17 Flyover-Noise Measurement and Prediction

Lead author _____

Noel A. Peart
The Boeing Co.
Seattle, Washington

Contributing authors _____

Boeing Noise Engineering
Organization
The Boeing Co.
Seattle, Washington

Introduction

Community noise in the vicinity of major airports around the world is an obstacle to the natural growth of airline traffic. During the almost 30 years since the advent of commercial jet transports in the late 1950's, flyover noise levels of individual aircraft have been dramatically reduced. This reduction in noise was brought about by a combination of market forces—for example, competition, Federal and international regulations, engine efficiency and cycle improvements, and noise reduction technology development. In the same time period, however, there has been only a slight increase in the number of airports, despite the tremendous growth in airport operations—especially since deregulation of U.S. airlines went into effect. These factors have combined to make airport noise a potential deterrent to the otherwise orderly growth of the world's air transportation system.

Details are presented in this chapter for the measurement and prediction of aircraft flyover noise to be used for certification, research and development, community noise surveys, airport monitors, and pass-fail criteria. Test details presented are applicable to all types of aircraft, both large and small, and the use of Federal Aviation Regulations (FAR) Part 36 (ref. 1) is emphasized. The test procedures described in FAR Part 36 are considered the best for all types of aircraft-noise testing. Accuracy of noise measurements is important. Thus, a pass-fail criterion should be used for all noise measurements. Finally, factors which influence the sound propagation and noise prediction procedures, such as atmospheric and ground effects, are also presented.

Measurement of Noise Produced by
Airplanes Powered by Turbofan Engines

Purpose and Objectives for Conducting Tests

A long-term goal of the aircraft manufacturing industry is to achieve community compatibility by phasing out the older, noisier airplanes and replacing them with newer, quieter designs. Improved flight operational procedures, land acquisition, and land usage are other methods being used to help reduce airplane-noise exposure. The imposition of local airport noise regulations and operating restrictions is becoming more prevalent as a means of improving airport compatibility with the community. In addition, some older jet transports have been modified to quieter versions by refitting them with higher-bypass-ratio turbofan engines or by adding sound-absorbing material to the nacelles. These events have resulted in the increased need for in-flight measurements together with the need to follow strict guidelines when acquiring flyover-noise measurements.

Certification

Flight-testing for aircraft-noise certification must be tightly controlled and rigorously specified in order to assure validity and credibility. In the United States, Federal standards intended to control aircraft noise began with the adoption of Federal Aviation Regulations (FAR) Part 36 in 1969. This regulation initially applied only to new designs of turbojet and transport category airplanes and required that they be markedly quieter than the earlier airplanes of these types. Since the adoption of FAR Part 36, the Federal Aviation Administration (FAA) has amended this regulation 15 times to cover all categories of aircraft, including helicopters. (See Amendment 15, ref. 1.)

A parallel set of aircraft-noise requirements was adopted by the International Civil Aviation Organization (ICAO) in 1971 as Annex 16 to the Convention on International Civil Aviation. As with FAR Part 36, Annex 16 has been continually reviewed and revised, with the latest change being Amendment 5, applicable on November 26, 1981 (ref. 2).

Research and Development

The major airframe and engine companies involved in the production of large commercial jet airplanes made extensive use of airplane flyover-noise measurements for research and development during the 1960's and 1970's. The prime purposes of those tests were to define the noise characteristics and to develop modified engines and/or nacelles that would reduce flyover-noise levels. Data from such flight tests have led to the development of analytical tools that enable noise measurements obtained during static engine operation to be projected to flight conditions for those airplanes. The result of these developments is that a large portion of turbofan engine noise research and development programs now rely heavily on static engine measurements, with some supplemental flight test data acquired usually in conjunction with a noise certification flight test.

358

Community Noise Surveys

An aircraft and airport community noise survey may be conducted for a variety of reasons:

1. Assessment of land use suitability

2. Comparison with local noise ordinances

3. Identification and quantification of major noise sources

4. Determination of sound exposure at particular locations

5. Determination of trend in sound exposure levels

6. Determination of need for new or additional noise control measures

Outdoor community noise measurements are generally made during a noise survey. The purpose of each survey plays a major role in deciding the extent, type, and quantity of equipment required to measure aircraft flyover noise.

Airport Noise Monitors

Aircraft-noise monitoring systems are usually set up at fixed locations in the vicinity of airports and are activated when the A-weighted sound level of an aircraft flyover exceeds a given threshold level. The monitor normally provides a printout that includes time of day, maximum A-weighted sound level in decibels, and A-weighted sound exposure level (SEL) in decibels.

Many airports throughout the world have round-the-clock monitoring of aircraft traffic. Some airports, such as Los Angeles and San Jose, California, have a public display located in the terminal where on-line readouts of each monitor microphone are visible to the general public.

Test Requirements

The objective of any flight test is to acquire noise levels that are representative of the flight conditions desired and that are from a sufficient number of flights of a particular aircraft to derive a subjective noise measure (e.g., effective perceived noise level (EPNL) as discussed in appendix B of ref. 1) for takeoff, sideline, and approach conditions.

Test Site Terrain

Tests to show compliance with aircraft-noise-level standards consist of a series of actual or simulated takeoffs and approaches during which measurements are taken at noise measuring stations located at reference points such as those shown in figure 1. For each actual or simulated takeoff, simultaneous measurements are made at the sideline noise measuring stations on each side of the runway and also at the takeoff noise measuring station. Each noise measuring station should be surrounded by relatively flat terrain having no excessive sound absorption characteristics, such as those which might be caused by thick, matted, or tall grass, shrubs, or wooded areas.
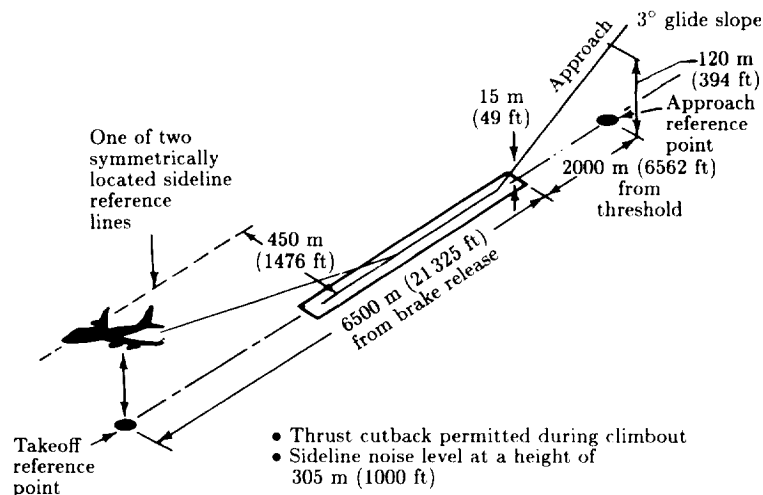
Figure 1. Noise certification measurement locations for new designs.

During the period when the flyover-noise time record is of interest, no obstruction should exist that would significantly influence the sound field from the aircraft.

Aircraft Testing Procedures

The aircraft height and lateral position relative to the extended centerline of the runway should be determined by a method which is independent of normal flight instruments, such as radar tracking, theodolite triangulation, or laser trajectography. Photographic scaling techniques have also been used.

Aircraft position along the flight path should be synchronized to the noise recorded at the noise measuring stations with time code signals. Also, the position of the aircraft should be recorded during the entire time period in which the acoustic signal is recorded for analysis.

Microphone Array

To acquire data consistent with the requirements of FAR Part 36 or ICAO Annex 16 (refs. 1 and 2), each microphone should be mounted with the center of the sensing element 1.2 m (4.0 ft) above the local ground surface. Each microphone should be oriented to provide a known angle of sound incidence at all times of interest throughout the significant duration of each flyover-noise measurement. To avoid ambiguity, most flyover-noise measurements are made with a windscreen around each microphone at all times. Correction for any insertion loss produced by the windscreen should be applied to the measured data.

The microphone array should consist of at least three microphones, one directly under the flight path and two to measure maximum sideline noise. Each sideline microphone should be placed symmetrically with respect to the one on the opposite sideline so that the maximum noise on either side of the airplane is measured.

360

Flight Path Intercepts

Simulated takeoffs and approaches consisting of flight path intercepts are often used in lieu of actual takeoffs and landings at an airport. For takeoff and sideline noise measurements, the procedure consists of intercepting and following the desired climb profile. To perform the approach intercepts, a normal approach path is maintained over the microphone array, the test condition being ended prior to landing with power being reapplied and a go-around initiated. Aircraft weights and configurations should be selected carefully in order to maintain near-constant indicated airspeed during each test condition.

The benefits of using flight path intercepts are that they permit much greater test site selection flexibility and they permit target altitude over the centerline microphone to be chosen to optimize the signal-to-noise ratio. Shorter test times and lower test costs are further benefits.

Measurement of Aircraft Noise

All noise measurements should be made with instruments meeting the specifications of FAR Part 36 (ref. 1).

Weather Restrictions

There should be no rain or other precipitation during the testing. Also, the ambient air temperature should be between 2.2°C and 35°C (36°F and 95°F), inclusive, over that portion of the sound propagation path between the aircraft and a point 10.0 m (32.8 ft) above the ground at the noise measuring station. The lower temperature will avoid freezing and the upper temperature will avoid takeoff power settings that result in lower than the flat temperature-rated takeoff power settings as well as highly absorptive atmospheric conditions. Relative humidity and ambient temperature over that portion of the sound propagation path between the aircraft and a point 10.0 m above the ground at the noise measuring station should be such that the sound attenuation in the 1/3-octave band centered at 8000 Hz is not greater than 12 dB/100 m (3.66 dB/100 ft) and the relative humidity should be between 20 and 95 percent, inclusive. A graphical representation of the foregoing weather restrictions is provided in figure 2.

Wind Limits

Tests may be conducted when (1) the wind speed over the noise measurement period does not exceed an average of 12 knots or a maximum value of 15 knots and (2) the crosswind component over the noise measurement period does not exceed an average of 7 knots or a maximum value of 10 knots. An averaging period less than or equal to 30 sec may be used to define wind speed. Wind measurements should be made 10.0 m (32.8 ft) above the ground in the vicinity of the microphones. No anomalous wind conditions (including turbulence) which will significantly affect the noise level of the aircraft when the noise is recorded at each noise measuring station should exist during any test.
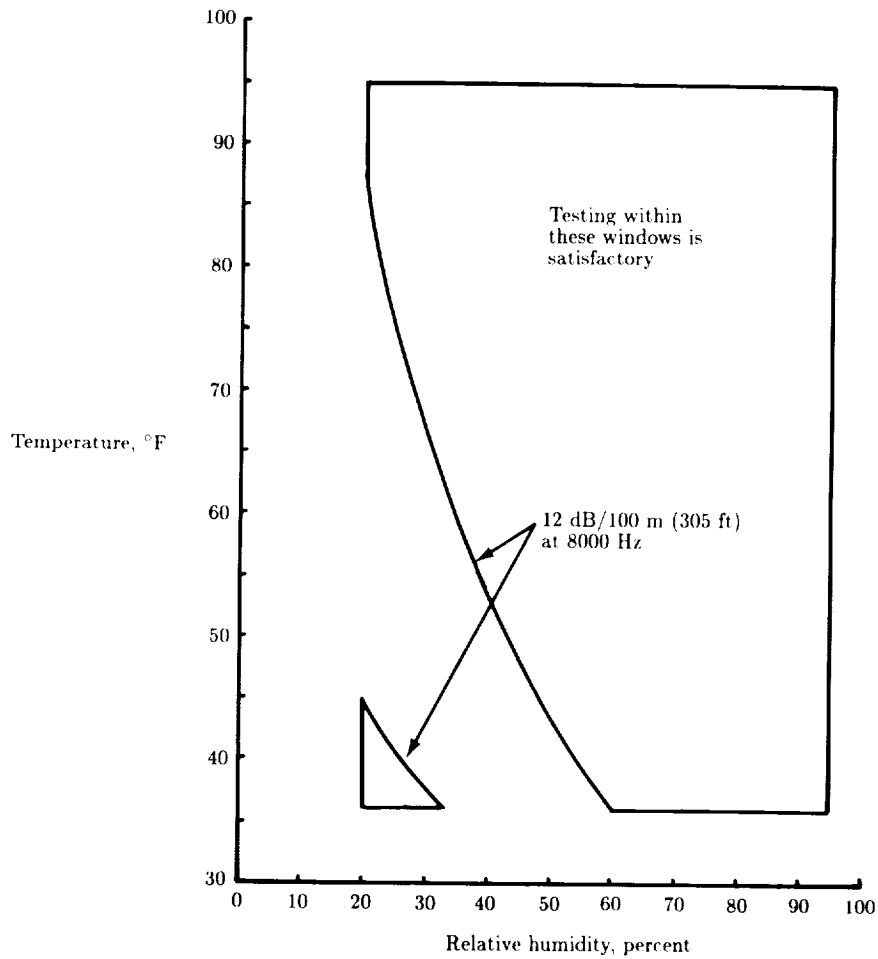
Figure 2. Test weather windows from 10.0 m (32.8 ft) to airplane height.

Reference Conditions

Aircraft position, performance data, and noise measurements should be adjusted to the following noise reference atmospheric conditions:

1. Sea level pressure of 101.3 kPa (1 atm)

2. Ambient temperature of 25°C (77°F)

3. Relative humidity of 70 percent

4. Zero wind

The above reference conditions provide near-minimum atmospheric absorption, that is, maximum aircraft flyover-noise levels.

Determination of a Subjective Measure

Noise Floor Corrections

Aircraft sound pressure levels within the 10-dB down times should exceed the mean background sound pressure levels by at least 3 dB in each 1/3-octave band to be included in the calculation of a subjective measure for a given aircraft flyover. In the case where the aircraft acoustic signal is greater than the background acoustic level, the true aircraft signal may be determined by subtracting the background mean-square sound pressure levels from the indicated mean-square aircraft-noise sound pressure levels.

When a 1/3-octave band sound pressure level from an aircraft-noise recording is not more than 3 dB greater than the corresponding 1/3-octave band sound pressure level of the background noise, the aircraft's signal in that 1/3-octave band is defined as being masked. When masking occurs, levels for the masked bands may be estimated by applying one or more of the correction procedures described in reference 3.

Pseudotone Identification

Aircraft-noise measurements obtained from microphones located 1.2 m (4.0 ft) above the ground are susceptible to spectral irregularities caused by ground plane reflections or introduced by data processing techniques that account for background noise contamination. Tone corrections to perceived noise levels are only intended to account for the subjective response due to the presence of pronounced spectral irregularities from aircraft-noise sources.

Any spectral irregularities not related to aircraft-noise sources are termed *pseudotones*, or fictitious tones, and may be excluded from the calculation of effective perceived noise levels. Methods to detect and identify pseudotones are discussed in reference 3.

Test Condition Acceptance and On-Line Systems

Test Condition Acceptance Criteria

Each acceptable aircraft-noise flyover measurement should comply with all the following criteria. The weather window between the aircraft and 10.0 m (32.8 ft) above the noise measuring station should consider temperature, relative humidity, and atmospheric absorption at 8000 Hz. The wind limits should consider average wind, maximum wind, and crosswind. Aircraft performance should consider lateral offset from the target flight path, overhead height, airspeed, and engine power setting.

On-Line Data Acquisition and Reduction

Most major airframe manufacturers have developed systems which enable an assessment of the quality of the test data and an initial determination of final noise levels to be made "on-line" and "on-site." The systems use digital computation to determine the test aircraft position in real time, integrate that information with airplane performance data, and telemeter the data to a ground-based test coordination

363

and control station. One such system is described in detail in reference 4. In this particular example a ground station performs an acceptance check on the telemetered data by comparison with predetermined positioning and performance limits. Data from a particular run are accepted and recorded if aircraft, engine, acoustical, and meteorological parameters are all within established tolerance limits.

The entire process takes place while the test aircraft flies a continual traffic pattern circuit. If the test site is free of other aircraft traffic, the typical time of 6 minutes between tests is interrupted only by the vertical soundings of the meteorological airplane.

Validity of Results

The sample size should be large enough to establish statistically a 90-percent confidence limit not to exceed ±1.5 dB. No test result should be omitted from the final values of effective perceived noise level in calculating this value. From each sample compute the arithmetic average of the effective perceived noise level for all valid test runs at the takeoff, approach, and sideline measuring stations. If more than one noise measurement system is used at any single measuring station, the resulting data for each test run (after correction) should be averaged as a single measurement. If more than one test site or noise measuring station location is used, each valid test run should be included in the computation of the average values and their confidence limits.

The minimum sample size for each of the three measurements (takeoff, approach, and sideline) should be six. For tests designed to determine the variation of effective perceived noise level as a function of engine power setting (for constant height and airspeed), there should be at least six valid data points over the power setting range of interest. The number of samples should be large enough to establish statistically for each of the three average noise levels a 90-percent confidence limit which does not exceed ±1.5 dB. No test result should be omitted from the averaging process.

Measurement of Helicopter Noise

Measurement of helicopter noise in flight has many requirements in common with that of airplane noise. However, there are several significant differences that make the planning and conducting of a noise test for helicopters somewhat unique. A major reason for the differences is that with helicopters, the primary noise sources are the rotor systems while the engines are usually secondary sources.

Because of the importance of the aerodynamic environment, helicopter noise tends to be more sensitive to flight conditions than to power or weight. For example, rotor noise in partial power descent tends to be higher than that during full power takeoff because rotor blades are closer to tip vortices shed from preceding blades in descent than in climb. Furthermore, noise during landing may be very sensitive to operating conditions such as combinations of airspeed and rate of descent.

Test Design

In general, there are three types of testing conducted to measure the external noise of helicopters. They are as follows:

1. Certification testing

2. Evaluation of flight procedures and measurement of noncertification test procedures

3. Rotor noise research

Most noise testing procedures are based on ICAO Annex 16 (ref. 2). That document contains information regarding all aspects of helicopter noise measurement, instruments, and analysis. Specifics of flight conditions, microphone locations, data analysis, and corrections, however, are rather narrowly defined and are applicable primarily to noise certification.

In many cases, it is desirable to include in the test program conditions that are more representative of the way helicopters are actually operated than those that are reflected by noise certification testing. For example, the approach condition for certification is a constant 6° approach angle at a constant indicated airspeed. In practice, however, many approaches are made by continuously varying both the airspeed and the rate of descent such that neither is held constant.

Test programs that are research oriented may often be designed to investigate a particular phenomenon, such as impulsive noise at high rotor tip speeds or blade vortex interaction in descent. In these cases, appropriate prediction analyses should be employed to define the range of operating parameters of interest.

When designing a helicopter noise test, keep in mind that the sound field around a helicopter is usually not symmetrical with respect to the aircraft centerline. This is because the main rotor advances on one side of the aircraft and retreats on the other side and because the tail rotor is usually located to one side of the aircraft. For these reasons it is important to make acoustical measurements on both sides of the flight path. Measurements obtained by placing a microphone on one side only and flying reciprocal headings to gather data should be restricted to extremely low wind conditions.

Configuration and Operation

The most important parts of the helicopter, with respect to external noise generation, are the rotor blades. The blades should be "tracked" to within manufacturer's specifications (i.e., the out-of-tolerance amount permitted by the manufacturer when the blades are hand turned) prior to testing.

It is recommended that testing be limited to gross weights not less than 90 percent of maximum and that the helicopter be refueled when this condition is reached. This range of weights represents the typical operating condition of a helicopter.

The following operating conditions should be considered and selection made as applicable to a specific test: ground idle with rotors not turning, flight idle with rotors turning, hover in ground effect, hover with wheels about 1.5 m (5 ft) from ground, takeoff at maximum continuous power, flyovers at various airspeeds up to the maximum, and approaches at various airspeeds and rates of descent. Most helicopters have a permissible range of rotor speed selection. Testing should always be conducted

at 100 percent of design rotor speed and at other rotor speeds applicable to the test objectives.

Some helicopters have special control features that are designed to perform certain functions, such as maintaining the fuselage at a level attitude. Some of these controls (for example, longitudinal differential cyclic trim on tandem rotor helicopters) can have a major influence on noise. The test should include operation of thes devices over their permissible range.

Most helicopters do not include engine-noise suppression devices as standard equipment. In some cases, such as critical rotor noise research, it may be desirable to equip the test helicopter with engine-noise suppression devices to further enhance a measurement of rotor noise.

Test Site

When selecting a site for hover noise tests, keep in mind that rotor downwash can cause local velocities in excess of 26.8 m/sec (60.0 mph). Loose articles that could be blown about and cause potential damage or injury should be secured or removed. Whenever possible, the area should be cleared of debris such as loose vegetation and gravel. In all other aspects the test site requirements should be the same as those for large airplanes.

Hover noise measurements should be made at a horizontal distance of at least two rotor diameters to avoid the acoustic "near field." Many researchers use 61.0 and 152.4 m (200 and 500 ft) as preferred distances since they are in the "far field" of the low-frequency rotor noise and yet are close enough to give a satisfactory signal-to-noise ratio.

Hover noise measurements should be made at several locations around the azimuth because of the directional nature of the acoustic field. Increments of 30° are adequate for general purposes, although smaller increments might be required for special purposes. Hover noise should be recorded for at least 30 sec to allow sufficient time to average what are often rather unsteady sound signals.

Flyover noise should be measured on both sides of the helicopter. The sideline distance on approach and departure depends on the specific helicopter; however, in general, valid data can be acquired from the time when the helicopter is about 1524 m (5000 ft) in horizontal ground distance on the approach side (approximately 152.4 m (500 ft) height) of the microphones to a distance of approximately 914.4 m (3000 ft) on the departure side.

Instruments

A typical acoustical spectrum of a helicopter is presented in figure 3. Examination of this spectrum reveals two important elements. First of all, the dominant spectral components are harmonic, and second, the highest amplitudes tend to occur at the main rotor passage frequency, which is of the order of 10 to 15 Hz. In order to properly measure such acoustic signals, the instrumentation system, from microphone through recorder, must be selected with these low-frequency requirements in mind. Many helicopter researchers use 1-in. microphones and FM recording to preserve the rotor noise signal. If the purpose of the test is more general,

such as measurement of the peak level (e.g., maximum A-weighted sound pressure levels and maximum perceived noise level), simpler systems may suffice.

Although microphones located above the ground level may be used for many measurements and are required for certification, ground-level microphones may be preferred for research in order to minimize distortion of the measured sound spectrum due to the reflected ground wave. Figure 4 illustrates the difference in sound pressure levels as sensed by a ground-level microphone and by an elevated microphone located near a rotor. In figure 4 the slope above 400 Hz is correct for the ground-level microphone.

In some flight conditions, the sound of a helicopter can become quite impulsive. A pressure-time history of such an event is illustrated in figure 5. In such situations, the high ratio of peak to root-mean-square sound pressure effectively eliminates noise measurement systems that include exponential time weighting (i.e., slow, fast, or impulse). Recording levels should be carefully selected to avoid overloading input amplifiers.

For many applications, such as noise certification and research (e.g., comparison with prediction), it is necessary to know the helicopter location with respect to the microphones and to have this information coordinated with the acoustical records. Several methods, including radar tracking, laser tracking, and photo-optical tracking, may be employed. When conducting precise research, it may also be important to instrument the helicopter for measurement of parameters such as fuselage attitude, rotor blade motions, and hub motions and to have these measurements coordinated with the acoustical data by use of time codes or telemetering.

Factors Influencing Sound Propagation (Full-Scale Static and Flight Testing)

Atmospheric Effects

Beyond the immediate vicinity (near field) of a sound source, the acoustic energy spreads out spherically, resulting in a level reduction described by the inverse-square law. The acoustic energy is also subject to absorption (by molecular resonance and thermal conduction), change of direction, focusing, impedance changes, scattering (by turbulent eddies), and Doppler shifts. Some of these effects are more significant than others, and in some cases the current technology is not adequate to correct for them.

The most important effect is certainly atmospheric absorption. It is a strong function of temperature and humidity (see fig. 6, from ref. 5) and can change sound levels substantially. Indeed, it is not uncommon for absorption at high frequencies to reduce sound levels below the test site background sound level, making it impossible to conduct a flight test until the weather conditions improve. Currently there are two standard methods for predicting absorption, the Society of Automotive Engineers (SAE, ref. 5) and the American National Standards Institute (ANSI, ref. 6) standards. Both methods calculate absorption as a continuous function of frequency. Absorption is such a strong function of frequency that it is difficult to generate accurate values for use in a 1/3-octave band. As an approximation, for aircraft noise spectra the SAE method specifies the use of absorption at 1/3-octave band center frequencies for bands of 4000 Hz and below and at 1/3-octave band lower
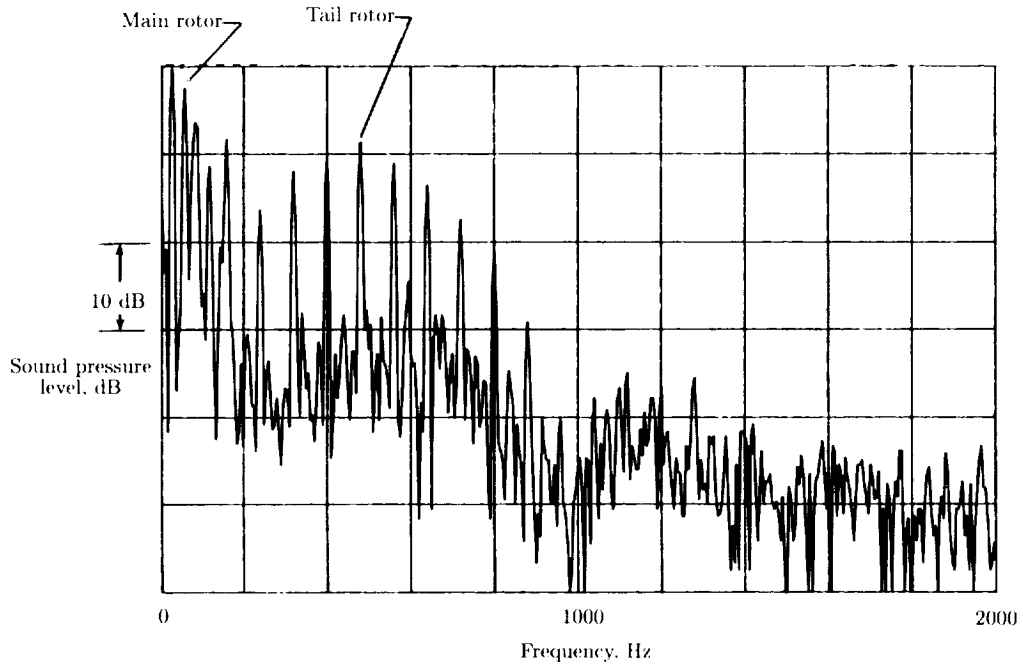
Figure 3. *Spectrum of recorded noise generated by helicopter in forward flight.*
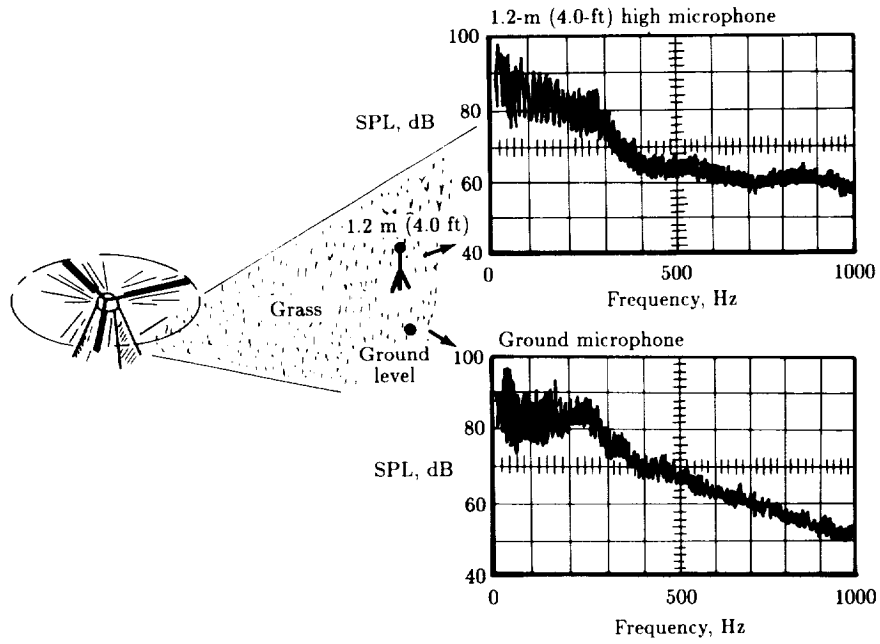

Figure 4. *Effect of microphone height on spectrum of sound from helicopter rotor.*
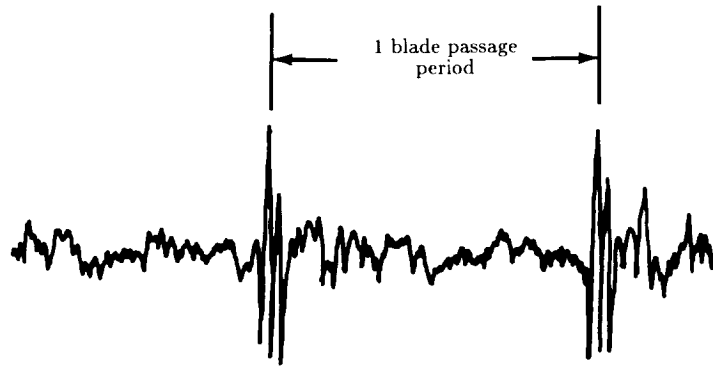
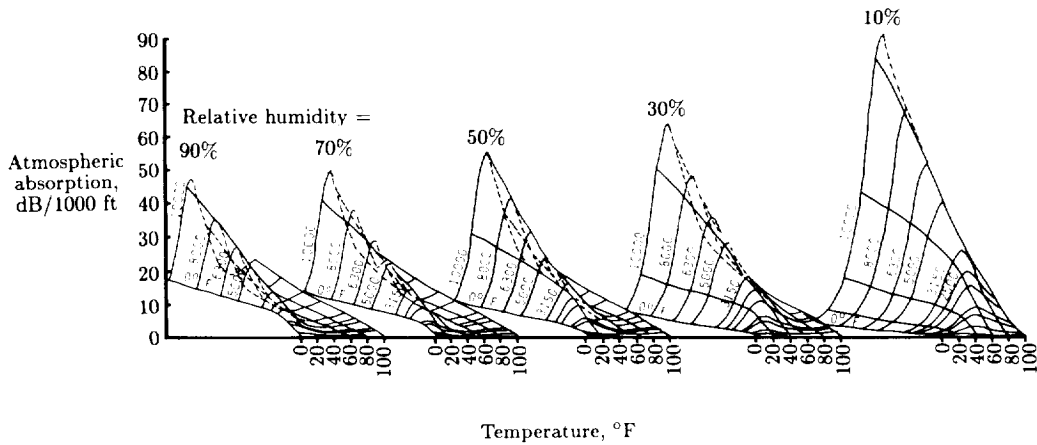*Figure 5. Example of impulsive helicopter rotor sound.*

Figure 6.   Atmospheric absorption coefficients for 1/3-octave bands of noise as function of temperature and humidity.   (From ref. 5. Reprinted with permission, copyright 1975, SAE, Inc.)

edge frequencies for bands above 4000 Hz. The current ANSI procedure does not specify a method to use with 1/3-octave spectra. For flight testing, it is important to acquire an accurate profile of the temperature and relative humidity between the ground and the aircraft, since the absorption can vary widely along the path.

For the presence of wind, accurate absorption calculations should be done in a frame of reference moving with the wind. The path length is then distorted and the frequencies are Doppler shifted from what they would be in a calm atmosphere. These effects combine to increase the levels for sound propagating downwind and decrease them for sound propagating upwind. In addition, wind and temperature gradients cause sound rays to curve and, especially at shallow angles to the ground, there can be focusing effects. As there are no standards for predicting these effects,

it is best simply to avoid testing in the presence of strong winds or temperature gradients.

Atmospheric pressure affects source noise. Sound pressure is directly proportional to atmospheric pressure for most noise sources important to aeroacoustics, so aircraft altitude may be an important consideration. In addition, as sound travels along a ray tube through moderate gradients of acoustic impedance it conserves power (except for absorption), but the sound pressure may vary. This variation results in a correction to the acoustic pressure, which is proportional to the square root of acoustic impedance and which typically partially cancels the ambient pressure effect on source level. Impedance gradients strong enough to cause significant reflections are unlikely in the atmosphere.

Doppler frequency shift in the case of a uniform stationary atmosphere is a well-known effect usually accounted for by the equation

$$f_o = \frac{f_s}{1 - M \cos \theta}$$

where f_o is observed frequency, f_s is source frequency, M is Mach number, and θ is the angle between the flight path and the ray direction. The frequency shift does change in the case of a windy atmosphere; it can be calculated (ref. 7) and basically depends on the aircraft speed relative to the air and the sound ray angle. The finite integration time of the measurement system may cause Doppler-shifted tones to appear to be spread out in frequency.

The presence of turbulence in the atmosphere causes scattering, but there are no good quantitative predictions of this effect available yet. For noise sources having narrow beams of sound, the peak is reduced and the beam is broadened, but aircraft-noise sources tend to be more nearly omnidirectional and are not likely to exhibit this effect. Turbulence may have a more significant effect on ground-reflection patterns near the ground.

It is common practice to restrict flight testing to those weather conditions within which atmospheric and propagation effects are either insignificant or calculable.

Ground Effects

Sound propagation near the ground is somewhat different from propagation through the atmosphere. Reflections from the ground affect the sound received by a microphone; turbulence may also play a role. Wind and temperature gradients may become steep enough near the ground to create "shadow zones" for shallow angle propagation.

Ground-reflection problems occur when a ray reflected off the ground combines with a direct ray at the microphone. The two rays may reinforce or cancel each other (depending on their relative phase), resulting in a spectrum modified by "ground dips" of as much as 15 dB. This effect can be ignored if the microphone installation and flight path of the normalized conditions are close enough to those of the measured conditions, but it is important if static data or predictions are to be extrapolated to flight. Propeller airplanes or other types with dominant low-frequency tones can produce noise which is extremely sensitive to the exact location in frequency of the ground dips, and even slight differences in flight path may need to be corrected.

370

Though there are no universally accepted standard methods for calculating ground-reflection effects, the work of Chessell (ref. 8) and others, especially as summarized in reference 9, is widely used. The situation is most difficult when shallow angles are involved, such as in static engine testing. When more repeatable results are needed, the microphone must be placed very near the ground on a hard surface. This method gives a microphone signal 6 dB above free field, at least up to 10 kHz; it is frequently used for static testing and occasionally for flight testing. Elevated microphones over natural terrain are subject to significant variations because of ground impedance variations, turbulent scattering of phase relations, and changes in ray arrival angle due to ray curvature; all these sources of variation are extremely difficult to predict. Occasionally, microphones are placed very high (10.0 m (32.8 ft) is common); they then have ground dips so closely spaced that the 1/3-octave band spectrum appears smooth, at least if there are no dominant low-frequency tones. For flight testing, note that ground dips can be spread out over frequency by the measurement system integration time in the same manner as Doppler-shifted tones.

When the wind or temperature gradients are such that the ray from the source to the microphone curves up, it is possible that the microphone will be in a shadow zone into which no direct ray penetrates. This is most likely in static testing when the ground surface is hot from solar heating and the ray is propagating upwind. This shadow zone problem is difficult to treat theoretically, and it is usually handled by using empirically derived wind and temperature limits or by using extra microphones to detect shadowing effects (because they show up most strongly at high frequencies).

Turbulence effects are more likely to be visible when sound is propagating near the ground. When ground reflections are involved, different turbulence in the two paths causes a randomization of phase and reduces the peaks and dips. This shows up first at high frequencies, where wavelengths are short, and is quite visible in narrow-band data. Turbulence also smooths out a shadow zone boundary, and scattering of eddies is responsible for what little sound does penetrate deep into shadow zones. Quantitative predictions of these effects are not yet available.

It has been common to lump the foregoing ground effects together as "lateral attenuation" or "extra ground attenuation (EGA)," using an empirically derived extra attenuation for shallow angle propagation. Although it is widely agreed that EGA is mostly ground-reflection effect, with some effects due to inaccurate atmospheric absorption used when the curves and source nonaxisymmetry are derived, the standard used for aircraft-noise prediction is that provided in reference 10.

Prediction of Noise for Airplanes Powered by Turbofan Engines

Noise Prediction Capability

In order to receive approval for production and operation in a particular country, essentially all aircraft must now satisfy that government's noise standards. In the United States, these standards are contained in FAR Part 36 (ref. 1), while most other countries have adopted the standards of ICAO Annex 16 (ref. 2). For turbojet and transport airplanes, noise limits are defined for approach, sideline, and takeoff locations, and are dependent on maximum certificated takeoff gross weight (mass). For the takeoff location, the noise limits are also dependent on the number of engines

mounted on the airplane. The unit of measurement is the effective perceived noise level (EPNL) in decibels. This unit takes into account the duration of the noise event and penalizes any discrete frequencies or tones which have been found to be more annoying than broadband noise of the same intensity.

The elements of a successful aircraft-noise prediction include a reliable definition of the aircraft performance, a confident prediction of the noise characteristics of the power plant (as a function of power setting, altitude, and flight speed), and, in some flight conditions, the noise of the airframe. When there are substantial measured noise data to support a new airplane-engine configuration, they can be projected to the new flight conditions through fairly clearly defined procedures. For example, if the new airplane incorporates power plants which are not very different from versions already in service, flight-test data can be transposed to the new conditions. Or, where the measured information is obtained from static engine tests during the development program prior to airplane flight, there are methods for transposing these data to the flight conditions (ref. 11). The least predictable mode of operation embraces the totally new airplane-engine configuration and, under such circumstances, it is necessary to rely on accumulated past experience in the form of component-based prediction procedures. These procedures have to embrace not only noise but also aircraft performance.

Figure 7 outlines the minimum elements necessary to provide a credible estimate of the noise of a given airframe–power-plant combination. The main features are expanded in the following sections.

Power-Plant Design Details and Performance Characteristics

At the very minimum, there should be either a design scheme for the power plant in question and a knowledge of how the individual noise-producing component areas perform or a credible extrapolation/interpolation of both noise and performance data from a similar power plant. If the latter exists then the detailed component noise prediction procedures described below may become unnecessary.

Component Noise Prediction Procedures

Component noise prediction procedures are required which allow all the significant noise sources to be related to leading engine performance parameters and to be integrated to reflect the noise of the total system, including any noise reductions resulting from specific noise control actions. The depth of detail and breadth of coverage of the component procedures necessary are related directly to the type of power-plant–propulsion system and the aims of the prediction exercise. For example, prediction of certification noise levels demands a knowledge of all the sources that lie within 10 dB of the peak level throughout the total noise-time history (see fig. 8), whereas a prediction of levels at large distances is controlled by low-frequency sources and thus it may be possible to limit the breadth of the coverage.

Normally, it is the propulsion system noise that controls the overall aircraft noise, and there are three fundamental types of "jet" propulsion system. (See fig. 9.) These types are the single shaft, single-flow-duct "pure" jet, or turbojet engine; the two-shaft, double-flow-duct low-bypass-ratio engine; and the two- or three-shaft, double-flow-duct turbofan engine. The total noise is illustrated in figure 8.
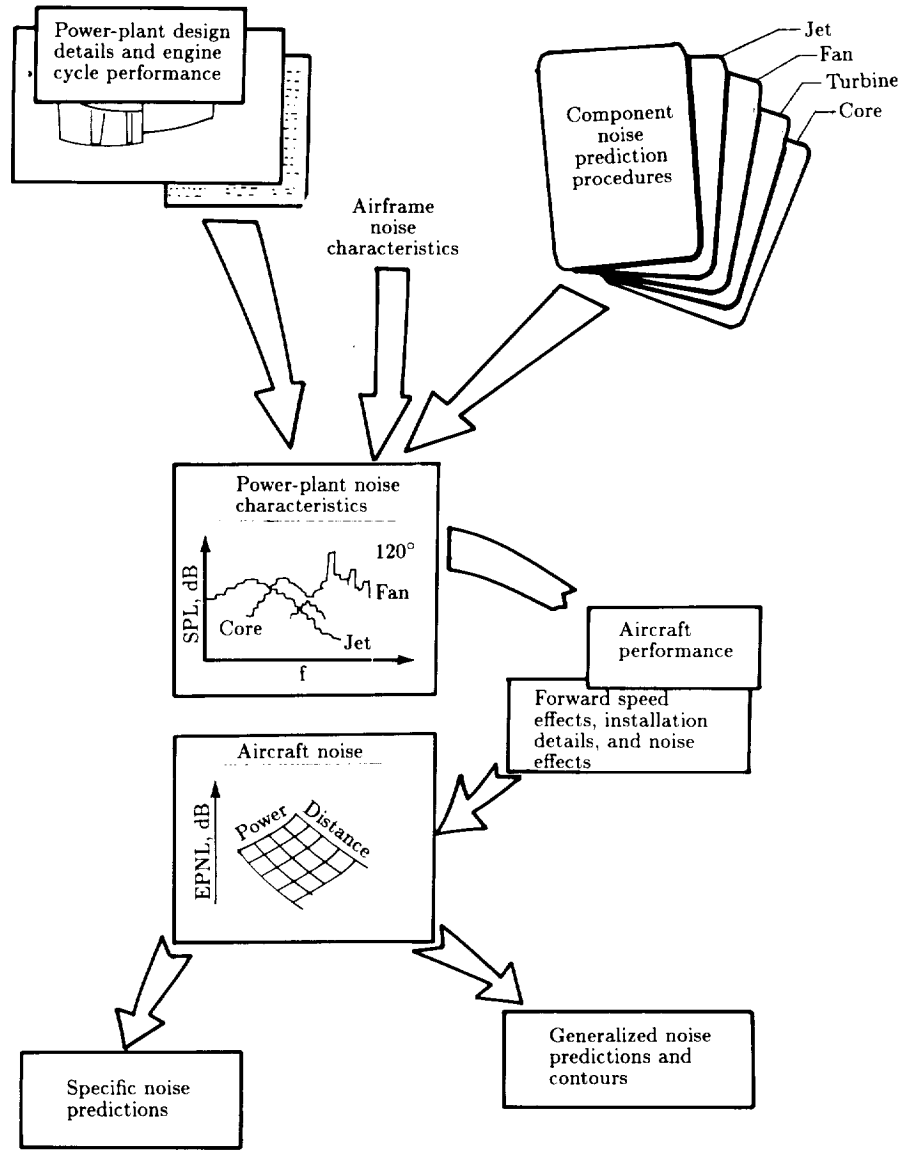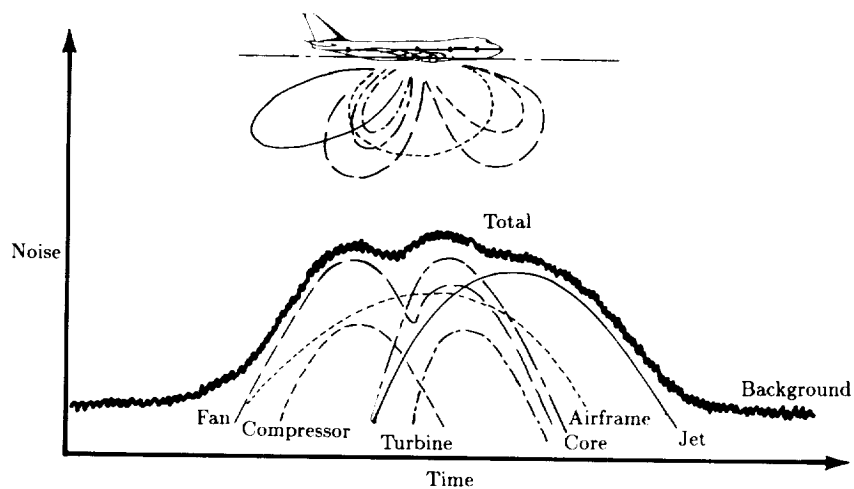
372

Figure 7. Elements necessary for noise prediction.

Figure 8. Contribution of major components to total noise.

Turbojet
Single shaft

Applications

1950's designs:
  Comet, Caravelle,
  Early B-707 and DC-8,
  Business jets (Concorde uses
  pure jet with afterburning)

Bypass
2 shafts

1960's designs:
  B-707, DC-8, VC-10,
  B-727, B-737-100/200,
  DC-9, BAC 111,
  Trident, F-28,
  Business jets

Turbofan
2 or 3 shafts

1960's designs (1-, 2-stage fan):
  B-707, DC-8, Military,
  Early B-747

1970's and 1980's designs (1-stage fan):
  B-737-300, B-747, B-757, B-767,
  L-1011, DC-10, A300,
  MD-80, BAe 146,
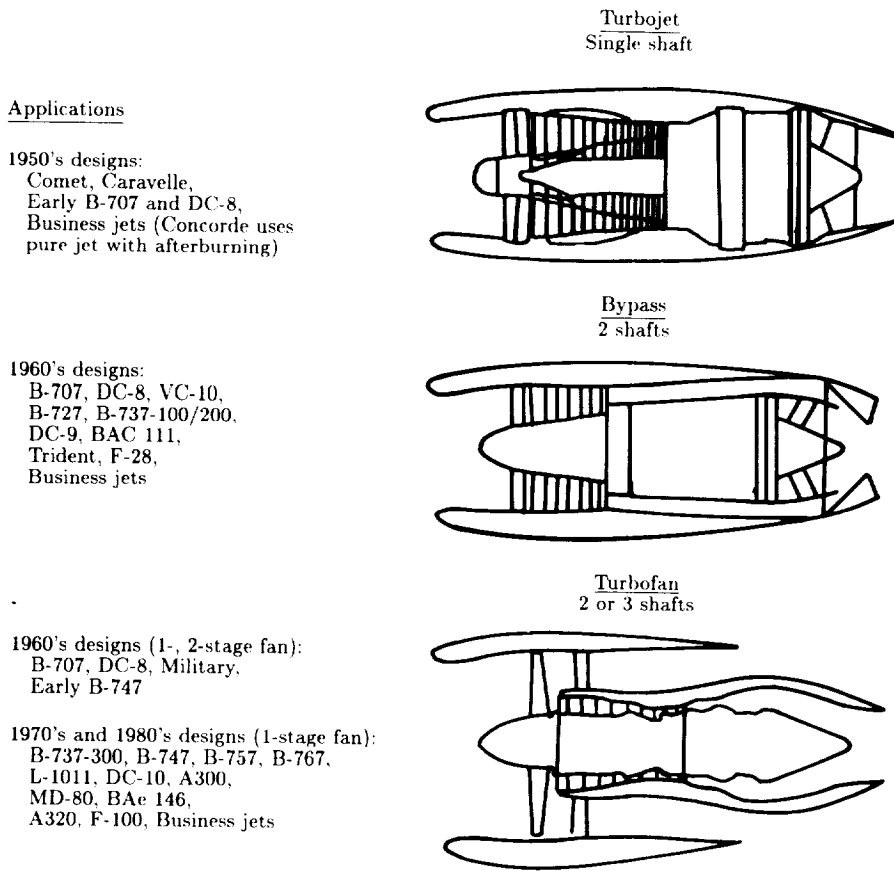 A320, F-100, Business jets

Figure 9. Three types of jet propulsion system.

Sources of Noise

Noise sources vary according to the engine cycle and are located both internally and externally. They may be summarized as follows:

1. In all cases, the exhaust-jet mixing process with the atmosphere produces broadband noise. Additionally, where the exhaust flow is supersonic (in zero- or low-bypass-ratio engines), there are other noise sources associated with the expansion-shock structure.
2. In all cases, compressor-generated tonal and broadband noise radiates through the engine air intake and, in all but the pure jet, may propagate down the bypass duct to radiate with the compressor exhaust stream.
3. In all cases, tonal noise from the turbine and broadband noise from this component and the "core" combustor propagate from the final nozzle in the hot core flow.
4. In a turbofan, tonal and broadband fan noise radiates both forward and rearward from the engine.
5. Other minor noise sources, peculiar to the engine design, may be present (e.g., bleed valves, flow mixers, and support struts).

Available Component Prediction Models

The following published component noise prediction procedures are available:

1. For single-stream exhaust flow conditions, SAE ARP 876C (ref. 12) provides the most widely used method of jet noise prediction. Based on normally available jet flow parameters, it provides both mixing and shock-associated spectral levels over a wide range of pressures, velocities, temperatures, and radiation angles.
2. For dual-stream flows there is no widely accepted method, but SAE AIR 1905 (ref. 13) describes three methods that could be used, one being a simple extension of the single-stream method of SAE ARP 876C.
3. For multistage compressor noise, the sensitivity of commercial organizations to compressor design details and noise data has meant that there is no method of the same acceptance level as that in procedure 1 for jet noise. However, the methods of House and Smith (ref. 14) and of Heidmann (ref. 15) are well-known and demand only the use of compressor performance parameters that are usually available.
4. For fan noise, it almost goes without saying that commercial sensitivity has the greatest effect on the availability of published data or prediction methodology. The method of Heidmann is the only freely available procedure.
5. For turbine noise, the same problem of commercial sensitivity exists, but the method of Matta, Sandusky, and Doyle (ref. 16) is available.
6. For combustor noise, the method of SAE ARP 876C (ref. 12) is the most widely accepted procedure.
7. Since most engines now incorporate noise-absorbent linings in the major air and flow ducts, a method is needed for computing duct attenuation as it affects fan, core compressor, turbine, and combustor noise. The method of Kershaw and House (ref. 17) is available.

375

Airframe Noise Characteristics

The above procedures allow predictions to be made of the component spectral levels in the far field at any given angle to the power plant. Unless it is a requirement to maintain spectral information in fine detail throughout the noise-time history of an aircraft flyover, it is normal to sum the noise energy to produce a single numerical expression of the noise of a single flight event at a given power setting, either in terms of peak level (e.g., peak PNL or peak A-weighted sound level) or time-integrated energy (EPNL or SEL). However, before this process can be conducted, it is important to consider the inclusion of one further source, which is most relevant at approach conditions.

The airframe noise varies with flight speed, mass of the airplane, and configuration. The most important feature is deployment of the wing flaps and landing gear. A procedure which provides the spectral information necessary to allow this source to be integrated into the total flyover level (in the same way as the engine components) is provided by Fink (ref. 18).

Total Airplane Noise

Having compiled a set of component noise predictions for the power plant and the airframe, we can construct a "carpet" of noise as a function of engine power and distance for the relevant flight speeds. For example, takeoff flight speeds are usually at Mach numbers of 0.25 to 0.30 and approach flight speeds are at Mach numbers of 0.20 to 0.25. Hence, for all the component sources, it is necessary to make appropriate corrections for changes in flight speed between the takeoff and approach conditions.

Even with these corrections, at this stage any noise-power-distance carpet that is constructed will apply only to the isolated power plant in the "overflight" condition, and it is necessary to make further adjustments for several other factors. For example, the effects of having more than one engine on the aircraft need to be accounted for. Equally, it may be that there are some special amplifying installation effects which can be computed from previous observations, or there may be some shielding of the noise because of the installation. Examples of these are the amplifying interaction between the jet and the wing flaps on the one hand and the shielding effect of a center engine installation of a trijet on the other hand. For a trijet, noise from the inlet is not heard by an observer beneath the airplane, but it becomes progressively audible as the observer moves to the side of the flight track.

There are no readily available methods for computing these effects, but generally noise from engines mounted under the wing is amplified whereas that from engines mounted at the rear of the fuselage is shielded, both beneath and to the side of the aircraft flight track. All these effects are normally no greater than 3 dB, except when the aircraft subtends a very small angle of elevation to the receiver.

Similarly, the effects of the ground plane (in the form of over-ground and airborne "lateral" attenuation) together with the effects of the measurement position (ground reflection) also have to be taken into account before the noise from the airplane can be presented (either instantaneously or integrated into a single-number index) from the observer's standpoint. These effects may be accounted for either in the manner presented by ESDU (ref. 9) or, more simply, in the manner of SAE AIR 1751 (ref. 10).

376

Prediction Methods Generally Available

The methods already referenced represent the latest available. In some cases there are no generally accepted procedures. There is only one comprehensive aircraft noise prediction method freely available, the Aircraft Noise Prediction Program (ANOPP) (ref. 19). This method utilizes many of the procedures referenced herein.

Accuracy

The component noise prediction procedures have variable accuracies, those associated with turbomachinery being the least reliable. Those procedures associated with zero- and low-bypass-ratio powered aircraft were studied in the 1970's and found to be sufficiently accurate to be utilized in a major study of supersonic transport noise by ICAO (ref. 20). No other comprehensive studies have been undertaken other than those conducted for NASA in validating ANOPP.

Prediction of Noise for Airplanes Powered by Propellers or Propfans

Components of Interest

Propeller and propfan noise is dominated by low-frequency tones. These tones consist of a fundamental, the frequency of which is given by the propeller or propfan rotation rate in revolutions per second times the number of blades, and integer multiples of the fundamental frequency (i.e., harmonics). For propellers, the fundamental frequency is typically 60 to 150 Hz. Propfans have fundamental frequencies from 125 to 300 Hz. Although it is possible to identify individual harmonics by use of narrow-band frequency analyses, the 1/3-octave band analyses performed for noise certification purposes allow the identification of the fundamental through the third harmonic. Higher harmonics are more closely spaced in frequency than the bandwidth of the 1/3-octave bands so that several harmonics fall within a band. The higher frequencies may thus appear as broadband noise, but really they are not.

Another component of propeller and propfan noise is broadband noise. This component is currently considered insignificant for normal operation in flight. During static and very-low-speed operating conditions, turbulence ingestion noise occurs. This noise has some characteristics of tones and broadband noise. However, it becomes insignificant during normal flight conditions. Finally, a propeller or propfan powered airplane may have contributions from other sources of noise such as that from the engines and the airframe. In this section only the dominant propeller and propfan tones are described, as the other components are insignificant during normal flight or are covered in another section.

Component Noise Prediction Models

Types of Noise Prediction Models

Propeller and propfan noise prediction models come in basically two types: empirical and theoretical. Empirical models are based on regression analyses of

test data. Theoretical models are based on mathematical modeling of the physical processes of propeller and propfan noise generation.

Empirical models for predicting propeller noise have been reasonably successful and work well for fairly conventional designs that operate over a reasonable range of tip speeds and power loading (power divided by propeller disk area). Empirical models have generally not been successful for propfan noise prediction.

The most commonly used empirical propeller noise prediction method is that of reference 21. This method allows calculation of propeller noise based on only five parameters: tip speed, diameter, number of blades, flight speed, and distance. Because it is based on a collection of measured data, mostly from turboprops, the method intrinsically contains most other sources of noise, such as installation effects, engine noise, and airframe noise.

Many theoretical models exist. These relate the radiated noise to the forces imparted to the air by the physical volume of the blades and the pressure distribution on the blade surfaces. Theoretical propeller noise prediction models consist of two parts: an acoustic radiation model, which "converts" the forces on the blades to noise, and an aerodynamic model, which allows the calculation of the forces on the blades. Both are needed, along with detailed definition of the propeller geometry, to perform noise predictions.

Relationship of Static to Flight Effects

As previously mentioned, under static conditions a significant amount of noise due to inflow turbulence ingestion occurs. This is a source of noise which disappears in flight. Figure 10, from reference 22, illustrates the influence of forward flight on propeller noise. Under static conditions, the noise spectrum is dominated by intense higher harmonics. In flight, the levels of these upper harmonics are greatly reduced. Figure 11 shows the effect as measured on the airplane and on the ground during static operation and during a flyover. The middle 1/3-octave bands show high levels during static operation while the flight data show much lower levels. The measured differences are greater than 10 dB.

It is thus apparent that static propeller noise data projected to flight generally result in significant overpredictions. Static propeller noise data are thus of little value. Even *trends* in noise under static conditions are suspect.

Installation Effects

Installation effects result in additional noise sources which generally raise propeller and propfan noise levels. These effects are due to distortions in the inflow which are caused by angle of attack, engine nacelle blockage, wing upwash, pylon wakes, etc., and which are unavoidable in the installation of a propeller or propfan on an airplane. The additional noise is caused by unsteady-loading noise, which results from the periodic loading variation on the blades as they pass through the flow distortion. Unsteady-loading noise is a source usually included in the theoretical noise prediction methods. For such calculations a means for calculating the flow field is required. Empirical noise prediction methods include some form of installation effects by default, as they are included in the data.
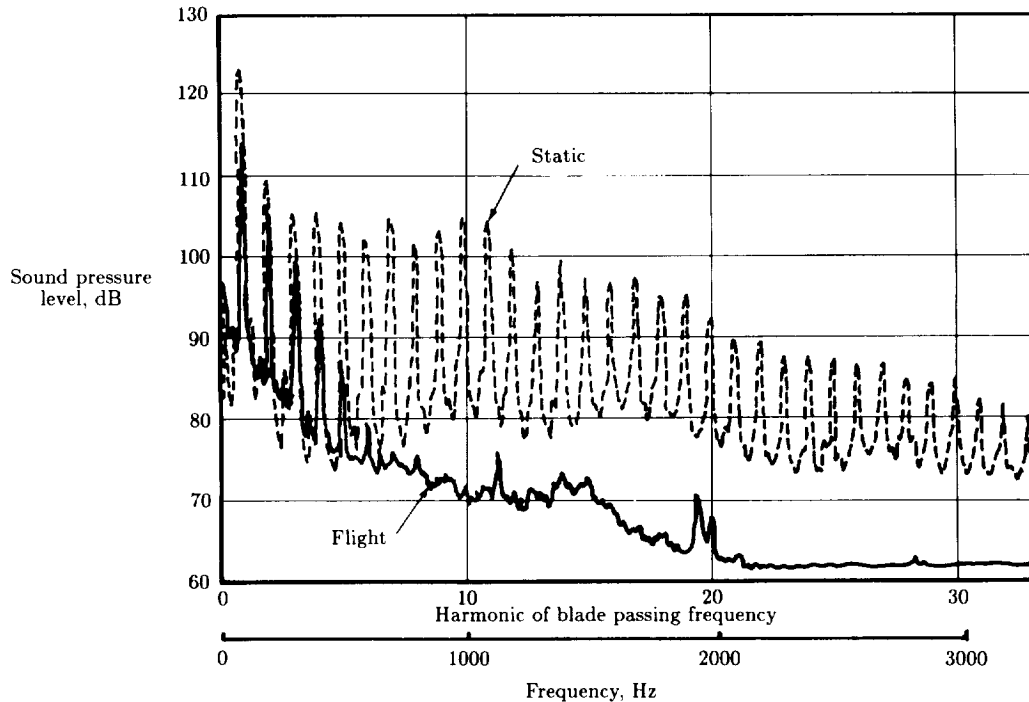
378

Figure 10. Comparison of static and flight propeller noise narrow-band spectra. (From ref. 22.)

Accuracy of Prediction

It is difficult to make a precise assessment of propeller and propfan noise prediction accuracy because of the types of methods available and the degree of detail which can be applied. In general, the accuracy of empirical noise prediction methods is about ±3 dB, providing that the noise of the configuration being estimated does not fall too far outside the data base inherent in the prediction method. It is not surprising to find errors of ±10 dB for unusual configurations.

The accuracy of theoretical noise prediction methods includes the accuracy of the actual noise radiation model, how well the blade geometry can be defined (propfan blades can have very complicated shapes), and how well the blade loading in both the chordwise and the spanwise direction can be defined. It is expected that a carefully calculated noise prediction in terms of effective perceived noise level or A-weighted overall noise would have an accuracy of about ±1.5 dB. Other variables, such as ground reflection effects, atmospheric absorption, and tilt of the propeller axis relative to the flight path, can introduce additional errors.

Future Developments

It is generally agreed that existing propeller and propfan noise radiation models are complete and detailed enough to provide good predictions. The prediction
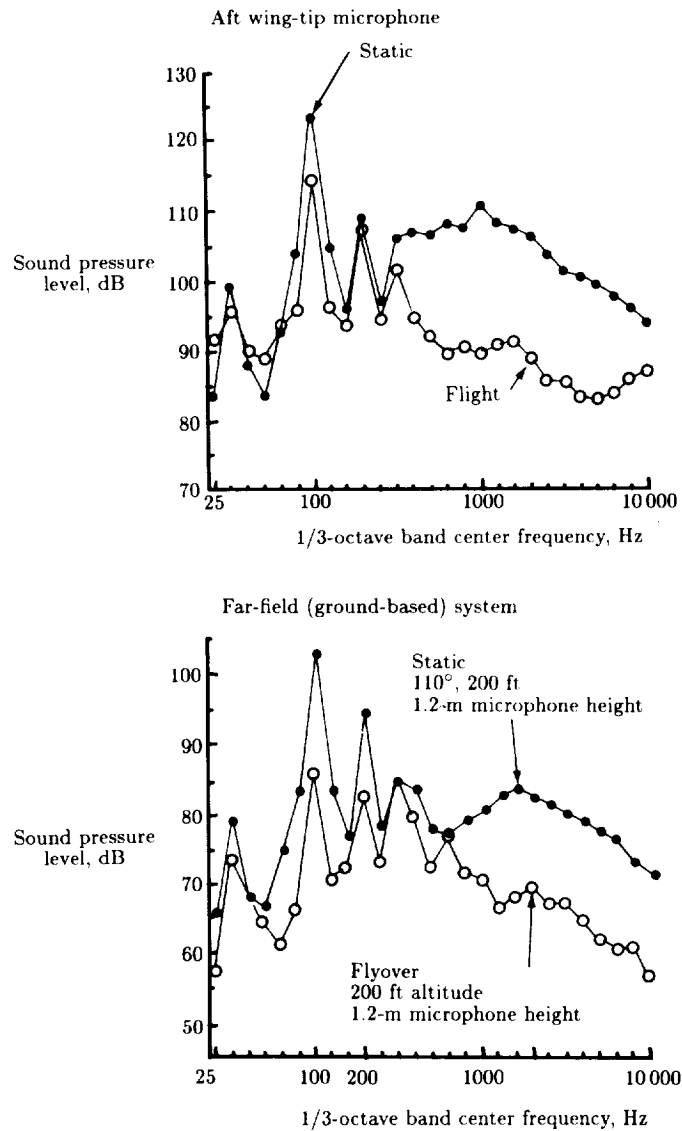
379

Figure 11. Comparison of static and flight propeller noise 1/3-octave band spectra. (From ref. 22.)

limitations appear to be in the aerodynamic codes required to define the inflow to the propeller and to define the steady and, especially, the unsteady blade loading. It is expected that improvements in propeller and propfan noise predictions will come from improved aerodynamic codes.

Other Prediction Methods

It is feasible to scale model propeller and propfan tone noise data to full scale. The scale limitation is not an acoustic one but rather one imposed by aerodynamics

(i.e., Reynolds number effects) and the ability to manufacture an accurate model preserving airfoil contours. From an acoustic standpoint a model propeller has the same harmonic spectrum as a full-scale propeller at the same blade angle, tip rotational Mach number, and flight Mach number. The tone frequencies are inversely proportional to the diameter ratio. Model broadband noise does not scale geometrically.

Experience has indicated that models in the 0.61-m (2-ft) diameter range (approximately 1/5 scale) or larger scale very well. It should be apparent from the foregoing discussion that the accuracy of scaling model data depends on how well the model simulates the actual installation. For accurate results, one should consider including a simulation of the flow field of the propeller. It is strongly cautioned that there is no means for acquiring propeller noise under static conditions that can be used for flight simulation.

References

1. Standards Governing the Noise Certification of Aircraft. *Fed. Regist.*, vol. 53, no. 88, May 6, 1988, pp. 16360-16372.
2. *Environmental Protection—Annex 16 to the Convention on International Civil Aviation. Volume I—Aircraft Noise, First ed.* International Civil Aviation Organization, Nov. 26, 1981. (As amended Nov. 21, 1985.)
3. *Noise Certification Handbook.* AC No. 36-4B, Federal Aviation Adm., Mar. 23, 1988.
4. Borfitz, Michael H.; and Glover, Billy M.: Community Noise Testing—New Techniques and Equipment. *Flight Testing Today: Innovative Management and Technology—14th Annual Symposium Proceedings,* Soc. of Flight Test Engineers, 1983, pp. 4.3-1–4.3-8.
5. *Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity.* ARP 866A, Soc. of Automotive Engineers, Mar. 15, 1975.
6. *American National Standard Method for the Calculation of the Absorption of Sound by the Atmosphere.* ANSI S1.26-1978 (ASA 23-1978), American National Standards Inst., Inc., June 23, 1978.
7. Roy, Dipankar: Doppler Frequency Shift in a Refractive Atmosphere. *J. Aircr.,* vol. 24, no. 9, Sept. 1987, pp. 577–586.
8. Chessell, C. I.: Propagation of Noise Along a Finite Impedance Boundary. *J. Acoust. Soc. America,* vol. 62 , no. 4, Oct. 1977, pp. 825–834.
9. *The Correction of Measured Noise Spectra for the Effects of Ground Reflection.* ESDU Item Number 80038 (With Amendments A and B), Engineering Sciences Data Unit (London, England), Nov. 1984.
10. *Prediction Method for Lateral Attenuation of Airplane Noise During Takeoff and Landing.* AIR 1751, Soc. of Automotive Engineers, Inc., Mar. 30, 1981.
11. *Environmental Technical Manual on the Use of Procedures in the Noise Certification of Aircraft, First ed.* Doc. 9501-AN/929, International Civil Aviation Organization, 1988.
12. *Gas Turbine Jet Exhaust Noise Prediction.* ARP 876C, Soc. of Automotive Engineers, Inc., Sept. 1982. (Supersedes ARP 876B.)
13. *Gas Turbine Coaxial Exhaust Flow Noise Prediction.* AIR 1905, Soc. of Automotive Engineers, Inc., Dec. 1985.
14. House, M. E.; and Smith, M. J. T.: Internally Generated Noise From Gas Turbine Engines Measurement and Prediction. ASME Paper 66-GT/N-43, Mar. 1966.
15. Heidmann, M. F.: *Interim Prediction Method for Fan and Compressor Source Noise.* NASA TM X-71763, 1975.
16. Matta, R. K.; Sandusky, G. T.; and Doyle, V. L.: *GE Core Engine Noise Investigation, Low Emission Engines.* FAA-RD-77-4, Feb. 1977. (Available from DTIC as AD A048 590.)

17. Kershaw, R. J.; and House, M. E.: Sound-Absorbent Duct Design. *Noise and Vibration*, R. G. White and J. G. Walker, eds., John Wiley & Sons, c.1982, pp. 477–495.

18. Fink, Martin R.: *Airframe Noise Prediction Method*. FAA-RD-77-29, Mar. 1977. (Available from DTIC as AD A039 664.)

19. Zorumski, William E.: *Aircraft Noise Prediction Program Theoretical Manual*. NASA TM-83199, Parts 1 and 2, 1982.

20. *Committee on Aircraft Noise, Seventh Meeting*. Doc. 9419, CAN/7, International Civil Aviation Organization, May 1983.

21. *Prediction Procedure for Near-Field and Far-Field Propeller Noise*. AIR 1407, Soc. of Automotive Engineers, Inc., May 1977.

22. Magliozzi, B.: *The Influence of Forward Flight on Propeller Noise*. NASA CR-145105, 1977.