for certain frequencies, from what would be expected considering only the effects of spherical spreading and atmospheric absorption in a free field. The difference between the signal that would be received in a free field and the actual received signal is called ground effects. The difference between flyover and sideline noise levels (for the same propagation distance) is referred to as lateral attenuation. Lateral attenuation is not due solely to ground effects. At low elevation angles, shielding effects of the aircraft on the emitted noise may alter the received signal. Shielding effects are aircraft dependent, while ground effects are functions of ground surface properties. Refraction by wind and temperature gradients may also affect lateral attenuation. A basic understanding of the effects contributing to lateral attenuation is required for accurate prediction of aircraft noise.

In the spring of 1980, the SAE A-21 Aircraft Noise Committee collected available data on lateral attenuation to develop an interim empirical prediction method.[1] One of the key sets of data, containing over 400 ground effects measurements, was from an experiment using a T-38 aircraft.[2,3] However, the Committee recognized that the available lateral attenuation data base contained very few data points associated with high-bypass-ratio engines. A ground effects experiment using a Boeing 747 aircraft was undertaken to fill this gap.[4]

This paper reviews the previous T-38 experiment, presents the new results of the 747 experiment, and compares both experiments with theory. Measured values of ground effects are presented here as functions of frequency, elevation angle, and slant range. Theoretical predictions are made using the method of Pao, Wenzel, and Oncley.[5] Lateral attenuations in units of effective perceived noise level are presented for both airplanes and compared with the SAE interim prediction method and with the Pao-Wenzel-Oncley method.

Experiments

The T-38 experiment was performed at Wallops Flight Center, Wallops Island, Va., in the fall of 1978. The T-38 was flown at low altitudes past the end of a 20 microphone array. The landing gear and speed brake were deployed to minimize the flight velocity. Microphones were positioned over grass and concrete and extended over 1500 m to the right side of the airplane ground track. Twenty-eight level flights were flown at altitudes of 10, 20, 40, 80, and 160 m in two days of testing. The airplane was operated with the right engine, facing the array, at military power and the left engine, facing away from the array, at flight idle, so that the dominant jet noise pattern would be axisymmetric. The T-38 experiment is described in more detail in Refs. 2 and 3.

The 747 experiment was performed at NASA Wallops Flight Center in the fall of 1980 and was a cooperative effort within the SAE A-21 Noise Committee. The major participants were American Airlines which supplied the airplane and the crew, the FAA which paid for the fuel, and NASA Langley Research Center which designed and conducted the experiment and reduced the data. The 747 was flown at low altitudes past a 20 microphone array similar to that used in the T-38 experiment. A diagram of the microphone array employed in the 747 experiment is illustrated in Fig. 1. A total of 16 level flights were flown with the 747 at altitudes of 30, 60, 120, 240, and 980 m. The 747 was flown with all four engines at a constant engine pressure ratio and with landing gear and flaps deployed. More details concerning the 747 experiment may be found in Ref. 4.

The grassy areas around the runways at Wallops are best described as covered with institutional grass which is cut every week. The width of the grassy area runway 04-22 and its taxiway is 115 m at the wider portion and 70 m at the narrower portion close to runway 10-28. The soil beneath the grass is a mixture of sand and clay. Runway 04-22 is a 2500 m

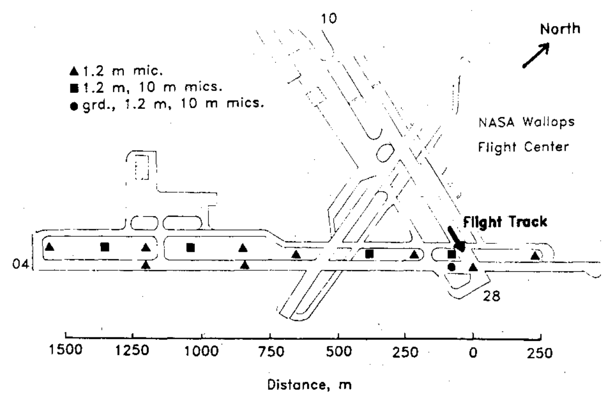

Fig. 1 747 microphone layout.

Presented as Paper 81-1988 at the AIAA 7th Aeroacoustics Conference, Palo Alto, Calif., Oct. 5-7, 1981; submitted Oct. 16, 1981; revision received July 12, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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long, 150 m wide landing research runway with a 1300 m long, 16 m wide test section located in the middle of the runway. The major portion of the runway is concrete, but the test section is comprised of four different sections of concrete and asphalt. The area around runway 04-22 is flat and free of large obstructions. See Ref. 3 for more details.

In both flight experiments, the test aircraft was tracked with a laser tracker. The flight paths in both experiments were above runway 10-28, from the west toward the east (see Fig. 1). Weather information was collected along the microphone arrays near ground level and at one location up to the altitude of the test aircraft. In both experiments the ground level winds during testing were less than 5 m/s and the temperature gradients were no more than $-0.02°C/m$.

Data Reduction

The acoustic data collected in both flight experiments were reduced to one-third-octave band spectral time histories and synchronized with the tracking and weather information. The 747 data were reduced with an averaging time of ¼ s and the T-38 data were reduced with an averaging time of ⅛ s. The shorter averaging time was necessary because of the higher speeds and lower altitudes involved in the T-38 experiment.

In both experiments the laser tracker lost track of the test airplanes for a brief period due to the unavoidable close proximity of the flight path to the tracker, coupled with the slew rate limit of the tracker pedestal. During the data reduction, straight-line interpolation was used to fill the gaps. Tracking information was recorded every 1/10 s.

Ground Effects

Ground effects are defined as the difference between the signal that would be received by a microphone in a free-field and the signal that is received when the microphone is in the presence of a ground surface.[5] This concept is illustrated in Fig. 2a. The free-field signal is the direct signal which propagates from the aircraft source to the microphone. The presence of the ground surface adds a reflected signal which is sensed by the microphone. Ground effects are defined as the direct signal minus the measurement signal. With this definition, cancellation effects and absorption effects appear as positive values on the decibel scale. Positive reinforcement due to reflection appears as a negative value.

Lateral attenuation is defined by a comparative method in which the signal measured to the side of the flight track is compared to a second signal measured underneath the flight track (see Fig. 2b).[1] The sideline signal is called the measurement signal and the signal underneath the flight track is called the reference signal. The reference signal is first corrected for atmospheric absorption and spherical spreading to the same slant range as the direct signal. Lateral attenuation is then defined as the corrected reference signal minus the measurement signal. A positive value of lateral attenuation represents an attenuation in excess of that due to spherical spreading and atmospheric absorption.

For ground effects as a function of frequency, the one-third-octave band spectrum emitted at an angle of 122.5 deg referenced to the forward inlet direction is selected to be the measurement signal. This emission angle corresponds to the obtuse angle between the microphone array and the aircraft flight path. The sound emitted from the airplane at this emission angle propagates parallel to the microphone array. This emission angle criterion enables all microphones positioned over the same surface to receive a signal which has propagated primarily over this surface.

In the actual data reduction procedure, a reception time is calculated for each microphone for the sound emitted at 122.5 deg. The two one-third-octave band spectra located on either side of this time in the microphone time history are averaged to yield the measurement signal. The average spectrum has an effective averaging time of twice the one-third-octave data reduction time constant, which gives values of – ¼ s for the T-38 data and ½ s for the 747 data.

The noise signals measured underneath the airplane at an emission directivity angle of 122.5 deg are used to estimate the free-field source spectrum by the following method. The measured spectra from the 1.2 and 10 m microphones positioned underneath the flight path are first corrected for the influence of the ground reflections. This is accomplished with the ground effects prediction procedure to be discussed in the next section. Each reference spectrum is then corrected for spherical spreading and atmospheric absorption to a slant range of 50 m. Absorption corrections are calculated using the American National Standards Institute (ANSI) standard method for the determination of molecular absorption.[6] These corrected spectra from each microphone are then averaged to yield a 50 m free-field direct source spectrum. The results for the T-38 and the 747 experiments are shown in Fig. 3; each spectrum represents an average of about 50 spectra.

To compute a ground effects result, the average direct spectrum is then corrected for spherical spreading and atmospheric absorption to the same slant range as the measurement spectrum. The measurement spectrum is

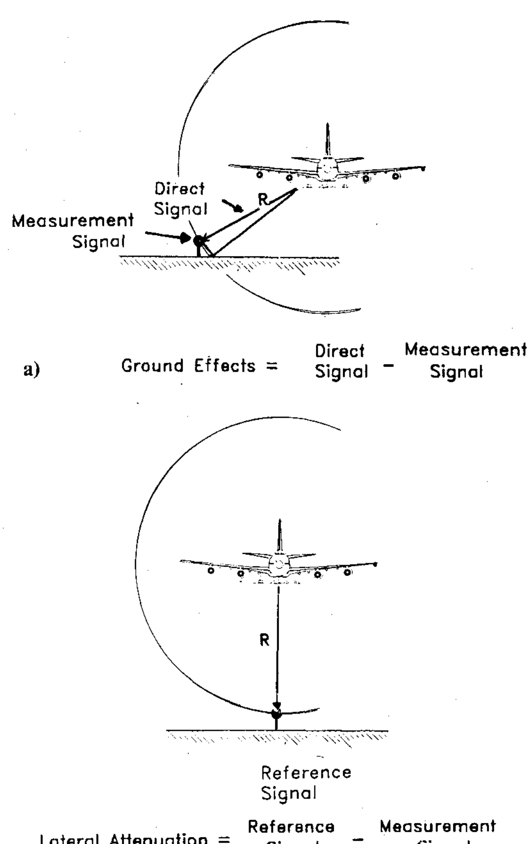

Fig. 2 Analysis methods: a) ground effects, b) lateral attenuation.

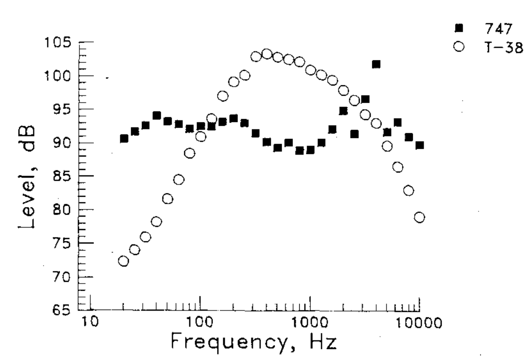

Fig. 3 50 m free-field source spectra.

subtracted from the direct spectrum to yield the ground effects results.

For effective perceived noise level (EPNL) analysis, the measurement EPNL value is calculated directly from the measurement microphone time history in the standard manner. The corresponding reference EPNL value for the same run is calculated in the following manner: each one-third-octave band spectrum in the measurement time history is replaced with an average reference spectrum from 1.2 m microphones underneath the flight path for the same emission angle. Ground effects are not removed from the reference spectra. The average reference microphone spectra are corrected to the same slant range as the measurement spectra they replace. In this manner, a reference time history congruous to the measurement time history is formed and is used in the reference EPNL calculation. The measurement EPNL value is subtracted from the reference EPNL value to yield a lateral attenuation measurement.

Theoretical Model

The theoretical model chosen to make ground effects predictions is the procedure recommended by Pao, Wenzel, and Oncley.[5] The formulation of the method is based on work by Chien and Soroka[7] and Thomasson.[8] The predicted mean square pressure p^2 at the observer position is

$$p^2/p_0^2 = 1 + 2R\exp(-ak\Delta r)^2\cos(\alpha + k\Delta r) + R^2$$

where p_0^2 is the mean square pressure without ground effects (free-field mean square pressure), R and α are the magnitude and phase of the complex reflection coefficient, a is a coherence factor, k the wave number, and Δr the difference in length between the reflected path and the direct path.

The complex reflection coefficient is defined as

$$Re^{i\alpha} \equiv \Gamma + (1-\Gamma)F(\tau)$$

where Γ is the plane-wave reflection coefficient. The function $F(\tau)$ is given by

$$F(\tau) = 1 - \tau W(i\tau)\sqrt{\pi}$$

with

$$\tau = (\sin\theta + \nu)\sqrt{kr_2/2i}$$

where θ is the angle between the reflected wave path and the ground, ν the normalized acoustic admittance of the ground, r_2 the total path length of the reflected wave, and W the complex error function defined by

$$W(A) = \frac{i}{\pi}\int_{-\infty}^{\infty} \frac{e^{-t^2}}{A-t}\mathrm{d}t \quad Im(A) > 0$$

where $Im(A)$ represents the imaginary part of the complex number A and t a dummy variable of integration.

The input required for these computations are the geometry of a source/receiver combination, frequency, the coherence a, and the normalized acoustic admittance of the ground (to compute the plane-wave reflection coefficient and τ). A two-parameter model requiring frequency and ground flow resistance given by Delany and Bazley[9] is used to describe the normalized acoustic admittance.

The ground effects prediction equation given above is for a discrete frequency. To make predictions comparable to the results of the one-third-octave band analysis of the measured data, the discrete frequency equation was integrated over one-third-octave bands.

To make ground effects predictions to be compared with the T-38 and 747 experimental results, values of 62,500 MKS rayls for the ground flow resistance and 0.1 for the coherence factor were used. These values were adjusted to give the best agreement between theory and the T-38 experiment. This value of ground flow resistance is roughly equivalent to a measured value for the same site obtained in another experiment.[10] The geometry of the measured results was also used as input in the theoretical calculations.

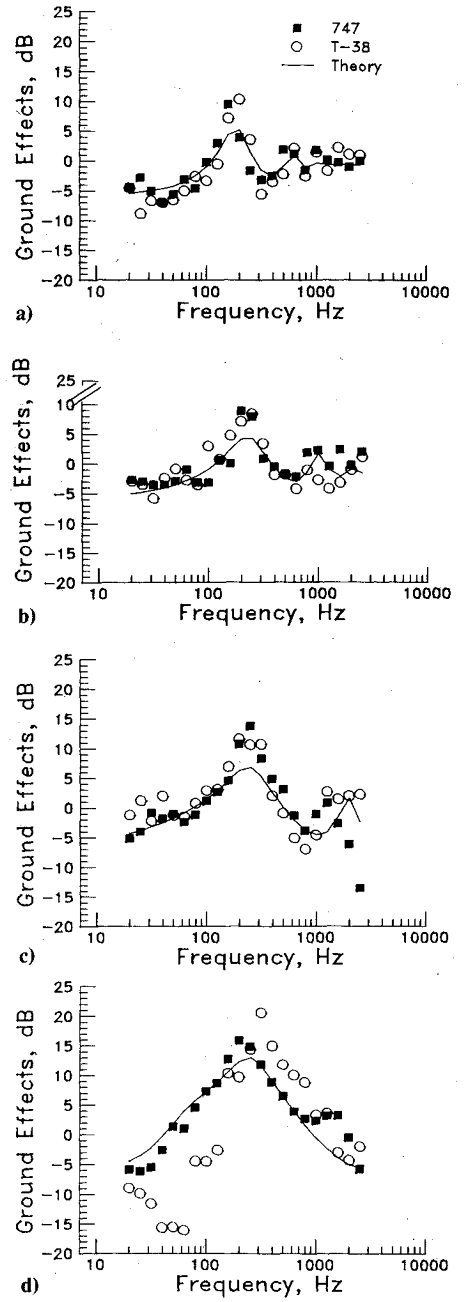

Fig. 4 Ground effects vs frequency: a) $R=458$ m, $\beta=17$ deg, b) $R=888$ m, $\beta=9$ deg, c) $R=1800$ m, $\beta=4$ deg, d) $R=1350$ m, $\beta=2$ deg.

Predictions of lateral attenuation in EPNL units are made in the following manner: free-field one-third-octave band spectra are obtained for a particular airplane for 20 emission angles between 40 and 160 deg. These spectra are obtained in the same fashion as the direct source spectra in the ground effects calculations. A time history is computed for a microphone by calculating the position of the airplane in ½ s intervals. The geometry between the airplane and microphone for each "frozen" position is used to select a free-field one-third-octave band spectrum, to propagate the spectrum to the proper slant range, and to make a ground effects prediction to correct for the influence of the ground. Paralleling a measured lateral attenuation result, reference and measurement predicted time histories are computed and integrated to yield EPNL values. The predicted EPNL values are subtracted to give a predicted lateral attenuation result.

Results

Measured ground effects as a function of frequency are given in Fig. 4 for both the T-38 and 747 experiments along with theoretical predictions. All results are for 1.2 m microphones positioned over grass. In each figure, the 747 and T-38 results are for approximately the same geometry, slant range, and elevation angle. The T-38 results are for a particular microphone and a single run. The 747 results represent averages for a particular microphone for two to four runs at the same altitude.

The agreement between the 747 and T-38 results is judged to be good. Flight experiments are necessarily performed outdoors. The outdoor environment is not uniform or ideal and no corrections, besides a limited amount of averaging were applied to account for the influence of turbulent scattering, gradients in meteorological parameters, or the nonflat terrain. Because a difference method was used to compute the results, the influence of source spectral shape is reduced. Shielding differences between the two airplanes, however, are incorporated in the results. No definite shielding differences are apparent in the results for the 747 and T-38 airplanes for a directivity angle of 122.5 deg. The measured ground effects are the largest around 200 Hz.

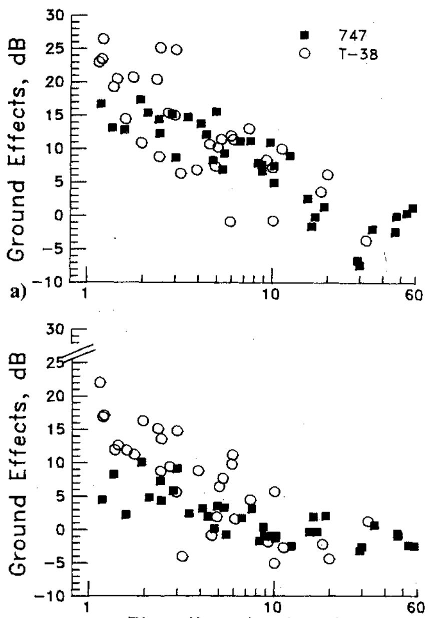

Fig. 5 Ground effects vs elevation angle: a) 250 Hz one-third-octave band, b) 500 Hz one-third-octave band.

The agreement between theory and measured ground effects is seen to be good, again allowing for the variability in an outdoor experiment. The significant details in the measured results are mirrored in the predicted results with the predicted amplitude at the frequency of maximum ground effects being lower than that measured.

Ground effects results as a function of elevation angle β are given in Fig. 5 for both flight experiments for the 250 and 500 Hz one-third-octave bands. The two sets of data show the same trend, having the largest values of ground effects at small elevation angles. However, there is considerable scatter in the data. Some of this is due to variation on slant range which is not identified in this figure. Less scatter is observed in the 747 results due (in part) to the averaging of the 747 results.

The data presented in Fig. 5 were partitioned into four slant range groups and replotted in Figs. 6 and 7 with theoretical predictions. These groups consist of data which have slant ranges which fall within 15% of the following slant ranges: 230, 440, 900, and 1600 m. This partitioning improved the agreement between the two sets of data. For small elevation angles, the T-38 ground effects are seen to be generally larger than the 747 ground effects.

The agreement between measurement and theory is reasonable, with the theory again underpredicting ground effects for small values of elevation angle. The agreement between theory and measurement is better for the 747 results than for the T-38 results.

Lateral attenuation in EPNL units for the 747 are compared with predicted results in Fig. 8. The predicted results again fall beneath the measured results for elevation angles of about 2-20 deg.

Measured lateral attenuation in EPNL units for both flight experiments is compared in Fig. 9 with the SAE interim lateral attenuation prediction procedure.[1] The T-38 and 747 curves are least square fits of the second order. The T-38 results were incorporated in the SAE curve and, although agreeing closely with this curve, fall below it. The 747 results fall beneath the T-38 results and the SAE curve.

The measured lateral attenuation in EPNL differed for the two airplanes because of spectral differences. In the case of the T-38, larger values of lateral attenuation were measured because ground effects greatly reduced the dominant frequency bands (near 200 Hz) of the T-38 source spectra. The low frequency content of the 747 source spectra was not affected greatly by ground effects or absorption. Since the integrated values of the 747 measurement spectra were

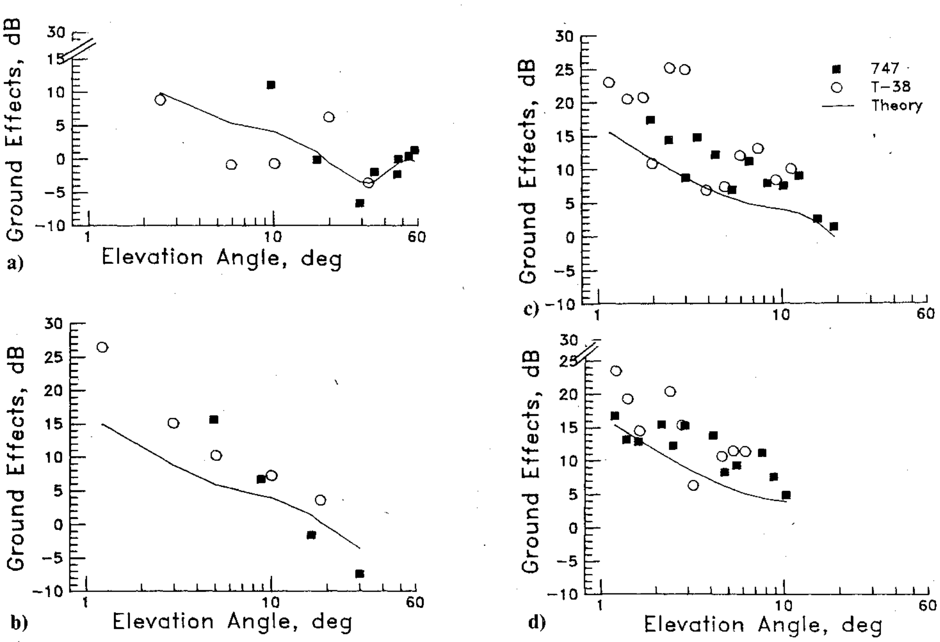

Fig. 6 Ground effects vs elevation angle for 250 Hz one-third-octave band: data at a) 230 m, b) 440 m, c) 900 m, d) 1600 m.

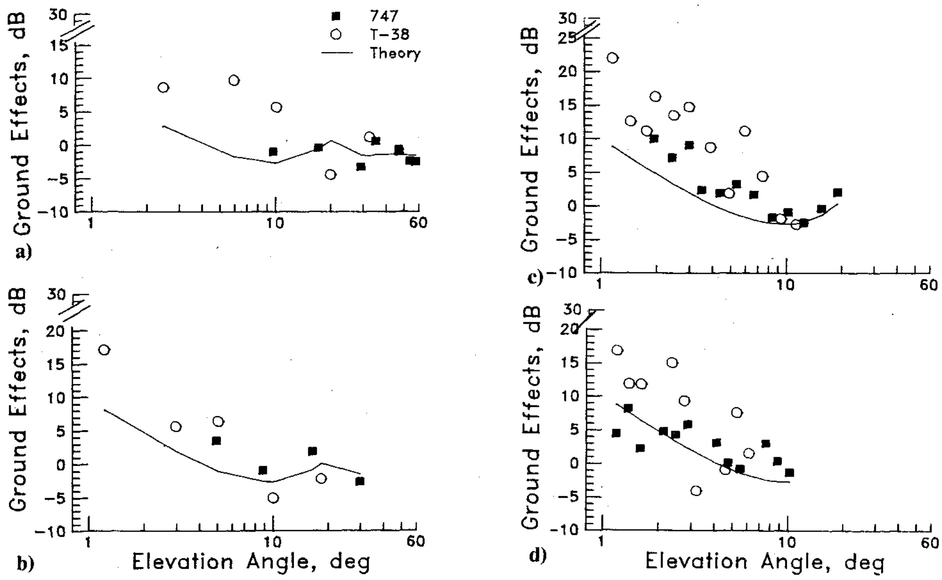

Fig. 7 Ground effects vs elevation angle for 500 Hz one-third-octave band: data at a) 230 m, b) 440 m, c) 900 m, d) 1600 m.

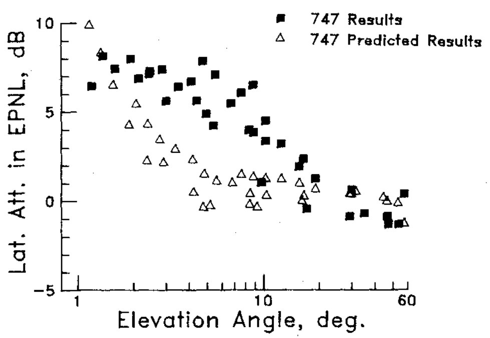

Fig. 8 Comparison of measured and predicted 747 lateral attenuation.

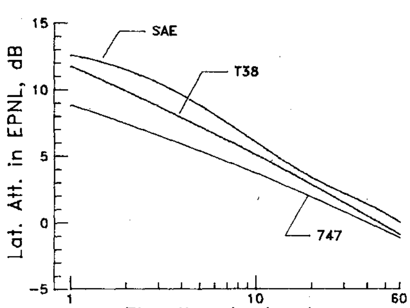

Fig. 9 Lateral attenuation in EPNL.

dominated by the low frequency content, less lateral attenuation was measured for the 747.

Conclusion

Two flight experiments have been conducted at the same test site to investigate ground effects on aircraft noise. A T-38 and a Boeing 747 were flown in two different tests at low altitudes over 20 microphone arrays. The two airplanes represent extremes of aircraft configurations, the small, effectively single-turbojet T-38 and the large high-bypass-ratio, multiengined 747.

Measured ground effects as a function of frequency for both airplanes were in good agreement. The measured results, when plotted as a function of elevation angle for particular one-third-octave bands, were in agreement and showed the same trend of increasing ground effect for decreasing elevation angle. The agreement between the measured results as a function of elevation angle was improved when the data were partitioned into slant range groups.

Shielding effects in the T-38 flight experiment were minimized due to the engine installations and the fact that the airplane was operated with one of its two engines at flight idle. No definite shielding differences were apparent in the measured results for the 747 and the T-38 airplanes at a directivity angle of 122.5 deg.

The ground effect prediction procedure recommended by Pao, Wenzel, and Oncley was used to make predictions of ground effect to compare with the measured results. The frequency dependence of the measured results was closely matched in the predicted results. The predicted attenuation was in agreement with the measured results, except at the frequency of maximum attenuation near 250 Hz, where the theory underpredicted the measured results. Predicted ground effects at small elevation angles were less than measured values. The predicted 747 lateral attenuation in EPNL units was significantly below the measured attenuation for elevation angles between 2 and 20 deg.

Comparison of measured lateral attenuation in EPNL units was made between the two airplanes and with the SAE interim recommended lateral attenuation prediction procedure. The 747 integrated (EPNL) results as a function of elevation angle fell below the T-38 results. Both the 747 and T-38 results were beneath the SAE recommended curve.

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