ICAS Paper No. 68-46

THE PROPAGATION OF AIRCRAFT NOISE

by

Robert L. Miller and John B. Large
Commercial Airplane Division
The Boeing Company
Seattle, Washington, U. S. A.

The Sixth Congress of the International Council of the Aeronautical Sciences

DEUTSCHES MUSEUM, MÜNCHEN, GERMANY/SEPTEMBER 9-13, 1968

Preis: DM 2.00

PROPAGATION OF AIRCRAFT NOISE

Robert L. Miller and John B. Large
The Boeing Company
Seattle, Washington

Abstract

With the growing importance of aircraft noise, it has become necessary to be able to predict accurately the characteristics of this noise. To do this, the effect of atmospheric parameters on noise propagation must be understood. Using some of these parameters, an extrapolation technique has been developed for predicting noise spectrum levels from aircraft during flyovers, takeoffs, and landings. Data from current research programs show that present attenuation standards do not adequately predict a real-life situation. Finally, the paper compares measurements with noise levels estimated by the extrapolation technique and discusses reasons for the differences.

I. Background

Improved noise prediction methods must be developed to meet the increasing need for land-use planning in the vicinity of airports and for use in proposed regulations in aircraft noise certification. The purpose of this paper is to show how predicted and measured noise spectra differ as a result of differences between accepted standard attenuation values and attenuation in the real atmosphere.

The measurement and propagation of noise from an aircraft in flight are complicated by the motion of the aircraft, variations in the atmosphere along the propagation path, and the effects of ground surfaces near the point of measurement. Noise levels are calculated for a specific location by estimating the attenuation of the sound as it is propagated through the atmosphere. The noise characteristics near the source may be measured or they may be calculated from engine performance data.

Most prediction methods specify limits of wind, temperature, and humidity for noise measurements and rely on standardized values for atmospheric noise attenuation. In the United States, the aircraft industry has generally agreed to follow the standards recommended by the Society of Automotive Engineers (SAE). Many other countries follow procedures recommended by the International Organization for Standardization (ISO). Standards recommended by the two organizations are generally compatible. Test data show that differences exist between measured and predicted noise levels when current standards are used. The following short discussion of the sources of data for the standards and the methods by which they were developed will help to explain the reasons for the differences.

Sound energy is attenuated or diminished as it is propagated through the atmosphere at a rate dependent on such factors as atmospheric conditions and the effect of the ground surface. In addition, the spreading of sound energy from a point source over a continually increasing surface area causes a decrease in sound pressure level (SPL) proportional to $1/d^2$, where d is the distance from the source. This is the well-known spherical divergence. The level decreases 6 dB per doubling of distance and is independent of frequency and atmospheric conditions. Attenuation in the atmosphere occurs as a result of molecular absorption and varies with the temperature and humidity of the air. SAE Aerospace Recommended Practice (ARP) 866 (1) presents a method for obtaining the absorption of sound in air over a wide range of temperature, humidity, and frequency. Experimental data from several aircraft manufacturers were used to adjust the theoretical and empirical formulas derived by Kneser (2) A set of mean data covering a limited range of temperature and humidity was derived from experimental data collected from a variety of sources. Revisions to ARP 866 are in progress to incorporate more recent data.

For calculating the propagation of noise from an aircraft on the ground or at a low altitude, the effect of wind and temperature gradients and turbulence should be considered. In addition, sound energy may be absorbed by the ground surface or deflected by terrain or buildings. For propagation over short distances, reflection from the ground may cause interference effects that depend on frequency and source-receiver geometry. There are currently no SAE recommended procedures for calculating the effect of the ground surface on noise propagation. The SAE has published Aerospace Information Report (AIR) 923 (3), which includes graphs for calculating the extra ground attenuation for various elevation angles and wind directions. AIR 923 is based primarily on the theoretical and experimental work of Ingard (4). The report calls attention to the fact that the curves represent average values of available attenuation data and cannot be expected to provide precise calculations of attenuation. The experimental data used in constructing the graphs were obtained primarily using an electromagnetic sound source or a model jet engine.

It is generally agreed that noise measurements should be made with temperature and relative humidity as close as possible to recommended "standard day" conditions of a 59° F and 70-percent relative humidity. These values, representative of conditions for major airports around the world, are those for which absorption is very nearly a minimum so that predicted noise levels should not be optimistic.

II. Characteristics of Aircraft Noise

Sound is produced by rapid fluctuations of atmospheric pressure in the audible frequency range and is measured by the rms of these pressure fluctuations. The wide range of sound pressure to which the ear responds is conveniently compressed into a logarithmic decibel (dB) scale with a reference pressure of 0.0002 microbars. For most acoustic investigations the frequency range from about 30 to 10,000 Hz is divided into a series of bands with the upper frequency limit double the lower limit. Common octave bands are numbered 1 through 8, starting with 37.5 to 75 Hz and ending with 4,800 to 9,600 Hz. For investigating high-pitched compressor noise or fan noise where energy may be concentrated in narrow frequency bands, a 1/3 octave or narrower band analysis may be required.

Although propagation of sound has been studied for many years, the subject of jet aircraft noise is relatively recent in origin and has been investigated intensively only during the past decade. In view of the complex noise-generating mechanisms of large, modern, high-bypass-ratio turbofan or afterburning turbojet engines, it is not surprising that our understanding of aircraft noise is still developing.

The noise-generating mechanisms of a turbofan engine (Fig. 1) are the fan, compressor, and the propulsive jet, each with its characteristic spectrum and direction pattern. The noise from the fan radiates both forward through the inlet and to the rear through the fan duct and is characterized by a high-pitched whine. This noise has a maxima at approximately 60 to 70 deg from the engine axis. The overall peak of the noise field occurs in the rear arc where the jet noise is predominant at high power settings and fan noise is predominant at low power settings. For turbojet engines, the noise characteristics are essentially the same except there is no fan noise and only forward-radiating compressor noise.

FIGURE 1. NOISE SOURCES OF A TURBOFAN ENGINE

Figure 2 shows a typical takeoff noise spectrum of the 707-320B measured on the ground with the aircraft at an altitude of about 400 ft. This figure illustrates the octave band and 1/24-octave band analyses of the combined effect of the various noise sources. The jet exhaust noise covers the full audio range of frequencies shown, decreasing in level with increasing frequency. The compressor and turbine noises with discrete tones generated by the blades produce noise levels and peaks from 1,000 to 10,000 Hz. Therefore, it is seen that noise from an aircraft engine is composed primarily of jet and compressor noise, each having its own directivity and spectral content

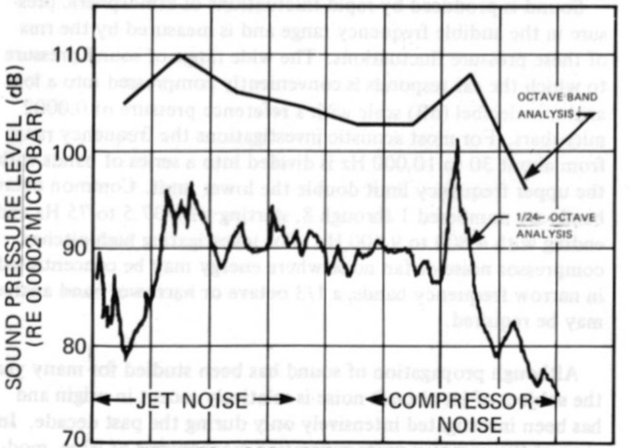


FIGURE 2. TURBOFAN-ENGINE NOISE SPECTRUM–707-320B

III. Noise Prediction Methods

The term "prediction" as commonly used in noise propagation investigations refers to the process of calculating the level and direction pattern of aircraft engine noise expected at a specified distance from the source. The prediction may be made using information obtained by measurements taken near the source or from data calculated directly from the engine parameters. The prediction process consists of extrapolating measured or computed noise data to greater distances, taking into account the attenuation resulting from spherical divergence and from the effects of the atmosphere and the ground surface.

Ideally, for a developmental engine, predictions should be made from design information. SAE AIR 876, *Jet Noise Prediction*(5) outlines a procedure for calculating the maximum flyby noise and maximum static ground operation noise from jet exhaust. No such standard reference exists for compressor noise prediction. Procedures have been developed by Boeing for calculating the compressor noise spectrum from engine parameters. The procedures use curves that were developed from the statistical analysis of a large number of engine performance and noise measurements. A composite spectrum is derived by selecting the maximum SPL in each octave band interval regardless of the angular position at which the maximum occurs. The assumption that peak SPL in the directivity pattern for each octave band occurs at a single angular position (called the equivalent angle) is not unrealistic for measuring peak flyover noise and simplifies the computational procedure.

It is recognized that subjective response must be considered when assessing community noise problems. Perceived noise levels or similar rating scales have been developed for this purpose; however, human response to aircraft noise is not a subject for discussion in this paper.

Examples of Noise Prediction

Several methods for predicting noise spectra are currently used by Boeing, depending on the information available. The following examples illustrate two of these procedures. The first example compares predicted and measured 1,500-ft sideline spectra. The predicted spectrum was calculated from 200-ft polar arc data measured during static operation of a single Pratt and Whitney YJ-75-P-3 afterburning turbojet engine at takeoff thrust. The second example compares a measured 1,000-ft flyover spectrum of a four-engine 707-320B at takeoff thrust with a spectrum computed from engine parameters.

The measured and predicted 1,500-ft sideline spectra of the YJ-75 engine used in the first example are for an angle of 140 deg from the jet inlet, which is approximately the angle of maximum jet noise. The octave band SPL values measured at 200 ft were extrapolated to a point on the 1,500-ft sideline by taking into account spherical spreading, atmospheric absorption, and extra ground attenuation.

The change in SPL as a result of spherical divergence is

$$\Delta_1 \text{ SPL} = 20 \log_{10} \frac{R_1}{R_2}$$

where Δ_1 SPL is attenuation due to spherical divergence and R_2 and R_1 are the distances from the engine to the 200-ft arc and from the engine to the 1,500-ft sideline, respectively. Figure 3 illustrates the arrangement of the engine and microphones and the distances applicable to this example.

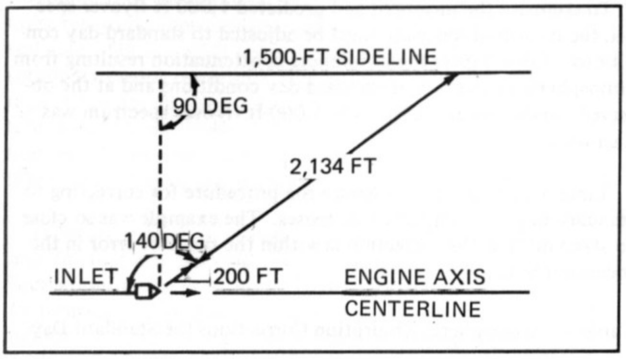


FIGURE 3. ACOUSTIC TEST GRID

The corrections in SPL due to atmospheric absorption over the 2,143-ft distance were computed using the methods given in SAE ARP 866 for a relative humidity of 64 percent and an air temperature of 51° F.

$$\Delta_2 \text{ SPL} = \alpha(R_1 - R_2)/1{,}000$$

where Δ_2 SPL is the change in SPL caused by atmospheric absorption over the distance from R_2 to R_1 and α is the attenuation rate per 1,000 ft. The values of extra ground attenuation were computed according to the method recommended in SAE AIR 923 for horizontal propagation.

Table 1 gives the predicted attenuation for each octave band resulting from the above causes as the noise is propagated over the 2,134-ft distance from the 200-ft arc at an angle of 140 deg to a point on the 1,500-ft sideline.

The measured and predicted 1,500-ft sideline spectra of the YJ-75 engine are shown in Fig. 4.

Table 1. Attenuation for Each Octave Band

Attenuation (dB)	Octave Band							
	1	2	3	4	5	6	7	8
Spherical divergence	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3
Air absorption	0.2	0.3	0.6	1.3	2.1	5.8	15.8	31.0
Extra ground	4.0	5.6	7.5	9.2	10.5	12.0	12.0	12.0
Total	25.5	27.2	29.4	31.8	33.9	39.1	49.1	64.3

Measured and predicted 1,000-ft flyover spectra at takeoff thrust from a 707-320B are illustrated in Fig. 5. The composite predicted spectrum was derived by combining compressor and jet exhaust noise spectra that were computed from engine parameters. The engine data used in the calculation of the jet exhaust noise spectrum are:

Thrust, F_N	14,000 lb
Weight density, ρ	0.03 lb/ft^3
Airplane velocity, V_A	270 ft/sec
Relative velocity, V_R	1,450 ft/sec
Velocity of jet exhaust, $V_J = V_R + V_A$	1,720 ft/sec
Cross-section area of jet exhaust, A_{exit}	3.73 ft^2
Effective diameter of jet, $D_e = 1.13\sqrt{A_{exit}}$	2.18 ft
D_e/V_R	0.0015
$\rho^2 A$	0.0034

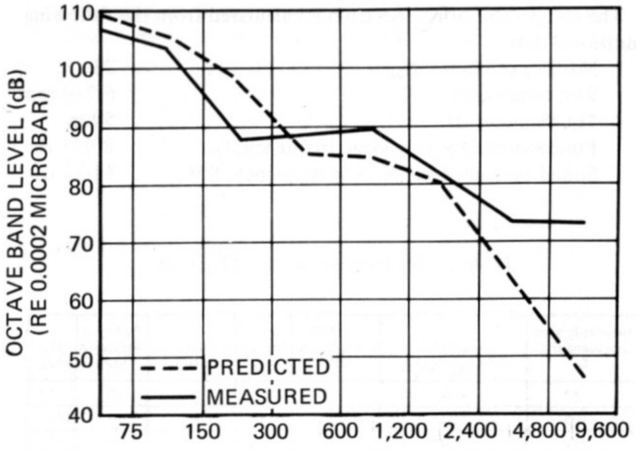


FIGURE 4. MEASURED AND PREDICTED SPECTRA AT 1,500-FT SIDELINE–YJ-75 ENGINE

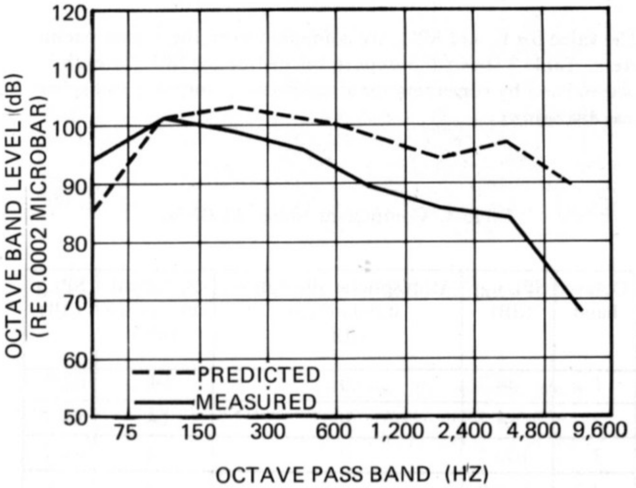


FIGURE 5. MEASURED AND PREDICTED 1,000-FT FLYOVER SPECTRA–707-320B AIRCRAFT

The following steps are followed in computing the maximum overall sound pressure level (OASPL_{max}) of the jet exhaust noise.

1. Read from graph (Ref. 4) 10 log f (V_R) = 141 dB
2. Calculate 10 log $\rho^2 A_{exit}$ = -24.7 dB
3. Step 1 + Step 2 = overall SPL_{max} = 116.3 dB
4. Adjustment for number of engines = 6 dB
5. Add steps 3 + 4, multiengine OASPL_{max} = 122.3 dB

Table 2 shows the steps in calculating the SPL for each octave band. The Strouhal number SN is computed from jet parameters, and the SPL for a 200-ft distance is calculated for each octave band by adding the corrections in column f(SN) to the OASPL_{max}. The 200-ft sideline spectrum must then be adjusted for atmospheric absorption at standard-day conditions and spherical divergence. Column SPL_d is the computed jet exhaust spectrum maximum for a distance d of approximately 1,150 ft. This distance is based on the assumption that maximum SPL occurs at an equivalent angle of 120 deg.

The compressor noise spectrum is calculated from the following additional data:

Number of blades, B_N	35
Rotational speed	6,740 rpm
Tip/diameter, D	50 in.
Fundamental blade passage frequency, f_o	3,931 Hz
Sound pressure level for this frequency, SPL_o	116.7 dB

Table 2. Jet-Exhaust Noise–JT3D-3B

Geometric mean frequency (Hz) f_n	Strouhal No., $SN = f_n \times D_e/V_R$	f (SN) (from Ref. 4) (dB)	SPL_{200} (dB)	Standard day (dB)	Spherical divergence (dB)	SPL_d (dB)
53	0.08	-13	109.3	0	14	85.3
106	0.159	- 7	115.3	0	14	101.3
212	0.318	- 5	117.3	0	14	103.3
425	0.635	- 6	116.3	0.6	14	101.7
850	1.276	- 9	113.3	1.0	14	98.3
1,700	2.555	-12	110.3	2.3	14	94.0
3,400	5.11	-17	105.3	5.7	14	85.6
6,800	10.22	-22	100.3	10.4	14	75.9

The value for f_o and SPL_o are computed from the engine parameters. Table 3 shows the steps in calculating the SPL for each octave band by correcting for atmospheric absorption and spherical divergence.

Table 3. Compressor Noise–JT3D-3B

Octave band	SPL_{200} (dB)	Atmospheric absorption, standard day (dB)	Spherical divergence (dB)	SPL_d (dB)
1	96.7	0	14	82.7
2	98.7	0	14	84.7
3	100.7	0	14	86.7
4	102.7	0.6	14	88.1
5	104.7	1.0	14	89.7
6	110.7	2.3	14	94.4
7	116.7	5.7	14	97.0
8	113.7	10.4	14	89.3

The compressor noise maximum on the JT3D radiates at approximately 70 and 110 deg, and the jet noise maximum is usually observed at about 135 deg. The equivalent angle in the above example is 120 deg. The maximum SPL in each octave band radiates at different angles and arrives at the ground at different times; however, as mentioned previously it is assumed that the peak flyover spectrum is composed of peak SPL radiating at an equivalent angle.

The peak SPL values for each octave band of the spectra for compressor and jet noise computed from engine data were combined to form a composite 1,000-ft flyover spectrum at an equivalent angle of 120 deg under standard-day conditions. The 1,000-ft flyover spectrum is predicted by correcting the SPL values for attenuation resulting from spherical divergence and atmospheric absorption from 230 to 1,150 ft. The extra ground attenuation is assumed to be zero for flyover predictions.

To compare the measured and predicted 1,000-ft flyover spectra, the measured spectrum must be adjusted to standard-day conditions. Table 4 gives the differences in attenuation resulting from atmospheric absorption at standard-day conditions and at the observed conditions at the time the 1,000-ft flyover spectrum was measured.

Table 4 is included to illustrate the procedure for correcting to standard day for comparison purposes. The example was so close to standard that the correction is within the range of error in the measured SPL.

Table 4. Atmospheric Absorption Corrections for Standard Day

	Octave Band							
Atmospheric absorption, α (dB/1,000 ft)	1	2	3	4	5	6	7	8
Observed: $T = 59^\circ F$; $RH = 67\%$	0	0	0	0.7	1.3	2.9	7.4	13.4
Standard day: $T = 59^\circ F$; $RH = 70\%$	0	0	0	0.7	1.3	2.9	7.1	13.0
Difference	0	0	0	0	0	0	0.3	0.4

Discrepancies Between Predicted and Measured Spectra

The differences in these examples are representative of those observed between measured and predicted spectra using current procedures. As would be expected, spectra predicted from measured data are more accurate than those calculated using engine parameters.

Figure 4 is a typical sample from a statistical analysis of a series of 52 noise tests conducted at the Boeing test site at Boardman, Oregon (6). The data show that the average difference between measured and predicted 1,500-ft sideline SPL at 140 deg varied from 4 to 6 dB in the first four octave bands and increased to a maximum of 30 dB in the eighth octave band. In the first four octave bands, the measured attenuations were higher than the SAE standard predictions, whereas in the last three octave bands the reverse was true. The reason for the latter difference appears to be a result of the large air attenuation values obtained at high frequencies using SAE ARP 866. Franken and Bishop (7) obtained similar results in studies conducted at Los Angeles International Airport and at Denver Stapleton Airport in 1965 and 1966. Their results showed the "standard" values of excess attenuation to be too low in the 125- to 250-Hz band and too high above 2,000 Hz.

In addition to atmospheric effects, the assumption that jet engine noise is generated as a point source may cause differences in observed and predicted SPL as a result of errors in calculating the propagation path length. The noise from a jet has been observed to be produced over a distance of 50 nozzle diameters from the exit.

In addition to the possible reasons for discrepancies between predicted and measured spectra discussed above, uncertainty or variability in the measurements used for extrapolation can cause apparent inaccuracies in the predictions. The measured SPL values provide the primary basis for assessment of the validity and reliability of prediction techniques.

Instrumental and system errors have been reduced to a value of approximately ± 1 dB; however, the signal processing and analysis procedures used in obtaining octave or narrow-band analyses may introduce apparent errors resulting primarily from rapid time fluctuations of the observed SPL. Procedures used at Boeing require recording approximately 10 sec of noise to obtain the spectral data. The recorded noise sample usually covers 1 min so that stationary engine conditions over at least that period of time are required to obtain reliable and repeatable acoustic data. In addition, when flyover noise measurements are made, fluctuations in SPL are more difficult to recognize because of the variation in overall noise levels resulting from the aircraft motion.

There are at least two factors that could contribute to the large fluctuations observed over the sample period. The first is fluctuations in the noise source and the second, fluctuations in the propagation medium. As far as possible, care is taken to monitor and control engine parameters in order to maintain stable engine operating conditions. Although the effects of temperature and humidity on engine parameters are well known, it is not known to what degree small-scale atmospheric fluctuations influence the stability of the engine as a noise source. The effects of turbulence and wind shear on an aircraft in flight during noise tests will cause fluctuations in the noise-producing engine parameters as a result of changes in power settings or flaps required to maintain required test conditions.

The atmospheric medium and the jet engine noise can be considered as two randomly varying fields occupying the same volume of space. The noise field is superimposed on the propagation medium so that variations in the propagation medium can be expected to affect the noise field. Correlations between noise measurements at two separated points are strongly affected by high-frequency atmospheric fluctuations. Apparent errors or discrepancies in predictions can occur if measurements used in the predictions are made under such conditions. These differences are in excess of those caused by lack of precise corrections for vertical gradients of wind, temperature, and humidity. The gross effects of rapid fluctuations on noise measurements have been observed and the existence of such conditions can usually be recognized. Since techniques have not been developed for correcting SPL measured under high-frequency atmospheric fluctuations, such conditions should be avoided.

An example of the effect of changes in wind direction and speed on measured octave band SPL is illustrated in Fig. 6.

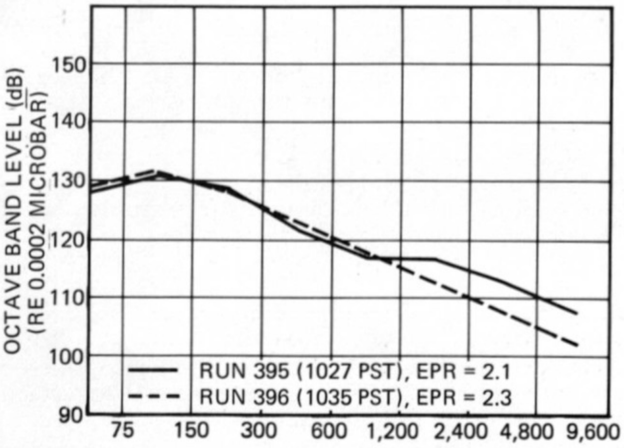
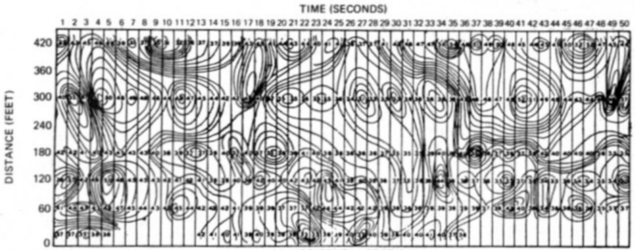


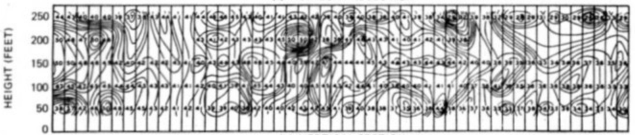
FIGURE 6. COMPARISON OF ENGINE TEST RUNS–YJ-75 ENGINE

The two spectra are from test runs of the YJ-75 engine at Boardman, Oregon, with the microphone at a 200-ft distance and at an angle of 140 deg. In less than 10 min, the wind changed from 150 deg, 3 mph, to 020 deg, 6 mph. The wind direction of 020 deg represents an upwind propagation in this example. The octave-band spectra show an increase in attenuation between measurements in the last three octave bands of about 6 dB. The 1-dB increase in SPL at low frequencies is a result of the higher engine pressure ratio (EPR) during run 396. If both runs had been at identical EPR, the difference in attenuation at higher frequencies should have been even larger.

Figure 7, which is reproduced from Ref. 8, shows the time-varying vertical velocity field measured on a 250-ft tower and at a 50-ft height over a horizontal distance of 420 ft.



(a) HORIZONTAL SECTION



(b) VERTICAL SECTION

FIGURE 7. STRUCTURE OF WIND GUSTS (MPH)

Wind-speed contours are at 1-mph intervals. The wind speeds in this example are extreme for acoustic measurements; however, they do indicate the small-scale wind gradients that exist in the atmosphere.

The homogeneity and stationarity of atmospheric conditions desired for precise acoustic measurements are seldom completely realized. The natural variability present in the atmosphere resulting from the complex interrelationship of solar heating, radiation, moisture, and terrain effects makes it impossible to completely eliminate anomalous propagation of noise. Restricting noise measurements to periods of favorable weather helps to reduce some of the variability; however, even with more restrictive weather criteria the desired accuracy and repeatability of noise measurements cannot be achieved, especially when extrapolated to the large distances required for community noise assessment. The alternative to testing only under ideal conditions is to develop improved techniques for correcting the measured acoustic parameters for atmospheric effects. The preliminary results of recent investigations indicate that improved measurements and predictions can be achieved by a combination of the two. The SAE procedures require only single-point measurements. However, it appears that profiles of wind, temperature, and humidity are required to ensure that test criteria are not exceeded and also to use as input to improved prediction procedures. Further investigations of the effects of turbulence on noise propagation are required to determine the feasibility of incorporating this parameter into the prediction technique. Propagation effects must be understood and accurate prediction methods developed for a wide range of atmospheric conditions for assessing community noise problems.

IV. Acoustic Research Program

The Boeing acoustic research program includes theoretical and experimental investigations designed to contribute to the solution of the problems discussed above. The current research program is directed toward (a) the development of techniques and devices to reduce noise at the source, (b) understanding the effects of the atmosphere and the surface plane on noise propagation, and (c) evaluation of the subjective response of individuals to aircraft noise. Whenever possible, scale models are used for demonstrating feasibility and effectiveness prior to full-scale testing. In addition to noise propagation research, considerable effort is devoted to research on the generating mechanisms of jet noise, compressor noise and lining research, structural response and interior noise, and subjective acoustics. The experimental work is conducted in laboratories and field test sites located in Seattle, Tulalip (50 miles north of Seattle), and Boardman, Oregon, which is located on the Columbia River about 150 mi east of Portland, Oregon. In addition, flyover tests are conducted over Puget Sound away from populated areas. With the development of large engines, more of the experimental noise work must be conducted at remote, unpopulated areas. As a result, an increasing amount of work is being done at the 100,000-acre test-site complex at Boardman. Figure 8 shows the acoustic measurement area. Acoustic testing of the Pratt and Whitney JT8D engine is currently being conducted at this facility. An SST facility is being installed, and testing is scheduled to begin in September 1968. In addition to the jet-engine research at Boardman, plans include a program of measurements from jet-aircraft ground runups, takeoffs, landings, and flybys at Moses Lake's Grant County Airport in eastern Washington. Propagation studies over distances to 4,000 ft are scheduled for Boardman and over similar distances from aircraft flybys at Moses Lake.

FIGURE 8. BOARDMAN, OREGON, ACOUSTICS TEST AREA

References

1. Society of Automotive Engineers, "Standard Value of Atmosphere Absorption as a Function of Temperature and Humidity for use in Evaluating Aircraft Flyover Noise," Aerospace Recommended Practice 866, August 31, 1964

2. H. O. Kneser, "Interpretation of the Anomalous Sound Absorption in Air and Oxygen in terms of Molecular Collisions," The Journal of the Acoustical Society of America, Vol. 5, 1933

3. Society of Automotive Engineers, "Method for Calculating the Attenuation of Aircraft Ground-to-Ground Noise Propagation During Takeoff and Landing," Aerospace Information Report 923, August 31, 1966

4. U. Ingard and Oleson, "Field Measurements of Sound Propagation Over Ground," NASA Report N63-15720

5. Society of Automotive Engineers, "Jet Noise Prediction," Aerospace Information Report 876, July 10, 1965

6. D. G. Dunn and J. V. O'Keefe, Acoustics Far-Field Investigations, T-6410 493-3, The Boeing Company, March 1968

7. P. A. Franken and D. E. Bishop, The Propagation of Sound from Airport Ground Operations, NASA, CR 767, May 1967

8. R. H. Sherlock, et al., Storm Loading and Strength of Wood Pole Lines and a Study of Wind Gusts, Edison Electronics Institute, c.1936