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PROCEDURE FOR THE CALCULATION OF AIRPLANE NOISE IN THE VICINITY OF AIRPORTS

ABSTRACT

This Aerospace Information Report (AIR) describes procedures for calculating sound exposure levels at ground locations resulting from operations of jet and propeller driven airplanes in the vicinity of an airport. The procedures assume that reference noise and performance data are available for each airplane involved. The fundamental element of the procedures is a method for calculating the A-weighted sound exposure level (SEL) that would be produced, on average, by any specific airplane when performing any specified operation. Procedures are given for calculating sound exposure levels for individual airplane operations and for the average sound level produced by the cumulative effect of a series of different airplane operations, normally expressed in terms of day-night average sound level (DNL) averaged over an appropriate long time period.

The principal purpose of using the procedures recommended in this AIR to calculate contours of equal average sound level is to assist in land-use planning around airports. Contours of equal sound level may be constructed by connecting lines through individual points of constant sound level. While the procedures of this AIR describe the computation of sound levels at any point in the vicinity of an airport, the procedure for calculation of contours is computer-program dependent and is not a part of this AIR.

PREPARED BY
SAE COMMITTEE A-21, AIRCRAFT NOISE

CONTENTS

1. INTRODUCTION: The sound exposure level produced at a fixed location near the ground by an airplane operation is dependent on a number of factors. Primary factors are: airplane and engine type; power, flap, and airspeed management procedures; distance from the location near the ground to the flight path of the airplane; and the effects of local topography and weather on sound propagation. Airport operations generally include different types of airplanes, various flight procedures, and a range of operational weights. Cumulative average sound levels computed by the procedure described in this AIR are suitable for land-use planning purposes.

In this document, noise from individual airplane operations is described in terms of sound exposure level (SEL, symbolized L_{AE}) while the cumulative noise from a series of airplane operations is described in terms of day-night average sound level (DNL, symbolized L_{dn}), in conformance with Reference 1. Recommendations for measurement of airplane sound levels, data normalization to reference atmospheric conditions, and extrapolation of the measured data to propagation distances normally occurring in contour constructions are included in this AIR. The method described for extrapolating the SEL may be applicable to other types of noise descriptors.*

Airplane performance is estimated from simplified equations which require airplane-dependent coefficients. This provides a practical method of including in the SEL modeling process the effects of changes in flight profile which result from changes in operational procedure or mission weight.

This AIR describes the step-by-step method for calculating SEL at any point near the ground in the vicinity of an airport. The total procedure for calculation of a single-event or cumulative noise contour is best accomplished by a computer. The description of computer programs to perform contour calculations is not a part of this AIR. Noise contours formed by connecting points of equal sound exposure level produced by one airplane during a single takeoff or approach operation have been generally referred to as single-event contours or "footprints." An example contour is shown schematically on Fig. 1. Contours formed by connecting points of equal cumulative average sound level produced by a series of airplane operations that have occurred over a specified time period, such as 24 hours, are called cumulative noise contours. In this AIR the computation of airplane noise contours is simplified by establishing a single set of airport reference conditions (temperature, humidity, airport altitude, and wind speed) based on yearly average conditions at several major world airports. Ranges of average annual environmental conditions are specified for which the noise levels resulting from the procedures can be considered sufficiently accurate for the purpose of land-use planning.

*SEL is recommended in ANSI S3.23-1980, (Ref. 1) and ISO 1996, Part 1, (Ref. 2). Other noise descriptors, e.g., Effective Perceived Noise Level, Maximum Perceived Noise Level, and Maximum A-Weighted Sound Level have also been, in some instances, used for airport noise assessments, including the determination of permissible land uses around an airport.

For a particular airplane, the relevant manufacturer should be consulted for the basic aerodynamic, engine-performance, and acoustical data needed to perform the computations in accordance with the recommendations of this AIR.

Application of the techniques presented herein to uses other than estimating airplane/airport cumulative noise levels was not considered.

2. PRINCIPAL CONSIDERATIONS IN COMPUTATION OF SOUND LEVELS: Calculation of sound exposure level near an airport requires three principal types of data; airplane flight performance, airplane noise characteristics, and adjustment factors to be applied to the baseline (individual airplane) noise characteristics.

2.1 Airplane Aerodynamic-Performance Characteristics: Determination of the distance between an observation point and the airplane flight path requires calculation of the location of the flight path relative to an airport coordinate system. Determination of the flight path requires knowledge of (or assumptions for) airplane weight, speed, flap and thrust-management procedures, airport elevation, and wind and air temperature.

Equations to calculate the required propulsion and aerodynamic parameters are given in Appendix A. Each equation contains coefficients (or constants) which are based on empirical data for each specific airplane type. The aerodynamic-performance equations in Appendix A permit the consideration of any reasonable combination of airplane operational weight and flight procedure, including operations at maximum takeoff gross weight.

2.2 Airplane Acoustical Characteristics: The noise characteristics of each airplane are specified by sound exposure levels at locations under the flight path as functions of the minimum distance to the airplane and the corrected net thrust* [or other appropriate engine-power parameter(s)] produced by each engine at prescribed reference conditions. The SEL reference data base is defined for the computational reference conditions of Section 2.3. Sound exposure levels for all other flight conditions, or locations not directly under the flight path, are determined by applying adjustments to the baseline data.

Appendix B describes recommended procedures for developing an airplane SEL reference data base from noise measurements made directly under the flight path. Since airplane sound levels must often be estimated for distances differing from those associated with the measured sound levels, a recommended method for extrapolating the measured sound levels to both shorter and greater distances is also provided in Appendix B.

*The terms "corrected net thrust" and "referred net thrust" are both in use to describe the quotient of the actual net thrust divided by the ratio of ambient pressure at the aircraft altitude to standard-day atmospheric pressure at mean sea level.

Sound exposure levels at locations to the side of an airplane's flight track are lower than the levels at locations directly underneath the airplane, at the same distance, due to ground attenuation and airplane shielding effects. This reduction in sound level is called lateral attenuation. Procedures for determining lateral attenuation are described in SAE AIR 1751, (see Ref. 3) and are summarized in Section 3.5 of this AIR.

In addition to lateral attenuation, other adjustments are required to account for the following:

(a) Increased sound exposure levels behind an airplane at the start of takeoff roll.

(b) Change in sound duration as a result of acceleration during takeoff.

(c) Change in sound duration for airspeeds different from the reference value.

(d) Change in sound exposure level for airplane to receiver distances differing from values specified in the reference data base.

(e) Change in sound exposure level for engine power settings different from those specified with the baseline acoustical data.

(f) Effect on sound exposure level of airplane turns during climbout and approach.

Procedures to account for those effects are described in Section 3.

2.3 Computational Reference Conditions: Atmospheric pressure, air temperature, relative humidity, wind conditions, runway gradient, and type of terrain influence airplane performance and noise received by an airport community. To simplify the calculation of airplane noise contours, airplane performance and noise data are developed for certain computational reference conditions. Use of reference conditions, while necessary for practical implementation of a computational procedure, also provides reasonably accurate calculations of cumulative sound level as described in Appendix D.

Variations in individual parameters cause deviations from the computational reference conditions that can offset each other or can be additive, e.g., a reduction in the maximum power available because of a high airport elevation can be offset by wind or temperature conditions. Furthermore, since noise propagation is influenced by relative humidity, temperature and local topography, deviations from reference values in those factors can offset each other or be additive in their effect on the resulting noise level. The final set of contours which are produced to represent a specific airport situation should always include a determination as to whether the reference conditions can be considered representative of the prevailing local conditions on a long-term average basis.

The following recommendations for computational reference conditions are based on values that have been typically used for airport noise studies and that also agree reasonably well with long-term average conditions existing at several major airports around the world.

Reference Conditions for Noise Data:

1) Atmospheric pressure: 101.325 kPa (1013.25 mb)
2) Atmospheric absorption: attenuation rates listed in Table B1 of Appendix B
3) Precipitation: None
4) Wind speed: Less than 8 m/s (15 knots)
5) Airspeed: 160 knots
6) Local terrain: flat and free of large structures or other reflecting objects within several kilometers of an airplane's ground track

Reference Conditions for Calculation of Airplane Aerodynamic and Engine Data:

1) Wind: 4 m/s (8 knots) headwind constant with height above ground
2) Runway elevation: mean sea level
3) Runway gradient: None
4) Air temperature: 15°C
5) Takeoff gross weight: 85 percent of maximum takeoff gross weight
6) Landing gross weight: 90 percent of maximum landing gross weight
7) Number of engines supplying thrust along any segment of the flight path: All

NOTES:

(1) Computational procedures detailed in Appendix A permit adjustment of airplane flight paths for local conditions that differ from the computational reference conditions, see Section 3.1. However, the reference conditions for calculation of aerodynamic and engine data, items 1-4, can remain as defined for most analyses without significantly impacting the accuracy of the calculated contours of cumulative average sound level.

(2) The takeoff and landing gross weights noted in items 5 and 6 above are appropriate values for use with the average coefficients for an airplane's aerodynamic-and engine-performance parameters in the procedures described in Appendix A. However, for computation of contours of cumulative average sound level around an airport, calculation of the takeoff and climbout flight paths should utilize the appropriate takeoff gross weights in conjunction with applicable performance coefficients. When long-term airport noise monitoring data are available and are considered to represent the noise produced by the types of airplanes and their average numbers of daily operations for the period of time of interest, then the takeoff gross weights of the representative airplanes may be selected to yield best agreement between predicted and measured cumulative noise levels. (See Section 3.8)

2.4 Acceptable Envelope for Local Conditions: It is intended that the procedures described in this AIR be applicable to estimates of long-term average sound levels for land-use planning purposes. Experience by members of the SAE A-21 Committee on Aircraft Noise in estimating airport noise levels and comparing the estimates with measured data was used to establish an envelope within which the defined noise reference conditions of Section 2.3 were deemed to be acceptably representative of local conditions. It is suggested that the procedures defined in this AIR may be used as long as the near-surface long-term average conditions are within the following envelope:

- Air temperature less than 30°C.
- Product of air temperature (°C), and relative humidity, (percent), greater than 500.
- Wind speed less than 8 meters per second (15 knots).

The acceptable envelope for average local conditions defined above is believed to encompass conditions encountered at most of the world's major airports. For situations where average local conditions fall outside the noted envelope, consideration should be given to modifying the methods described in this AIR for developing the reference noise data base, as well as noise adjustment factors, if appropriate. Specification of procedures to accomplish such modifications was not within the scope of this AIR and it is suggested that the relevant airplane manufacturers should be consulted for specific recommendations. The effect of airport elevation on airplane performance is expressly considered in the equations of Appendix A. Airport elevation effects on sound propagation are negligible.

3. COMPUTATIONAL PROCEDURES:

3.1 General: Consider an airplane performing the takeoff operation depicted on Fig. 2. The airplane accelerates from zero speed at the start of the takeoff roll to the initial-climb speed. During this operation the sound exposure level will decrease as the airspeed increases as a result of the shorter duration of the noise as the airplane's speed increases and also because an airplane's noise source level generally decreases with increasing speed. Hence, the sound exposure level at liftoff is less than the sound exposure level at the start of takeoff, for a given sideline distance.

After airplane liftoff, the sound exposure level, at a given sideline distance, increases because the lateral attenuation decreases as elevation angle increases. The reduction in lateral attenuation is more significant than the decrease in airplane noise that results from the increased distance to the aircraft caused by height gained during this part of the takeoff flight path (see Figs. 1 and 2). Noise reduction from increased distance to the airplane becomes more significant while the lateral attenuation effect becomes negligible as elevation angle and airplane height continue to increase during climbout. For jet powered airplanes, maximum noise generally occurs at lateral locations for which the elevation angle is approximately 35 degrees. Finally, contour closure occurs when the sound exposure level under the flight path reaches the sound exposure level of the contour being calculated. The overall process of contour generation is illustrated on Fig. 3.

3.1 (Continued)

For each specific airplane type, the general procedure for determining the sound exposure level, at any specified location, is to select appropriate sound exposure levels from the acoustical data base corresponding to the minimum distance between the airplane and the observer, and then to add, algebraically, adjustments to account for differences between the actual airplane operational conditions and the reference conditions specified for the noise data base. For example, sideline-location noise estimates are based upon flyover (under-the-flight-path) noise measurements plus adjustments for the location.

In this AIR, four adjustments, in decibels, are defined for addition to the basic acoustical data to determine sound exposure levels:

$$L_{AE} = L_{AE}(P,d) + \Delta_V - \Lambda(\beta,\ell) + \Delta_L + \Delta_\phi \qquad (3.1)$$

The first two of the four adjustments listed in Eq. (3.1) apply for any ground location. The second adjustment is applicable whenever the observer to airplane elevation angle is less than 60 degrees. The Δ_L term is applicable only for locations behind the start of ground roll. The last adjustment, Δ_ϕ, applies only for locations that are inside or outside a curved ground track when an airplane flies a turning flight path.

Following is a description of the factors in Eq. (3.1):

$L_{AE}(P,d)$ The sound exposure level interpolated from the reference data base to correspond with the engine power P and distance d relevant to the particular airplane flight segment and ground location (see Section 3.4).

Δ_V A speed adjustment if the actual groundspeed differs from the 160 knot true airspeed associated with the acoustical data base (see Section 3.4, Eq. 3.9).

$\Lambda(\beta,\ell)$ A lateral attenuation adjustment if the observation point is not on the airplane's ground track, (see Section 3.5). Angle β is the elevation angle between the observation point and airplane, and ℓ is the perpendicular distance from observation point to airplane ground track.

Δ_L A directivity pattern adjustment for locations behind the start-of-takeoff roll (see Section 3.3.1).

Δ_ϕ A duration adjustment to account for differences between the effective duration of the baseline SEL data and the SEL at a ground location if the actual flight path includes a turn and the ground location is inside or outside the turn (see Section 3.6).

3.2 Selection of Flight Profile Segments: For a "straight-out" departure at any operational takeoff weight, the flight profile for an airplane's operation is approximated by a series of straight-line segments as depicted on Fig. 3. Straight-line segments are also used to represent landing-approach flight paths. Curved flight paths are represented by segments of circular arcs. The lengths of the individual segments should be selected to match different portions of the flight path that correspond either to sections of nominally constant engine power and airspeed, or to sections where acceleration occurs from one steady airspeed to a second steady airspeed. A takeoff profile such as shown on Fig. 3 would typically have six segments.

1. Ground roll with acceleration from start-of-takeoff to the initial climb segment;

2. Climb at initial climb speed, engine power, and flaps;

3a. Reduce engine power and climb at initial climb speed and flaps; or

3b. Maintain initial engine power and accelerate while retracting from takeoff to climb flaps;

4. Climb at reduced-flap climb speed, with or without reduced engine power;

5. Retract flaps and accelerate to zero-degree-flap airspeed;

6. Continued climbout with zero-degree flaps, climb airspeed, and climb power.

The procedure described in Appendix A permits calculation of airplane position along flight profile segments corresponding to each of the above operations. To calculate sound exposure levels, engine power and airspeed must be specified for each profile segment. A power setting parameter and airspeed must be specified at the beginning and end of each flight segment in which acceleration takes place; the average rate of climb over the duration of an acceleration segment must also be specified.

3.3 Takeoff Roll Noise Modeling: Modeling the takeoff roll noise received at ground positions near the airport runway requires several modifications to the SEL baseline data. The modifications result from the fact that the airplane is on the ground accelerating from essentially zero velocity to its initial climb speed, whereas the SEL data base represents constant-airspeed overflight conditions. To accommodate these differences, consideration must be given to changes in generated sound resulting from jet relative velocity effects, to changes in directivity pattern resulting from a moving aircraft, to the change in effective duration with increased speed and to over-ground sound propagation at near zero elevation angles. The present model has been derived from jet airplane operations, however, this procedure is also recommended for propeller-driven airplanes until a more suitable propeller method is developed.

3.3 (Continued)

The method of modeling the sound exposure level (SEL) during takeoff roll is described in Sections 3.3.1 and 3.3.2 with an indication of the assumptions involved and of the general utility in calculation procedures for describing aircraft noise in the vicinity of airports. The method is based on empirically determined "fleet weighted average" sound exposure level representation at the start of takeoff roll for an international airport with a typical mix of jet airplane types. The "fleet average" representation is related to the specific airplane and takeoff-roll procedure through the noise-power-distance data. The noise contours predicted are, in any case, intended to represent long term averages, in which movement-by-movement variations are not significant.

3.3.1 Sound Exposure Level Behind the Start-of-Takeoff Roll: The "fleet weighted average" method of describing the start of the takeoff roll segment, discussed in Section 3.3 above, was empirically derived from noise monitoring data measured at Logan International Airport, Boston, Mass. The method was substantiated with additional measurements taken at Seattle-Tacoma and London Heathrow International Airports. The measurements were normalized to a distance of 1000 ft and then a mean square average was calculated for each airplane type. A "fleet average" value was then computed to permit the development of an effective directivity pattern for use in estimating airport noise exposure.

Using the coordinate system illustrated on Fig. 4, the sound exposure level for locations behind start of roll is computed as follows:

1. Compute the radial distance, r, from the airplane's location at start of roll, P_0 (0,0), to observer point, P'(-x,y), where primes denote positions behind start of roll.

2. Determine the obtuse angle, θ in degrees, (angle between the centerline of the runway and the radial to location P'). The effective directivity pattern is symmetric about the runway axis.

3. Calculate the directivity pattern adjustment, Δ_L, in decibels, such that

   a. For $90° \leq \theta \leq 148.4°$

$$\Delta_L = 51.44 - 1.553\,\theta + 0.015147\,\theta^2 - 0.000047173\,\theta^3 \qquad (3.2)$$

   b. For $148.4° < \theta \leq 180°$

$$\Delta_L = 339.18 - 2.5802\,\theta - 0.0045545\,\theta^2 + 0.0000044193\,\theta^3 \qquad (3.3)$$

4. Determine the sound exposure level at P'

$$L_{AE}(P') = L_{AE}(P,d) + \Delta_V - \Lambda(0,r) + \Delta_L \qquad (3.4.1)$$

3.3.1 (Continued)

where

$L_{AE}(P,d)$ is the sound exposure level derived from the reference data base, corresponding to takeoff power setting and distance d = r

Δ_V is the speed adjustment for the difference between a minimum airspeed of 32 knots and the normalization airspeed of 160 knots at takeoff power

$\Lambda(0,r)$ is the lateral attenuation adjustment for an elevation angle of zero degrees and distance r

Δ_L is the directivity pattern adjustment defined in step 3 above

Noise contours for behind start of roll are produced by computing values of L_{AE} using Eq. (3.4.1) at a series of grid points and by interpolation between the grid points.

3.3.2 Sound Exposure Level During Takeoff Ground Roll:

For sound exposure levels adjacent to the takeoff ground roll (Fig. 4)

$$L_{AE}(x,y) = L_{AE}(P,d) + \Delta_V - \Lambda(0,d) \qquad (3.4.2)$$

where

$L_{AE}(P,d)$ is the sound exposure level derived from the reference data base, corresponding to takeoff power and distance normal to the runway (airplane)

Δ_V is the speed adjustment for the difference between the 32 knot minimum groundspeed and the lift-off groundspeed at takeoff power assuming constant acceleration,

i.e., $\Delta_V = 10 \lg(160/V)$

where

$$V = \sqrt{32^2 + (V_{tg}^2 - 32^2)\,(x/s_g)}$$

x is the airplane distance along the takeoff ground roll

s_g is the equivalent takeoff ground roll distance

V_{tg} is the airplane true ground speed at liftoff.

An elevation angle of zero degrees is used in the lateral attenuation adjustment, $\Lambda(0, d)$. Distance, d, corresponds to the lateral distance of the selected point from the runway centerline.

3.4 Sound Exposure Level for Flight Segments Having Constant Airspeed and Constant Engine Power: The acoustical data base for a specific airplane, developed in accordance with the procedures described in Appendix B, provides sound exposure level, for several power settings normalized to an airspeed of 160 knots, as a function of minimum slant distance, for observer location elevation angles that are not influenced by lateral attenuation. As shown on Fig. 2, minimum slant distance (or minimum slant range) is the distance of closest approach between the flight path and the observer location.

Consider an x, y, z coordinate system, where the ground track of the flight path progresses along the x axis in the y = 0 plane. Lateral distance y is perpendicular to the airplane's flight ground track in the z = 0 plane. Airplane height above ground is specified by the value of the z coordinate. The slant, or minimum, distance d_m, from any point x_o, y_o in the x-y plane after liftoff, to the airplane is given by

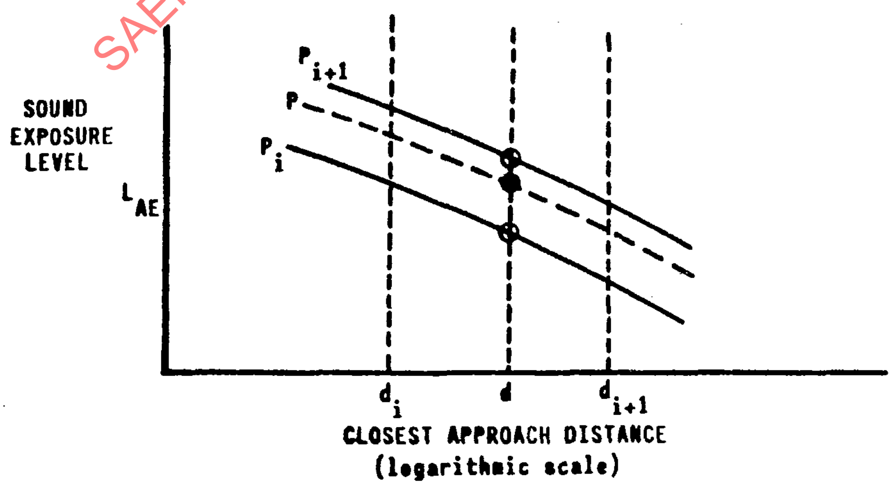
$$d_m = [y_o^2 + z_o^2 \cos^2\gamma]^{1/2} \qquad (3.5)$$

where γ is the geometric airplane flight path angle relative to the horizontal, and z_o is the height of the airplane above ground at $x = x_o$, $y = y_o = 0$.

Elevation angle β from the general observation point at x_o, y_o to the airplane is defined at the time of closest approach and is given by

$$\beta = \cos^{-1} (y_o/d_m) \qquad (3.6)$$

When using tabulated SEL data (e.g., Table B2 of Appendix B) interpolation between tabulated powers and distances will generally be necessary. Sound exposure levels for intermediate powers are determined by linear interpolation, and for intermediate distances by logarithmic interpolation.



Let Pi and P_{i+1} be tabulated power values in Table B2 for which noise data are provided at some set of distances. Sound exposure level at the same distance for intermediate power P, between P_i and P_{i+1}, is given by:

$$L_{AE}(P) = L_{AE}(P_i) + [L_{AE}(P_{i+1}) - L_{AE}(P_i)] [(P-P_i)/(P_{i+1}-P_i)] \quad (3.7)$$

Let d_i and d_{i+1} be tabulated distances in Table B2 for which noise data are provided at some set of power settings. Sound exposure level at the same power for an intermediate distance d, between d_i and d_{i+1} is given by

$$L_{AE}(d) = L_{AE}(d_i) + [L_{AE}(d_{i+1}) - L_{AE}(d_i)] [(\lg d-\lg d_i)/(\lg d_{i+1}-\lg d_i)] \quad (3.8)$$

By using Eqs. (3.7) and (3.8) sound exposure levels may be calculated for any power setting P and any distance d that is within the envelope of the data base.

The adjustment, Δ_V, is an adjustment to the duration correction based on true groundspeed which may be different from the 160 knot normalization speed used for the data base. The airspeed adjustment is calculated from

$$\Delta_V = 10 \lg(160/V_{tg}) \quad (3.9)$$

where V_{tg} is the true groundspeed* in knots.

Appendix E presents sound exposure level contours of 90 dB and 110 dB computed by the above method for an airplane powered by two turbofan engines.

3.5 Lateral Attenuation: Procedures for determining lateral attenuation, for an average airplane, are given in SAE AIR 1751 (1981), Ref. 3. The adjustment consists of three equations which apply (1) when the airplane is on the ground, (2) when the airplane is airborne and the lateral distance is less than 914 m, or (3) when the airplane is airborne and the lateral (or sideline) distance is greater than 914 m (3000 ft). The adjustment procedure described in AIR 1751 was developed for jet-propelled airplanes. Lateral attenuation effects should be ignored for propeller-driven airplanes.

The equations for specifying lateral attenuation when the airplane is on the ground are

$$G(\ell) = 15.09[1 - e^{-0.00274\ell}] \text{ for } 0 \le \ell \le 914 \text{ m}, \quad (3.10)$$

and $G(\ell) = 13.86$ for $\ell > 914$ m (3.11)

*For most practical applications the true groundspeed may be represented by the calibrated (or indicated) airspeed used in airplane flight path calculations. However, if maximum accuracy is required, and the airport is at high altitude or in a very hot climate and/or the headwind is significantly greater than 8 knots, use of the actual groundspeed should be considered.

3.5 (Continued)

where $G(\ell)$ is the overground lateral attenuation in decibels as a function of the horizontal lateral distance ℓ in meters. [The general symbol ℓ is used for distance to be consistent with the usage of Ref. 3, and is the same as perpendicular distance y_0 in Section 3.4 or radial distance as in Section 3.3.1].

When the airplane is airborne and the horizontal lateral distance is greater than 914 m, air-to-ground lateral attenuation, is given by

$$\Lambda(\beta) = 3.96 - 0.066\beta + 9.9\, e^{-0.13\beta} \text{ for } 0^\circ \leq \beta \leq 60^\circ\text{, and} \qquad (3.12)$$

$$\Lambda(\beta) = 0 \text{ for } 60^\circ < \beta \leq 90^\circ \qquad (3.13)$$

where $\Lambda(\beta)$ is in decibels and elevation angle β is in degrees.

Lateral attenuation is given by a transition equation when the airplane is airborne and the horizontal lateral distance is less than, or equal to, 914 m, namely

$$\Lambda(\beta,\ell) = [G(\ell)][\Lambda(\beta)]/13.86 \qquad (3.14)$$

where $G(\ell)$ and $\Lambda(\beta)$ are given by Eqs. (3.10) to (3.13).

3.6 <u>Effect of Airplane Turns on Sound Exposure Level</u>: When a flight path incorporates a turn, the SEL inside the turn will be greater than outside of the turn because of the longer duration inside the turn and the shorter duration outside the turn relative to the duration of the sound produced by an airplane flying a straight flight path. At an airspeed of 160 knots, a standard-rate turn of 3 degrees per second has a radius of about 1600 meters (5300 feet) and requires an airplane bank angle of approximately 23 degrees. For most operations by civil aircraft, turns will be made at bank angles of less than 20 degrees and through a total turn angle of less than 180 degrees. When the turn radius is large (e.g., greater than 2000 meters) and the total turn angle is less than 90 degrees, the change in SEL as a result of the turn is negligible and may be ignored. Where turn radii are less than 2000 meters or total turn angles are sufficiently large, e.g., more than 90 degrees, it may be desirable to account for the change in the duration effect on SEL. A procedure for calculating the adjustment $\Delta\phi$ in Eq. (3.1) for the increase in SEL on the inside of a turn, and the decrease on the outside of a turn, is outlined in Appendix C.

3.7 <u>Power Changes from One Segment to the Next Segment</u>: For the purpose of this AIR, changes in engine power settings are considered to occur instantaneously at the ends of individual flight-profile segments. Finite spool-down or spool-up times are not included in this procedure. Computer implementation of the procedures, however, should be constructed to eliminate discontinuities in SEL contours at points perpendicular to the coordinates defining segment intersections, see Fig. 3. Elimination of discontinuities

3.7 (Continued)

may be accomplished either by defining a series of short profile segments with small incremental changes in engine power, or by smoothing algorithms in the computer program or the contour-plotting process, for example, to provide a linear transition in noise level over the first 300 meters (1000 feet) of the next flight segment.

3.8 Cumulative Noise Contours: Computation of sound exposure level caused by a single-event airplane operation is repeated to determine contours of cumulative noise resulting from multiple airplane operations.* The sound exposure from each operation is summed. Average sound levels are then determined from the total sound exposure. A change in airplane operational weight alters the flight profile so that if an airport study is to consider different weights for a particular airplane, the analysis must consider each weight of the same airplane as a different airplane. Different operational procedures are processed in a similar manner. The computational process is repeated as many times as required to determine the total or cumulative noise.

Computation of cumulative noise contours involves consideration of:

1) Types of airplanes operating at the airport. The consideration of airplane types usually requires aggregating airplanes having similar performance and noise characteristics into representative categories.

2) Number of operations (takeoffs and landings) for each airplane type and time period for each operation. Consideration of the time period is required only if a time-of-day weighting is to be applied.

3) Takeoff (or landing) weight for each operation. In some instances, it is necessary to approximate the weight from operational range information. To simplify the computational process, it is sometimes expedient to specify weight ranges and to assume that a single airplane gross weight adequately represents the specified range. Long-term airport noise monitoring data may also be used. (See Note (2) in Section 2.3.)

4) Flight procedures. Engine power setting, airspeed and flap-retraction schedules must be established for use in determining the takeoff flight profile by the procedure explained in Appendix A. For landings, the nominal approach glideslope angle, flap, and engine power setting must be specified, see Section A.9 of Appendix A.

*Similar procedures are required to compute contours for noise descriptors other than sound exposure level.

3.8 (Continued)

5) Runway usage and airplane flight ground tracks. Prevailing flight patterns and runway usage must be established. At some airports, certain runways are not used for nighttime operations and some flight procedures use turns during climbout to avoid residential areas. These situations should be identified and incorporated into the computation process. Where detailed runway usage data are not available, estimates may be made from long-term wind direction data.

6) Flight path dispersion. Airplane traffic-control procedures are usually specified by instructions to the pilot to turn to specific compass headings upon reaching specified pressure altitudes. Depending on airplane weights and flight performance, the locations for initiating turns and the turn radii may vary substantially. The variations will introduce significant dispersion in actual flight tracks. A nominal flight track representing average conditions will often not provide an adequate description of actual flight track dispersion and can lead to an incorrect depiction of actual average sound levels. Care should always be taken to represent flight path dispersion by an appropriate procedure. A similar dispersive effect can also take place in nominally "straight-out" departures and that effect should also be assessed in airport noise analyses.

Since many hundreds of operations may occur at a large commercial airport in a 24-hour period, all the different operations may be considered as being comprised of a finite number of airplane classes, with a number of operations in each class. The number of airplane classes, and the number of operational weights that are required within each class to represent all airport operations influence the accuracy of the calculated contours. Typically, many airports might be represented by as few as five classes of airplanes with two or three weights in each class, e.g., one class might be three-engine narrowbody jet transports having low-bypass-ratio turbofan engines with corresponding weights for short-range, medium-range, and long-range operations. If substantially different operational procedures are used within an airplane class, each procedure should be separately represented. The time of day of each occurrence will also be required if a weighting penalty for nighttime operations is included as in calculations of day-night average sound level (DNL).

A representative airplane for each class may be selected and the flight performance and noise data for that specific airplane used to represent all airplanes in that class. For each airplane class, a representative airplane takeoff gross weight may be selected for each range of operations by the following procedure. First, calculate the sound exposure levels at a selected location along the extended runway centerline for at least three representative takeoff gross weights. Second, determine the average of the calculated sound exposures, i.e., the "energy" average of the individual sound exposure levels. Third, determine the takeoff gross weight which

3.8 (Continued)

would produce that average sound exposure level and use that weight to define the takeoff gross weight of the representative airplane for the class. The takeoff gross weight of the resultant representative airplane by this process will be greater than the arithmetic average of the three assumed representative takeoff gross weights.

Developing contours of cumulative noise levels around a typical airport may require computing the average sound level at 2000 to 6000 (or more) positions in the vicinity of the airport. The extensive amount of calculations and record keeping involved is amenable to machine computation and computer programs are available for such purposes. Although different computer programs may use different approaches to perform the required calculations, use of the procedures recommended in this AIR for specifying airplane performance and noise should minimize differences in the computation of average sound levels by different computer programs.

Recommended sound level measures for use in representation of cumulative noise contours are provided in Appendix D. Appendix E presents a worked example of the calculation at four representative locations. Appendix F discusses the estimated accuracy of cumulative sound level predictions.

4. REFERENCES:

1. "American National Standard Sound Level Descriptors for Determination of Compatible Land Use," ANSI S3.23-1980; Standards Secretariat, Acoustical Society of America, New York, NY 10017 (1980).

2. "Acoustics - Description and Measurement of Environmental Noise - Part 1: Basic Quantities and Procedures," International Standard ISO 1996/1 - 1982, International Organization for Standardization (1982).

3. "Prediction Method for Lateral Attenuation of Airplane Noise During Takeoff and Landing," Aerospace Information Report AIR 1751, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096 (1981).

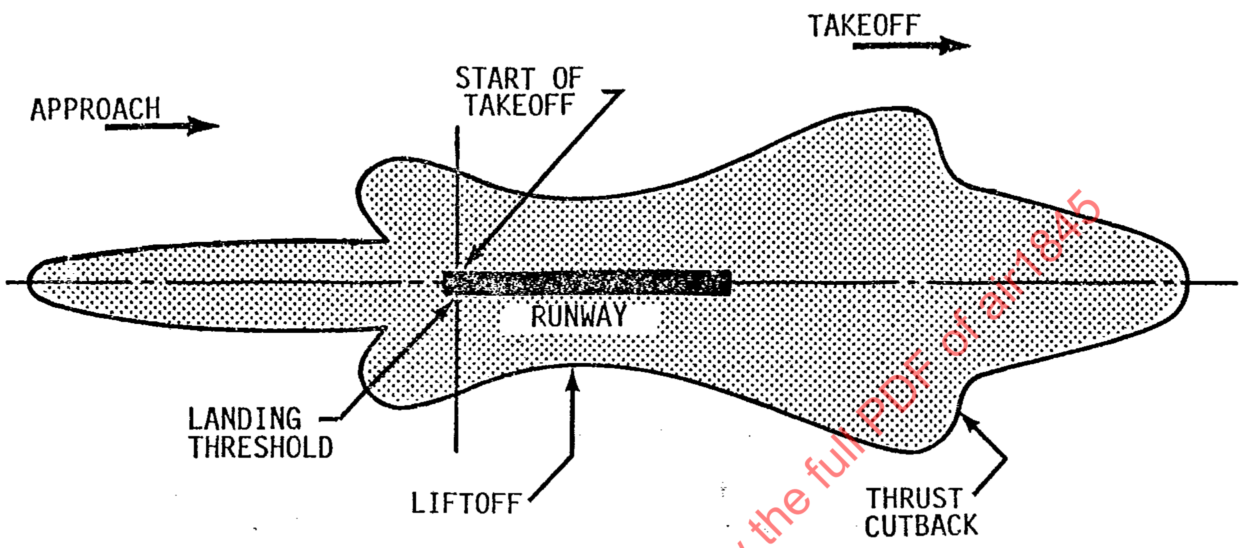


FIGURE 1. SOUND EXPOSURE LEVEL CONTOUR FOR A SINGLE EVENT (TAKEOFF AND APPROACH) OPERATION

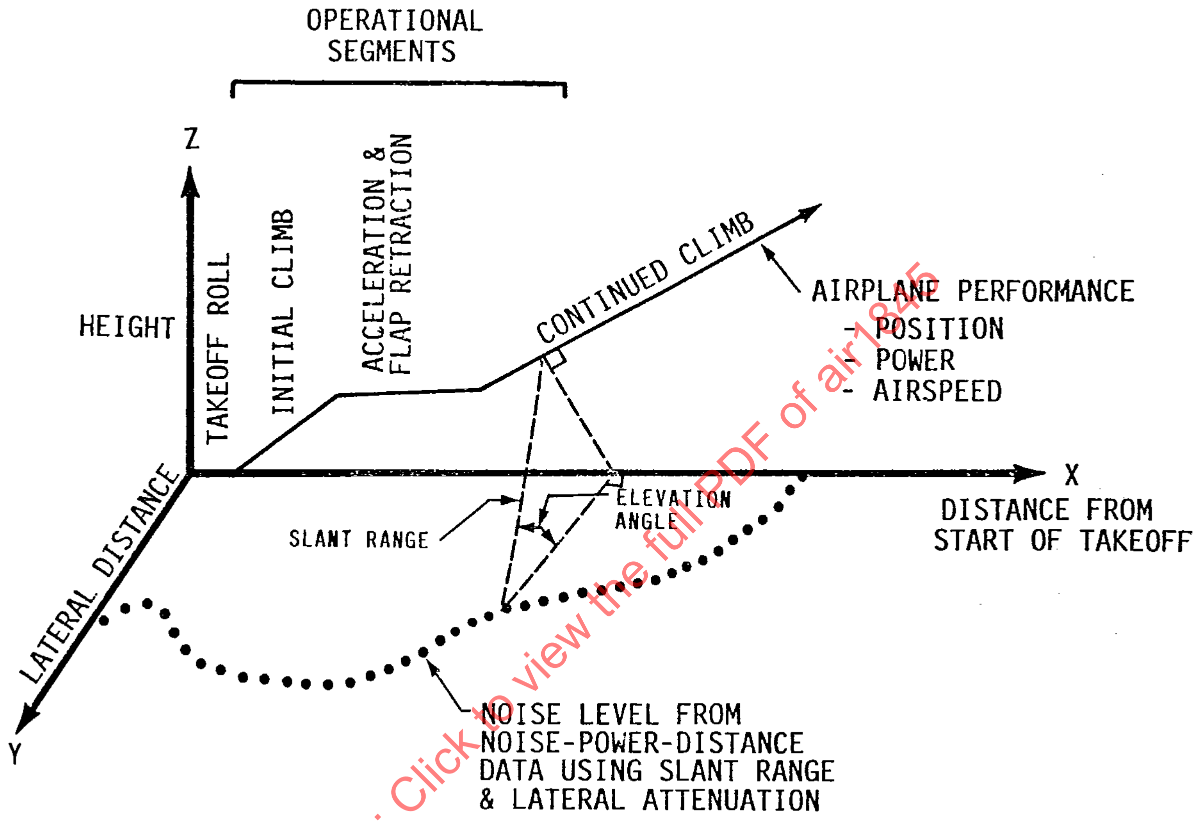


FIGURE 2. NOISE COMPUTATIONAL SCHEME

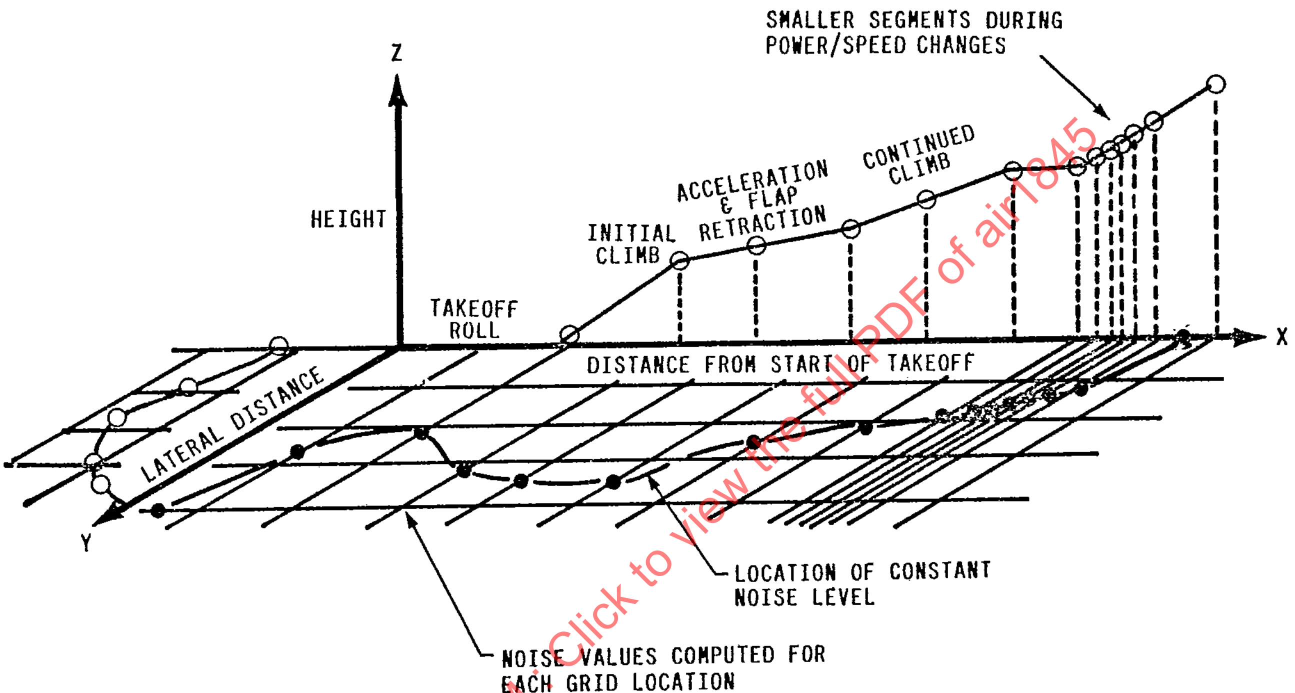


FIGURE 3. SCHEMATIC OF NOISE COMPUTATION DURING TAKEOFF GROUND ROLL AND CLIMBOUT

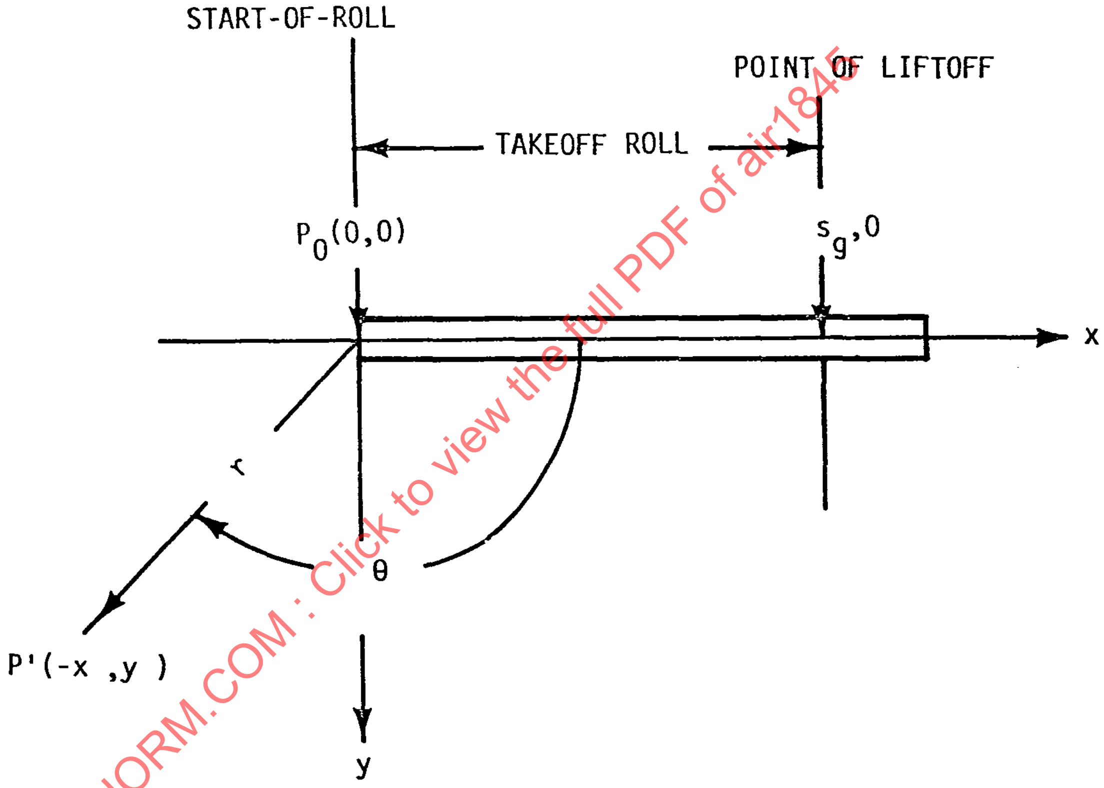


FIGURE 4. GEOMETRY FOR CONSTRUCTION OF TAKEOFF ROLL SEL CONTOURS

APPENDIX A

AIRPLANE AERODYNAMIC AND ENGINE DATA

A.1 Introduction: This Appendix presents recommendations for procedures to determine the airplane-specific data that are required to define an airplane's aerodynamic performance along takeoff and approach flight paths. The aerodynamic-performance data determined by the procedures described in this Appendix and the acoustical data determined by the method described in Appendix B constitute the basic input data required for computing contours of airplane noise levels in the vicinity of an airport.

Takeoff and approach flight paths are represented by a series of straight-line segments. (The ground track of the airplane is represented by straight line segments and arcs of circles.) The method is comprised of a few aerodynamic and thrust equations containing coefficients and constants which must be available for each specific combination of engine and airplane.

To make use of the equations, one must specify (1) airplane gross weight, (2) the number of engines, (3) air temperature, (4) runway elevation, and (5) the flight schedule (thrust settings, flap deflections, airspeed, and average rate-of-climb during the acceleration segments of the climbout) that is to be followed during takeoff or approach.

Aerodynamic-performance parameters calculated by the recommended method provide an accurate representation of an airplane's actual flight path for the computational reference conditions of Section 2.3 of the AIR. The equations also permit the calculation of aerodynamic-performance data for conditions other than reference for airplane weight, wind speed, air temperature, and runway elevation (air pressure), with sufficient accuracy for computing contours of average sound levels around an airport.

Appendix E provides a worked example of the calculation of a departure flight path for a jet transport airplane to illustrate application to noise calculations. The example illustrates the format by which the aerodynamic-performance data should be assembled for each segment of the flight path.

Coefficients and constants used in the equations have units which must be consistent with the units of the corresponding parameters in each equation. Separate sets of equations are provided to determine the net thrust produced by jet engines and by propellers. Unless noted otherwise, the equations for the aerodynamic performance of an airplane apply equally to jet and propeller-powered airplanes.

A.2 Engine Thrust: The value of the corrected net thrust (F_n/δ_{am}) produced by each engine is one of the four quantities that need to be specified at each end of a flight path segment. Net thrust represents the component of engine gross thrust that is available for propulsion. For aerodynamic and acoustical calculations, the net thrust is referred to standard air pressure at mean sea level.

A.2 (Continued)

The net thrust will be determined either by the net thrust available when operating at a specified engine rating, or by the net thrust that results when the thrust-setting parameter is set to a particular value. For turbojet and turbofan engines, corrected net thrust should be provided, either in the form of graphs showing the effects of velocity, altitude and temperature, or defined by an equation having the general form

$$(F_n/\delta_{am}) = E + FV_c + Gh + HT_{am} \qquad \text{(A1)}$$

where

F_n is the net thrust per engine;

δ_{am} is the ratio of the ambient air pressure at the airplane to the standard air pressure at mean sea level, i.e., to 101.325 kPa or 1013.25 mb for air pressure in kilopascals or millibars. (see Refs. A-1 or A-2 in Section A.12)

V_c is the calibrated airspeed;

h is the pressure altitude (height) above sea level at which the airplane is operating;

T_{am} is the ambient air temperature in which the airplane is operating, and

E,F,G and H are constants or coefficients which must be determined for a particular engine at the thrust ratings used by the airplane along various segments of the takeoff/climbout or approach flight path.

All terms in the equation will not always be necessary. For example, for rated thrust, when the air temperatures are within the envelope defined in Section 2.4 of the AIR, the temperature term may not be required since most jet engines maintain rated thrust to an air temperature of approximately 30°C. For engines not flat rated, ambient temperature must be considered in designating rated thrust.

When the engines are being operated at thrusts other than rated thrust, the thrust developed is a function of the thrust-setting parameter. Equation (A1) for net thrust has the following form when engine pressure ratio (EPR) is used to set thrust:

$$(F_n/\delta_{am}) = E + FV_c + Gh + HT_{am} + K_1(EPR) \qquad \text{(A2)}$$

Where K_1 is the average slope of the curve expressing the relationship between installed referred net thrust and engine pressure ratio in the vicinity of the engine pressure ratio of interest for the specified airplane Mach number.

A.2 (Continued)

When engine rotational speed is the parameter used by the cockpit crew to set thrust (e.g., the rotational speed of the low-pressure compressor and turbine stages), then Eq. (A2) for corrected net thrust should be replaced by an equation of the form

$$(F_n/\delta_{am}) = E + FV_c + GH + HT_{am} + K_2(N_1/\sqrt{\theta_T}) + K_3(N_1/\sqrt{\theta_T})^2 \quad \text{(A3)}$$

where

N_1 is the engine's low pressure rotor speed;

θ_T is the ratio of the absolute total air temperature at the engine inlet to the absolute standard air temperature at mean sea level, i.e., to 288.15 K for air temperature in kelvins, see Refs. A-1 or A-2;

$N_1/\sqrt{\theta_T}$ is the corrected low pressure rotor speed; and

K_2 and K_3 should be derived from installed engine data encompassing the referred shaft speeds of interest.

Airplane manufacturers will usually have to furnish appropriate values for the constants and coefficients in Eqs. (A1) to (A3). It is recommended that the data used to evaluate the constants and coefficients represent the performance of an average engine when operating under the computational reference conditions of Section 2.3 of the AIR.

For propeller driven airplanes, corrected net thrust per engine should be provided by graphs or calculated by an equation of the form

$$(F_n/\delta_{am}) = (\eta P_P/V_t)/\delta_{am} \quad \text{(A4)}$$

where

η is the propeller efficiency for a particular propeller installation and is a function of propeller rotational speed and airplane flight speed.

V_t is true flight speed.

P_p is installed net propulsive power

A secondary equation should be provided to relate P_p to the power setting parameters used in the cockpit, such as engine rotational speed and manifold pressure for reciprocating engines, or engine rotational speed and torque for turboprop engines.

NOTE: The foregoing discussion assumes that the equations for the various thrust ratings and the general relationship to the engine setting parameter, all yield net thrust directly. Alternatively, only the general relationship Eq. (A2) or (A3) could be provided and other equations used to define the limiting values of the engine setting parameters at the various rated thrusts.

True airspeeds may be approximated from equivalent or calibrated* (or indicated) airspeeds by making use of the relationship

$$V_t = V_c/\sqrt{\sigma_{am}} \quad \text{(A5)}$$

where σ_{am} is the ratio of the density of the ambient air at the airplane's pressure altitude to the standard density of air at mean sea level. The density ratio σ_{am} also equals δ_{am}/θ_{am}, see Eq. (A6).

A.3 Vertical Profiles of Air Temperature, Pressure, and Density: For the purpose of this AIR, the variation of temperature, pressure and density with height above mean sea level is assumed to be equal to the standard conditions of Refs. A-1 or A-2 for an International Standard Atmosphere.

A.4 Takeoff Ground Roll: During takeoff, an airplane uses a specified takeoff-rated thrust to accelerate along the runway until liftoff. Airspeed is assumed to be constant throughout the initial part of the climbout. Landing gear, if retractable, are assumed to be retracted shortly after liftoff.

For the purpose of this AIR, the actual takeoff ground-roll is approximated by an equivalent ground-roll distance, s_g, defined as shown in Fig. A1, by the distance along the runway from the start of takeoff roll to the point where a straight line extension of the initial landing-gear-retracted climb flight path intersects the runway.

For computation purposes, the equivalent takeoff ground-roll distance, with zero degree runway slope, is determined from

$$s_g = B\theta_{am}(W/\delta_{am})^2/[N(F_n/\delta_{am})] \quad \text{(A6)}$$

where

B is a coefficient appropriate to a specific airplane/flap-deflection combination for the reference conditions of Section 2.3 of the AIR, including the 8-knot headwind.

W is airplane gross weight at brake release.

N is the number of engines supplying thrust.

F_n is the net thrust calculated for the airspeed and engine power settings used during initial climbout.

δ_{am} and θ_{am} represent the ratios of the ambient air pressure and temperature to the standard-day sea level values, respectively.

NOTE: Since Eq. (A6) accounts for variation of thrust with airspeed and runway elevation, the coefficient B for a given airplane varies only with flap deflection.

*Calibrated and equivalent airspeed are used interchangeably for the purpose of this AIR.

A.5 Initial Climb: The airplane is assumed to have an initial-climb airspeed which has a consistent relationship to fundamental aerodynamic lifting capability and hence to brake release gross weight. The recommended equation for calculating the calibrated initial climb airspeed is

$$V_C = C\sqrt{W} \qquad (A7)$$

where

C is a coefficient appropriate to the flap setting.

W is brake release gross weight.

When the airplane climbs with a given configuration, flap setting, and calibrated airspeed into an 8-knot headwind, the average geometric climb angle γ (see Fig. A1) should be determined from

$$\gamma = \arcsin(1.01 \left\{ [N(F_n/\delta_{am})_{avg}/(W/\delta_{am})_{avg}] - R \right\}) \qquad (A8)$$

where

the factor of 1.01 accounts for the increased climb gradient associated with the 8-knot headwind and the acceleration inherent in climbing at a reference climb equivalent airspeed of 160 knots.

and

R is the nondimensional ratio of the airplane's drag coefficient to lift coefficient for a given flap setting and airplane configuration. The landing gear is assumed to be retracted.

The average net thrust, $(F_n/\delta_{am})_{avg}$, should be the average of the net thrusts at the beginning and end of the flight-path segment or the mid-segment value. The ambient pressure ratio to use with the airplane gross weight, $(W/\delta_{am})_{avg}$, should correspond to the pressure altitude that is the average of the pressure altitudes at the beginning and end of the climb segment.

The distance along the ground track, s_c, that the airplane traverses, while climbing at angle γ to a specified increment in pressure altitude, Δh, above the runway elevation should be calculated from

$$s_c = \Delta h/\tan\gamma \qquad (A9)$$

A.6 Acceleration and Flap Retraction (See Figure 3 for Illustration): Departure flight paths generally include a segment, after the initial climb segment, where the airplane accelerates to an airspeed great enough to permit retraction of the flaps.

A.6 (Continued)

The horizontal, or ground-track, distance, s_a, traversed while accelerating from an initial true airspeed V_{ta} to a final airspeed V_{tb}, and while climbing at a specified average true vertical speed or average rate-of-climb V_{tz}, should be calculated from

$$s_a = \frac{(1/2g)\,(0.95)\,(V_{tb}^2 - V_{ta}^2)}{[N(F_n/\delta_{am})_{avg}/(W/\delta_{am})_{avg}] - R_{avg} - (V_{tz}/V_{tavg})} \quad \text{(A10)}$$

where

g is acceleration caused by gravity for free fall at mean sea level*.

The nondimensional factor of 0.95 represents the headwind effect on the ground-track distance when climbing at the 160 knot reference airspeed into an 8-knot reference headwind.

and

(F_n/δ_{am})avg, (W/δ_{am})avg, R_{avg}, and V_{tavg} are averages between the values applicable to the conditions and heights at true airspeeds V_{ta} and V_{tb}.

NOTE: V_{tz} should be an average rate-of-climb during the acceleration from V_{ta} to V_{tb} in order to preserve the approximation of the flight-path segment as a straight line instead of a curve. If the airplane configuration remains constant as the airplane accelerates from V_{ta} to V_{tb}, the drag-to-lift ratio R may be considered to remain constant.

The units for V_{ta}, V_{tb}, and g must be consistent with those for s_a. For example if s_a is in meters, g should be in m/s^2 and V_{ta} and V_{tb} should be in m/s. If s_a is in feet, g should be in ft/s^2 with V_{ta} and V_{tb} in ft/s. Suitable conversion factors may be required for other units such as knots for airspeed. Conversion factors may also be required to ensure a nondimensional ratio for (V_{tz}/V_{tavg}) in the denominator of Eq. (A10).

At the beginning of the acceleration, the airplane's pressure altitude is known because it is the same as that at the end of the previous segment. Thus, the values for δ_{am} and σ_{am} are also known at the beginning of the acceleration segment. The pressure altitude, and hence δ_{am} and σ_{am}, at the end of the acceleration segment is unknown. As a consequence, it is necessary to provide an estimate of the pressure altitude at the end of the acceleration segment in order to supply corresponding estimates for δ_{am} and σ_{am}. The calculated height gain is then to be compared against the estimated height gain to determine if a second iteration is needed to improve the accuracy of the calculation.

*Recommended values for g are 9.807 m/s^2 or 32.17 ft/s^2.

A.6 (Continued)

The gain in height, Δh, relative to the height at the beginning of the acceleration, is calculated from

$$\Delta h = (s_a V_{tz}/V_{tavg})/0.95 \quad \text{(A11)}$$

If the calculated height gain is within 10 percent of the estimated height gain, the calculated height gain is considered sufficiently accurate. If the calculated height gain is not within 10 percent of the estimated height gain, another iteration should be performed using the calculated height gain as a replacement for the initially estimated height gain.

A.7 Continued Climb After Acceleration and Flap Retraction: Additional climb segments at constant calibrated airspeed and constant airplane configuration may be calculated by making use of a modified form of Eq. (A8). The modification consists of a reduction in the magnitude of the constant in the argument of the arcsin. The value of the constant should be reduced because the effects of acceleration associated with climb at constant calibrated airspeed instead of constant true airspeed are different at the higher airspeeds typically flown after gear retraction. When deriving the equation, the calibrated airspeed during climb after flap retraction was assumed to be 250 knots because that speed is the limiting airspeed in controlled air space at less than 10,000 ft (3000 m) of pressure altitude.

With this assumption the geometric climb angle for continued climb after flap retraction is defined by.

$$\gamma = \arcsin\left(0.95\left\{[N(F_n/\delta_{am})_{avg}/(W/\delta_{am})_{avg}] - R\right\}\right) \quad \text{(A12)}$$

The average corrected net thrust is to be determined at the average pressure altitude for the segment. The value of the net thrust and the ratio R should be determined for the calibrated airspeed and airplane configuration appropriate for the segment.

A.8 Additional Acceleration Segments After Flap Retraction: If additional acceleration segments are included in the climbout flight path, Eqs. (A10) and (A11) should be used again to calculate the ground-track distance, average climb angle, and height gain. An iteration may again be needed to ensure that the calculated height gain is within 10 percent of the estimated height gain.

A.9 Landing Approach: The landing approach calibrated airspeed, V_{CA}, is assumed to be approximately 10 knots more than the reference approach airspeed. That assumption allows the approach airspeed to be related to the landing gross weight by an equation of the same form as Eq. (A7) for the calibrated airspeed during initial climb, namely

$$V_{CA} = D\sqrt{W} \quad \text{(A13)}$$

where the coefficient D is to be evaluated at a landing flap setting.

A.9 (Continued)

The value of net thrust per engine which is required by the airplane during descent along the approach glideslope may be calculated by solving an equation of the form of Eq. (A8) for a given landing weight and a drag-to-lift ratio R appropriate for the flap setting with landing gear extended. The flap setting should be that typically used in actual operations. During landing approach, the geometric glideslope descent angle may be assumed to be constant. For jet-powered and multi-engine, propeller-powered airplanes, angle γ is typically minus 3 degrees. For single-engine, propeller-powered airplanes, angle γ is typically minus 5 degrees.

As for the continued-climb segments of Section A.7, the constant in Eq. (A8) is modified to account for the deceleration inherent in flying a descending flight path into an 8-knot reference headwind at the constant calibrated airspeed calculated by Eq. (A13). The form of the equation to use to relate the glideslope descent angle to airplane and engine parameters is

$$\gamma = \arcsin \left(1.03 \left\{ [N(F_n/\delta_{am})_{avg}/W/\delta_{am})_{avg}] - R \right\} \right) \quad \text{(A14)}$$

Equation (A14) can be solved for the average net thrust to yield

$$(F_n/\delta_{am})_{avg} = (1/N)(W/\delta_{am})_{avg} \left\{ R + [(\sin\gamma)/1.03] \right\} \quad \text{(A15)}$$

Equation (A15) may also be used to calculate the net thrust required by the airplane to maintain nominally level flight (γ = zero) with flaps deflected and landing gear extended.

A.10 <u>Adjustments for Headwinds:</u> A headwind other than the 8-knot reference headwind will affect the equivalent takeoff ground-roll distance, s_g, the initial climb angle, y, the ground-track distance traversed while accelerating, s_a, and the average net thrust during landing approach, $(F_n/\delta_{am})_{avg}$.

If the quantities calculated by the equations for the 8-knot reference headwind are denoted by an additional subscript r for reference, then equations to be used to calculate values appropriate for other than an 8-knot headwind are as follows:

$$s_g = s_{gr}[(V_c - V_w)/(V_c - 8)]^2 \quad \text{(A16)}$$

$$\gamma = \gamma_r[(V_c - 8)/(V_c - V_w)] \quad \text{(A17)}$$

$$s_a = s_{ar}[(\bar{V}_t - V_w)/(\bar{V}_t - 8)] \quad \text{(A18)}$$

$$(F_n/\delta_{am})_{avg} = (F_n/\delta_{am})_{avg,r} + [1.03(W/\delta_{am})_{avg}(8-V_w)/V_{CA}] \sin \gamma/N \quad \text{(A19)}$$

In Eqs. (A16) to (A19), the calibrated airspeed, V_c, and the speed of the headwind, V_w, have units of knots for consistency with the use of the 8-knot reference headwind.

A.10 (Continued)

The calibrated airspeed to use in Eqs. (A16) and (A17) is the initial-climb airspeed. In Eq. (A18), use the average of V_a and V_b to represent the true airspeed V_t. For Eq. (A19), use the landing-approach airspeed calculated from Eq. (A13).

A.11 Procedure for Evaluating B, C, D, R, and the Thrust Parameters: The coefficients B, C, D and the ratio R should be evaluated for each specific model of an airplane, generally by the manufacturer. The evaluation should be performed for the reference conditions and takeoff and approach gross weights defined in Section 2.3 of the AIR.

To derive airplane specific coefficients the following steps are recommended:

1) Extrapolate the initial landing-gear-retracted climbout flight path back to the ground plane (see Fig. A1) to determine the equivalent takeoff ground-roll distance, s_g, for the reference takeoff gross weight, reference airplane configuration, and reference initial-climbout calibrated airspeed.

2) Calculate the net thrust available by making use of Eq. (A1), or its variants, for the reference value of initial-climbout calibrated airspeed.

3) Knowing reference values for s_g, θ_{am}, (W/δ_{am}), and (F_n/δ_{am}), calculate coefficient B from Eq. (A6).

4) Knowing the initial climbout calibrated airspeed and the reference take-off gross weight, calculate coefficient C from Eq. (A7).

5) Knowing the landing-approach calibrated airspeed for the reference landing weight at the reference airplane configuration, calculate coefficient D from Eq. (A13).

6) Values for ratio R may be calculated from the equations for the average geometric flight-path angles during initial climb, Eq. (A8), continued climb, Eq. (A12), and landing approach, Eq. (A14), when values for all other quantities are known. Alternatively, values for ratio R may be obtained from aerodynamic data as the effective ratio of drag coefficient to lift coefficient for specified airspeeds and airplane configurations under the reference conditions of Section 2.3.

7) The constant and the coefficients in the equations for net thrust per engine at any power setting should be evaluated as follows:

   a) The speed-dependent coefficient, F, should be evaluated as the ratio of the change in net thrust to a change in airspeed when altitude (or height) and air temperature are held constant.

A.11 (Continued)

b) The height-dependent coefficient, G, should be evaluated as the ratio of the change in net thrust to a change in height when airspeed and air temperature are held constant.

c) The temperature-dependent coefficient, H, should be evaluated as the ratio of the change in net thrust to a change in air temperature when airspeed and pressure altitude are held constant.

The terms in the equations giving the relation between referred net thrust and engine power setting parameters should be evaluated in a similar manner. Airplane, or engine, manufacturer's data will usually be required.

A.12 References:

A-1. Manual of ICAO Standard Atmosphere, Document Number 7488, 1964.

A-2. U.S. Standard Atmosphere, 1976. National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, United States Air Force; U.S. Government Printing Office NOAA-S/T 76-1562 (October 1976).

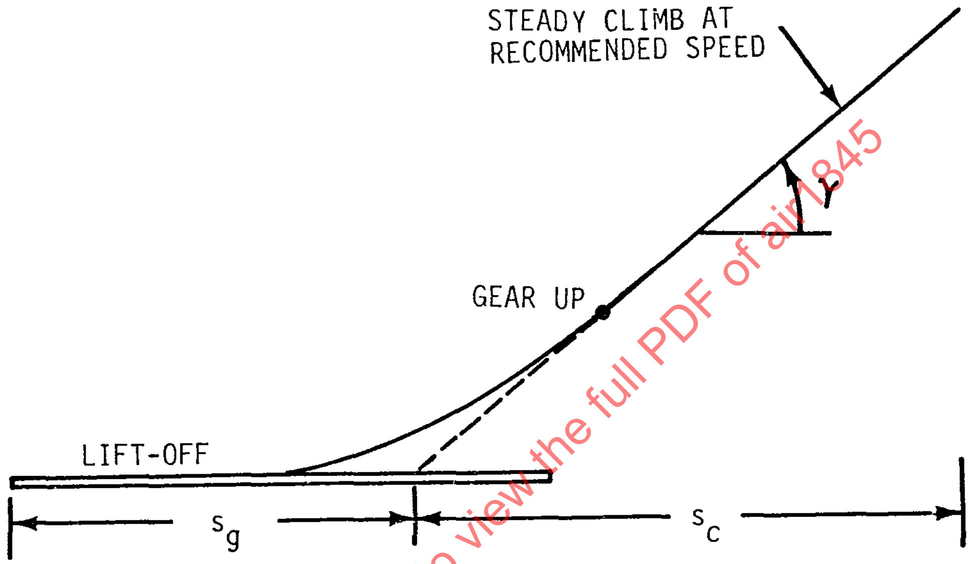


Figure A1. - Illustration of Equivalent Takeoff Ground Roll Distance, s_g.

APPENDIX B

AIRPLANE SOUND LEVELS

This Appendix describes the development of generalized relationships for the dependence of sound exposure level on minimum distance to the flight path and engine power setting, i.e., the Noise-Power-Distance (NPD) data needed to calculate noise levels at locations around an airport for operations by individual airplanes. Sound exposure levels, determined in accordance with the procedures recommended in this Appendix, are based on 1/3-octave-band sound pressure levels that have been adjusted to reference meteorological conditions, airspeed, and engine power setting.

B.1 Reference Sound Pressure Levels: Whenever possible reference acoustical data should be based on the results of tests conducted under controlled conditions and should be comparable in quality to acoustic data acquired for aircraft noise certification purposes [B-1,B-2]*. During controlled flyover noise tests, the position of the airplane along the flight path is measured and synchronized with the sound recordings. The airplane's engine power setting, flap deflection, gear position, and airspeed are maintained at nominally constant values throughout the duration of each sound recording. Meteorological conditions of the atmosphere are sampled at sufficient intervals and heights to establish the atmospheric conditions over the sound transmission path for each sound recording. The terrain around the microphones is flat and unobstructed to the extent that the sound from the airplane is not significantly influenced. When measuring airplane sound levels, the airplane's flight path may be nominally level, have a constant climb angle or a constant descent glideslope.

For the computation of sound exposure level, measured sound data are analyzed as 1/3-octave-band sound pressure levels in decibels relative to a reference pressure of 20 micropascals. Sound pressure levels are obtained, for the 24 1/3-octave-bands with center frequencies ranging from 50 to 10,000 Hz, at 0.5 second intervals throughout the duration of each flyover sound recording. The measured 1/3-octave-band sound pressure levels are corrected for instrument calibrations and background noise contamination.

The corrected sound pressure levels are then adjusted to account for differences between the atmospheric absorption losses that occurred during the test and the losses that would have occurred if the meteorological conditions aloft had been such as to yield the attenuation rate coefficients of Table B1 which was taken from Reference B-3. Atmospheric absorption coefficients applicable to the meteorological conditions prevailing at the time of the test should be obtained from Reference B-4. The number of 0.5-second data samples to which to apply the atmospheric-absorption adjustments and the specification of sound propagation pathlengths depends on the type of data available and the data-analysis procedure, see Sections B.3, B.4, and B.5.

*References for Appendix B are given in Section B.8.

B.1 (Continued)

For many jet and propeller driven airplanes, the preferred nominal height above ground level for noise measurements is of the order of 300 m (1000 ft) for each engine power setting. However, the actual height during a flyover noise test is often different for each airplane type and may range from 100 m (330 ft) to 800 m (2625 ft). This range of heights encompasses those normally encountered in noise certification compliance demonstrations.

B.2 Sound Exposure Level: Sound exposure level [abbreviated by SEL and with the letter symbol L_{AE}] is determined from the integral over time of the square of the instantaneous A-weighted sound pressure. A-weighted sound level in each 0.5 second time interval is obtained from the 1/3 octave band sound pressure levels by applying the A-weighting defined in References B-5 and B-6.

Thus, sound exposure level, SEL, in decibels is determined from

$$L_{AE} = 10 \lg \left\{ \left[\int_{t_1}^{t_2} P_A^2(t)\, dt \right] / P_0^2 t_0 \right\} \tag{B1}$$

where $p_A^2(t)$ is the A-weighted squared sound pressure as a function of time t in seconds, p_0 is the reference sound pressure of 20 micropascals, t_0 is the reference time of one second, and $p_0^2 t_0$ is the reference sound exposure. The time interval from t_1 to t_2 in Eq. (B1) designates the time in seconds, from the beginning to the end of the integration period for the sound produced by the airplane. The duration (t_2-t_1) should be long enough to include all significant contributions to the total sound exposure. Sufficient accuracy is usually achieved by integrating over the time interval during which the A-weighted sound level is within ten decibels of its maximum value. Integration over longer durations than that defined by the 10-dB-down times will, in general, yield sound exposure levels that are no more than 0.5 dB greater than those determined by integrating over the 10-dB-down time interval.

Because 1/3-octave-band sound pressure level data are usually only available at discrete time intervals, the integral in Eq. (B1) is evaluated numerically and approximated by a summation. The limits of the summation from t_1 to t_2 are defined, for the purpose of this document, to correspond to the first and last data-sample times when the A-weighted sound level is at least 10 decibels less than the maximum sound level, i.e., includes, as a minimum, all points within $L_{Amx} - L_A(t) \leq 10$ decibels.

$$L_{AE} = 10 \lg [(1/t_0) \sum_{i=t_1}^{t_2} (10^{0.1 L_A(i)} \Delta t)] \quad \text{(B2)}$$

where t_1 and t_2 are the 10-dB-down times, Δt is the interval between data samples, and $L_A(i)$ is the time-averaged, A-weighted sound level at time i.

B.3 Noise-Power-Distance Data Sets: Measured airplane sound data are normally available for only one distance (height) per engine power setting. Thus, to develop generalized Noise-Power-Distance, NPD, data it is necessary to adjust available data for each power setting to other distances. However, since sufficient test data are not always available to permit sound exposure levels to be determined experimentally for the range of engine power settings and distances needed for airplane noise contours, any of the following four types of data may be used (in order of preference).

Type 1. Measured noise and performance data where spectral data are available for the complete flyover time period of interest.

Type 2. Measured noise and performance data where spectral data are available only for the time of occurrence of the maximum sound level.

Type 3. Noise measurements obtained during normal airport operations where airplane position and performance data are not available as a function of time throughout the duration of a sound recording. Such data, although subject to considerable scatter and airport-specific influences are normally the only type of data available for airplanes manufactured prior to the requirement for noise certification.

Type 4. Noise and airplane/engine performance data derived from analytical estimates. This is normally the only type of data available for projected new type airplanes.

For each of the above four types of data, the sound from the airplane is assumed to be measured, or calculated, at a location that is nominally under the flight path. The following is a broad overview of the procedures recommended for the development of generalized noise-power-distance data using each of the different types of data identified above. Detailed procedures are contained in Sections B4 and B5.

Full Spectrum Time History Data (Type 1):

1. For an initial reference flight path, adjust each 0.5-second set of 1/3-octave-band sound pressure levels by the method described in Section B.1 using sound propagation pathlengths appropriate for the test and reference flight paths and the integrated procedure of Section B.5.

B.3 (Continued)

2. For minimum airplane-to-microphone distances of 800 m or less, establish noise-power-distance relationships at the other minimum distances specified in Table B2 by extrapolating the 1/3-octave-band sound pressure levels at each 0.5 second interval, calculating the A-weighted sound levels, and then computing sound exposure levels for each distance in accordance with the integrated procedure of Section B.5.

3. For a distance of 800 m determine the sound exposure level, L_{AEr}, the maximum value of A-weighted sound level, L_{Amxr}, the 24 1/3-octave-band sound pressure levels, $L_{pr}(j)$ for j = 1,24, and the sound-emission angle, θ_{rei}, corresponding to L_{Amxr}.

4. For distances in Table B2 greater than 800 m, compute L_{Amx} for the adjusted spectral data, using the 800 m data as reference, then determine sound exposure levels by the simplified procedure described in Section B.4.

Spectral Data at L_{Amx} Plus Sound Exposure Level (Type 2):

1. Adjust measured spectral data corresponding to L_{AmxT} by the method described in Section B.1 using applicable test-day and reference-day sound propagation path lengths.

2. For the measured distance, determine the maximum value of A-weighted sound level, L_{AmxT}, and the sound emission angle θ_{ei} corresponding to L_{AmxT}.

3. Use the simplified procedure described in Section B.4 to obtain sound exposure levels for the minimum distances specified in Table B2.

Airport In-Service Sound Measurements (Type 3):

1. Use overhead or minimum distance (as measured by camera or other device) and the best available temperature and humidity information to adjust measured spectral data corresponding to L_{Amx} for atmospheric-absorption losses by the method described in Section B.1.

2. For the measured distance, determine L_{Amx}, the 1/3-octave-band sound pressure levels corresponding to L_{Amx}, and L_{AE}. The reference sound exposure level is computed by applying the incremental difference between reference and test day values of L_{Amx} to the test day sound exposure level. The resultant sound exposure level is identified with the measured minimum distance.

3. Use the simplified procedure described in Section B.4 to obtain sound exposure levels for the minimum distances specified in Table B2.

B.3 (Continued)

Noise Data Derived from Analytical Estimates (Type 4):

1. Follow the procedures for Type 1 data if sufficient spectral and airplane-positio information are provided by the analytical model, otherwise follow the procedures for Type 2 data where spectral and airplane-position information are available only for the time of maximum sound level.

B.4 Simplified Adjustment Procedure: The simplified adjustment procedure is used to calculate SEL at a specified distance different from that at which the airplane sound pressure levels were measured. It is used for Type 1 and Type 4 data at distances greater than 800 m, and for all Type 2 and 3 data calculations.

At the closest approach test distance, d_{Tm} (see Fig. B1 for illustration of geometry) the sound exposure level calculated by use of Eq. (B2) can be written as the sum of the maximum sound level, L_{AmxT}, and an effective duration D_{AET}, as

$$L_{AET} = L_{AmxT} + D_{AET} \tag{B3}$$

At any reference minimum distance, d_{rm}, greater or less than the test minimum distance, Eq. (B3) can be written as

$$L_{AEr} = L_{Amxr} + D_{AEr} \tag{B4}$$

where L_{Amxr} is the maximum sound level obtained by adjustment of the test spectra to the desired minimum distance d_{rm}. D_{AEr} is the corresponding effective duration from Eq. (B6).

Subtracting Eq. (B3) from Eq. (B4) yields

$$L_{AEr} = L_{AET} + (L_{Amxr} - L_{AmxT}) + (D_{AEr} - D_{AET}) \tag{B5}$$

where the test sound exposure level has been adjusted by application of Eq. (3.9) for the effect on duration of differences between test and reference airspeed. Experimental results suggested that the following empirical expression adequately describes the difference in effective duration

$$D_{AEr} - D_{AET} = 7.5 \lg(d_{rm}/d_{Tm}) \tag{B6}$$

The general expression for sound exposure level at any reference minimum distance d_{rm} different from the test minimum distance d_{Tm} is found by combining Eqs. (B5) and (B6) to yield

$$L_{AEr} = L_{AET} + (L_{Amxr} - L_{AmxT}) + 7.5 \lg(d_{rm}/d_{Tm}) \tag{B7}$$

where a method to estimate L_{Amxr} is all that is now required to calculate L_{AEr} since L_{AET}, L_{AmxT}, and d_{Tm} are known.

B.4 (Continued)

For each 1/3-octave-band sound pressure level, the extrapolation procedure is represented by

$$L_{pr}(j) = L_{pT}(j) - 20 \lg (d_{rpi}/d_{Tpi}) - [a_r(j)][d_{rpi} - d_{Tpi}] \quad \text{(B8)}$$

where $L_{pT}(j)$ is a band sound pressure level from the set of 1/3-octave-band sound pressure level measurements at the test distance for some particular engine power setting and airspeed, $a_r(j)$ is the reference atmospheric attenuation rate for the jth 1/3-octave-band center frequency, and d_{rpi} and d_{Tpi} are the reference and test sound propagation distances at the time of maximum A-weighted sound level, respectively. Atmospheric attenuation rates are given in Table B1.

The calculations indicated by Eq. (B8) are performed with the assumption that the sound emission angle at the time of occurrence of the maximum sound level for the test distance does not change with increased distance. With the assumption of a constant sound emission angle, the sound propagation distance can be expressed in terms of the minimum (closest approach) distance d_{Tm} or d_{rm} (see Fig. B1 or B2)

$$d_{Tpi} = d_{Tm} \csc \theta_{ei} \text{ and } d_{rpi} = d_{rm} \csc \theta_{ei} \quad \text{(B9)}$$

giving

$$L_{pr}(j) = L_{pT}(j) - 20 \lg (d_{rm}/d_{Tm}) - [a_r(j)][d_{rm} - d_{Tm}] \csc \theta_{ei} \quad \text{(B10)}$$

The assumption of a constant sound emission angle for the time of occurrence of the maximum sound level is not always valid at distances much larger than the reference distance because atmospheric-absorption effects significantly reduce the high-frequency sound pressure levels at large distances.* Thus the relative time of occurrence of the maximum sound level may change as the distance increases. However, the variation of sound emission angle with distance is taken into account by the empirical correlation used to estimate the duration factor by Eq. (B6).

B.5 Integrated Procedure:

B.5.1 Introduction: The "integrated procedure" is recommended for adjusting measured Type 1 data to reference conditions suitable for developing a noise-power-distance (NPD) acoustical data base.

For the purpose of this AIR, the test airplane's noise signal is assumed to be measured at a location that is nominally under the average test flight path such that the elevation angle, β, at the time of closest approach as defined in Reference B-7, is greater than 60 degrees.

*Note: Sound emission angle, θ_{ei}, must be determined from measured data.

B.5.1 (Continued)

Data required to perform the analyses described in this Section consist of:

(1) 1/3-octave-band sound pressure levels, $L_{pT}(i,j)$, that are time averaged over an appropriate time period and available at 0.5-sec intervals throughout the significant duration of the airplane noise signal;

(2) time, t_i, relative to any suitable reference time, at the midpoint of each averaging time period;

(3) X,Y,Z coordinates, with respect to a reference origin of coordinates, of an airplane reference point on the average test flight path at the midpoint times, t_i, associated with the samples of acoustical data;

(4) location (X_{TM}, Y_{TM}, 0), with respect to the origin of coordinates, of the measurement microphone in the reference X-Y plane and nominally under the test flight path;

(5) temperature and humidity of the air, at the time of the measurement of the airplane noise signal, from near the ground surface to the height of the airplane;

(6) X and Z coordinates, with respect to the same origin of coordinates, of the airplane on an initial reference flight path over the ground track along the X-axis. A reference microphone location is on the ground track at X_{rM},0,0.

Height coordinate Z is measured above a reference X-Y plane that includes the measurement microphone. The height of the measurement microphone above the local terrain should be known, e.g., 1.2 meters. The location of the measurement microphone does not necessarily coincide with that of the reference microphone position. The elevation of the local terrain should be known relative to the elevation of the origin of coordinates.

For the purpose of this AIR, the average test flight path is assumed to be a straight line consistent with the airplane flight paths determined by the methods of Appendix A. The position of the airplane along the average path may be specified, at any time during the period of interest, from time-correlated airplane-position data. Alternatively, airplane-position data may be obtained from a single measurement, such as the minimum or "overhead" distance between the measurement microphone and the airplane at a time correlated with the corresponding time of the acoustical data that are being recorded. The minimum distance and corresponding time are used in conjunction with assumptions for the average straight flight path and average true airspeed along the path to estimate the X,Y,Z coordinates of an airplane reference point at any time during the period of interest.

B.5.1 (Continued)

A-weighted sound levels are computed from each set of 1/3-octave-band sound pressure levels after adjustment to the conditions of the initial reference fight path. The resultant sound levels are numerically integrated over the relevant portion of the flyover time period of interest to arrive at an A-weighted sound exposure level for that engine power setting and minimum distance to the initial reference flight path. The effect of differences in true airspeeds along the test and reference flight paths on the duration of the sound is accounted for by differences in the time intervals between samples of acoustical data.

Sound exposure levels associated with other reference flight paths parallel to the initial reference flight path are obtained by repeating the analysis except that the true airspeed along each path is always the reference airspeed of 160 knots and the speed of sound is always that for an air temperature of 25 C (77 F). The process is repeated for minimum distances to 800 meters to yield sound exposure level in accordance with the format of Table B2 for each engine power setting of interest. The simplified-procedure adjustment method of Section B.4 is applied for minimum distances greater than 800 meters.

The integrated procedure is different from the simplified procedure in three major respects. First, geometric differences between the measured and initial reference airplane flight paths are accounted for throughout the relevant portion of the time history. Second, because of the geometric differences, time intervals between successive samples of adjusted acoustical data are longer, or shorter, than the 0.5-second interval between successive samples of measured acoustical data. Third, differences between effects of atmospheric absorption are accounted for along the sound propagation paths associated with the various positions of the airplane's effective source of sound emission on a reference flight path instead of just along the sound propagation path associated with the maximum A-weighted sound level.

Differences between atmospheric absorption losses associated with test-time conditions aloft and the losses determined from attenuation coefficients of Table B1 are used to calculate the adjustments from the test flight path to the initial reference flight path. Thereafter, adjustments for atmospheric absorption use only the attenuation coefficients of Table B1 and the differences in spherical-divergence over the different sound propagation pathlengths for each sound-emission angle.

Section B.7 contains a description of the symbols for the quantities needed to determine adjustments by the integrated-procedure method.

For the test flight path, the following subsections present the equations needed to determine (1) the minimum microphone-to-flight-path distance, (2) the sound-propagation times, and (3) the sound-emission angles between the average test flight path and the average sound-propagation distances to the microphone. For reference flight paths, the only parameter to be determined is the minimum distance from the reference microphone location to the flight path.

B.5.2 Minimum Microphone-To-Test-Flight-Path Distance: Referring to Figure B1, the distance from the location of the measurement microphone at point K_T to point R_T on the average test flight path is the minimum microphone-to-test-path distance, d_{Tm}.

When airplane-tracking data are used to define the coordinates of points along the average flight path as a function of time, the minimum distance may be calculated from

$$d_{Tm} = [(X_{RT} - X_{TM})^2 + (Y_{RT} - Y_{TM})^2 + (Z_{RT})^2]^{1/2} \qquad \text{(B11)}$$

The (X_{RT}, Y_{RT}, Z_{RT}) coordinates of point R_T may be determined from the general equation for the angle between two lines where one line is the average straight test flight path and the other line is the minimum distance line from K_T to R_T. An initial estimate of the (X_{RT}, Y_{RT}, Z_{RT}) coordinates may be made from the known X_{TM} coordinate of the microphone. Alternatively, time correlated airplane tracking data may be used directly to determine the test-path sound-propagation distances, sound propagation times, and sound-emission times.

B.5.3 Sound-Propagation Times and Sound-Emission Angles for Test Flight Path: When the coordinates, and hence the time, t_{Tm}, for the point on the average test flight path associated with the minimum microphone-to-flight-path distance, d_{Tm}, are established, test-flight-path sound-propagation times, at any data-sample time, t_i, may be computed from

$$\Delta t_{Tpi} = [1/(c_T^2 - V_T^2)] \left\{ BV_T^2 + [(c_T^2 - V_T^2)(d_{Tm})^2 + B^2 c_T^2 V_T^2]^{1/2} \right\} \qquad \text{(B12)}$$

where the time difference B is given by

$$B = t_{Tm} - t_i$$

c_T is the average speed of sound along the sound-propagation path, and V_T is the average true airspeed of the test airplane along the path.

The average speed of sound along the sound-propagation path should be calculated from the average absolute temperature of the air between the surface, T_S, and the neight of the airplane, T_A, i.e., from

$$c_T = [\gamma^* R^*/M_0)(T_S + T_A)/2]^{1/2} \qquad \text{(B13)}$$

Sound-emission angles, θ_{ei}, at points Q_{ei} associated with the samples of acoustical data at times t_i may be determined from the minimum distance and the sound-propagation pathlength, d_{Tpi}, using

$$\sin \theta_{ei} = d_{Tm}/d_{Tpi} = d_{Tm}/[(\Delta t_{Tpi})(c_T)] \qquad \text{(B14)}$$

B.5.3 (Continued)

NOTE: If the engines' average thrust axis or the airplane's pitch angle are not aligned with the average flight path, the average sound-emission angle is different from that computed as recommended above. For the purpose of this AIR, the small effect on the adjustments to the measured sound pressure levels of differences between engine-thrust-axis angle or airplane pitch angle and average-flight-path angle were ignored because the differences would have had negligible effect on the calculated sound exposure levels or on day-night average sound levels.

B.5.4 Minimum Distance to the Reference Flight Path: Figure B2 shows geometry for a reference flight path in the X-Z plane over the reference microphone location at K_r on the reference ground track at $(X_{rM},0,0)$ in the reference X-Y ground plane. The reference flight path is inclined at a specified flight path angle γ_r relative to the horizontal. The airplane flies along the reference flight path at constant true airspeed V_r = 160 knots.

As indicated on Figure B2, sound-emission angles, θ_{rei}, along the reference flight path are assumed to equal the corresponding sound-emission angles, θ_{ei}, along the average test flight path for the corresponding samples of acoustical data. The coordinates of the sound-emission points along the reference flight path may be readily calculated from geometrical considerations.

Since X and Z coordinates along the reference flight path may be specified by an equation, the height, h_{ro}, over the reference microphone location, K_r, may be calculated readily at reference distance X_{rM}. Minimum distance, d_{rm}, from K_r to the reference flight path at point R_r may then be determined from

$$d_{rm} = h_{ro} \cos \gamma_r \tag{B15}$$

B.5.5 Adjustment from the Average Test Flight Path to the Initial Reference Flight Path: For each sample of acoustical data at some sound-emission angle, i.e., for each sample time t_i and corresponding reference time t_{ri}, the test-time sound pressure levels, $L_{pT}(i,j)$, for each of the j-th frequency bands, are adjusted for the difference in spherical-divergence and atmospheric-absorption losses over the test and the initial reference pathlengths by use of the following expression

$$\begin{aligned} L_{pr}(ri,j) &= L_{pT}(i,j) - 20 \lg(d_{rpi}/d_{Tpi}) - \left\{ [a_r(j)]d_{rpi} - [a_T(j)]d_{Tpi} \right\} \\ &= L_{pT}(i,j) - 20 \lg(d_{rm}/d_{Tm}) - \left\{ [a_r(j)]d_{rm} - [a_T(j)]d_{Tm} \right\} \csc \theta_{ei} \end{aligned} \tag{B16}$$

where the test and reference minimum flight-path distances and sound-emission angles are determined as described above. Reference atmospheric attenuation rates, $a_r(j)$, as a function of nominal band-center frequency j, are given in Table B1. Test atmospheric-absorption coefficients, $a_T(j)$, are given in Ref. B-4 as a function of air temperature, relative humidity, and nominal band-center frequency j.

B.5.5 (Continued)

To minimize the magnitude of the adjustments from test to reference conditions, it is recommended that the initial reference minimum distance be selected from those in Table B2 and be close to, and larger than, the test minimum distance, for example, select 125 meters if the test distance was 120 meters or select 315 meters if the test distance was 300 meters.

NOTE: Measured test-day sound pressure levels to be adjusted to reference conditions by Eq. (B16) should be checked to ensure that they are free of contamination from background noise. After the adjustment, sufficient inspection of the spectra is recommended to make sure that neither background acoustic nor electronic noise have resulted in anomalous high frequency spectral shaping.

B.5.6 Reference-Path Sound Exposure Level: After applying the A-frequency weighting from Refs. B-5 or B-6 to the adjusted 1/3-octave-band sound pressure levels to determine A-weighted sound levels for each reference time t_{ri}, the sound exposure level for the initial reference minimum distance is found from

$$L_{AEr} = 10\ lg[(1/t_0 \sum_{i=1}^{n} (10^{0.1\ L_{Ar}(t_{ri})}\ \delta t_{ri})] \qquad (B17)$$

where times t_{ri} through t_{rn} include the first and last 10-dB-down times for the A-weighted sound levels $L_{Ar}(t_{ri})$, and δt_{ri} is the average interval around the time associated with the A-weighted sound level at t_{ri} when the airplane is at position Q_{ri}. The reference time t_0 is one second for sound exposure as given in Eqs. (B1) and (B2).

Because, as shown in Fig. B2, two successive airplane-position reference times, t_{ri} and $t_{r(i+1)}$, occur after the time t_{rei} at the sound-emission point, the average interval of time for the product terms in Eq. (B17) is found from

$$\delta t_{ri} = [\Delta t_{ri} + \Delta t_{r(i-1)}]/2 \qquad (B18)$$

To initiate the summation in Eq. (B17), set $\Delta t_{r0} = \Delta t_{r1}$ so that $\delta t_{r1} = \Delta t_{r1}$. To terminate the summation, assume that $\Delta t_{rn} = \Delta t_{r(n-1)}$ so that $\delta t_{rn} = \Delta t_{rn} = \Delta t_{r(n-1)}$.

B.5.7 Reference Time Interval Δt_{ti}: The interval Δt_{ri} between successive reference times is not equal to 0.5 seconds as it is for the interval between successive samples of acoustical data measured at locations such as those shown on Fig. B1. The reference time interval between samples of A-weighted sound levels is given by

$$\Delta t_{ri} = t_{r(i+1)} - t_{ri}$$

B.5.7 (Continued)

For the test flight path, acoustical-data-sample times, sound-emission times, and sound-propagation times are related by

$$t_i = t_{ei} + \Delta t_{Tpi}; \text{ or } t_{(i+1)} = t_{e(i+1)} + \Delta t_{Tp(i+1)}$$

For reference-path conditions, the difference between successive times may be written as

$$\begin{aligned} \Delta t_{ri} &= [t_{re(i+1)} + \Delta t_{rp(i+1)}] - [t_{rei} + \Delta t_{rpi}] \\ &= [t_{re(i+1)} - t_{rei}] + [\Delta t_{rp(i+1)} - \Delta t_{rpi}] \end{aligned} \quad \text{(B19)}$$

For a reference flight path, Equation (B19) shows that the difference between successive times is the sum of the time for the airplane to travel, at average speed V_r, from one sound-emission point to the next along the reference flight path plus the difference between the sound-propagation times from the sound-emission points to the microphone at K_r. Coordinates of sound-emission points may be determined from geometrical considerations for equal sound-emission angles on the reference and average test flight paths.

The speed of sound, c_r, under reference conditions is that for an air temperature of 298.15 K (25 C or 77 F), i.e., 346.15 m/s (1135.66 ft/s) by Eq. (B13).

Because the average test flight path is assumed to be a straight line and because the sound-emission angle to the reference flight path is the same as the sound-emission angle to the test flight path at corresponding sound-emission points, the interval between two reference times may be calculated from

$$\begin{aligned} \Delta t_{ri} = (d_{rm}/d_{Tm})[(V_T/V_r) \left\{ 0.5 - [\Delta t_{TP(i+1)} - \Delta t_{Tpi}] \right\} \\ + (c_T/c_r)(\Delta t_{Tp(i+1)} - \Delta t_{Tpi})] \end{aligned} \quad \text{(B20)}$$

B.5.8 <u>Adjustment from Initial Reference Flight Path to Other Reference Flight Paths:</u> To adjust the 1/3-octave-band sound pressure levels and hence the A-weighted sound levels and sound exposure levels from the initial reference flight path to any other reference flight path parallel to the initial reference flight path, say to the k-th reference flight path, the sound pressure levels obtained by Eq. (B16) are adjusted to the new reference minimum distance by

$$\begin{aligned} L_{pr}(ri,j,k) = L_{pr}(ri,j,k-1) - 20 \lg[d_{rm}(k)/d_{rm}(k-1)] \\ - [a_r(j)][d_{rm}(k) - d_{rm}(k-1)] \csc \theta_{ei} \end{aligned} \quad \text{(B21)}$$

where only the attenuation rates of Table B1 are needed because the atmospheric conditions are the same for all reference flight paths. See Eq. (B10) for a comparable adjustment by the simplified procedure.

B.5.8 (Continued)

A-weighted sound levels for the k-th reference minimum distance are computed as for the initial reference flight path. The A-weighted sound exposure level for the k-th reference minimum distance is determined by use of Eq. (B17). Because the 160 knot airspeed and the air temperature, hence sound speed, are the same for all reference flight paths, the increment $\Delta t_{ri}(k)$, between corresponding reference times of two A-weighted sound level samples for the k-th path is given by:

$$\Delta t_{ri}(k) = [drm(k)/d_{rm}(1)][\Delta t_{ri}(1)] \qquad \text{(B22)}$$

where $d_{rm}(k)$ is the minimum distance from point K_r to the k-th path

$d_{rm}(1)$ is the minimum distance to the initial reference path, and

$\Delta t_{ri}(1)$ is the time interval by Eq. (B20) for the initial reference path and the same sound emission angle as for $\Delta t_{ri}(k)$.

For each engine power setting of interest, repeat the above process to develop the acoustical data base by extrapolating to the reference minimum distances of Table B1 (i.e., to 800 meters).

NOTE: While the number of samples, n, to include in the summation in Eq. (B17) only needs to include the first and last 10-dB-down times from the maximum A-weighted sound level for the initial reference minimum distance, more than the minimum number of data samples needed to calculate the sound exposure level for the initial reference flight path should be available from the test data to ensure coverage of the 10-dB-down times for the lower sound levels associated with the increasingly longer total spans of time as the minimum distance increases to 800 meters.

B.6 Data Presentation: Sound exposure levels should be calculated and tabulated for a range of closest approach distances to the flight path using the methods of this Appendix for distances as short as 80 meters and for longer distances as required, up to the distance corresponding to a sound exposure level of about 75 dB. If lower values of sound exposure level are required they may be obtained by further extrapolation.

For consistency, all sound exposure levels should be presented to the nearest 0.1 dB.

Table B2 illustrates the general format preferred for presentation of sound exposure level data for a particular airplane as a function of closest approach distance for various values of the thrust-related, engine-power setting parameter.

The thrust-related engine-power-setting parameter shown as the parameter for the sound exposure level data in Table B1 should be one of the following, as appropriate:

(1) Corrected net thrust per engine, F_n/δ_{am}, in kilonewtons (kN) or pounds force (lbf);

B.6 (Continued)

(2) Corrected low-pressure shaft speed per engine, $N_1/\sqrt{\theta_T}$, in revolutions per minute or percent;

(3) Corrected shaft power applied to a propeller, $SP/(\delta_{am}\sqrt{\theta_T})$ in kilowatts (kW) or horsepower, at a stated propeller speed;

(4) Any other power-setting parameter used for specific engine model.

The quantities used to normalize the above parameters are defined by:

(1) The ambient pressure ratio

$$\delta_{am} = P_{am}/P_{am,std}$$

where P_{am} is the ambient or atmospheric pressure, in kilopascals, at the height of the airplane and $P_{am,std}$ = 101.325 kPa.

(2) The temperature ratio

$$\theta_T = T_T/T_{am,std}$$

where T_T is the absolute total air temperature in kelvins at the fan inlet and $T_{am,std}$ = 288.15 K.

B.7 Nomenclature for Section B.5, Integrated Procedures:

NOTE: Subscript r for reference conditions; subscript T for test-day conditions.

$a_r(j);a_T(j)$	reference atmospheric attenuation rates from Table B1; average test-day atmospheric absorption coefficients
A	A-frequency weighting
$c_r;c_T$	speed of sound at reference, or average test-day, air temperature
$d_{rm};d_{Tm}$	minimum distance from reference microphone location at K_r to reference flight path at R_r; or from test-day microphone location at K_T to average test flight path at R_T
$d_{rpi};d_{Tpi}$	sound-propagation pathlength at time t_{rei} from sound-emission point Q_{rei} on the reference flight path to the reference microphone location at K_r; or at time t_{ei} from sound-emission point Q_{ei} on the average test flight path to the test-day microphone location at K_T
h_{ro}	height vertically over the reference microphone location at K_r to the reference flight path

B.7 (Continued)

$K_r;K_T$	location on the X-axis for the reference microphone; or on the X-Y plane for the test microphone
$L_{pr}(ri,j)$; $L_{pT}(i,j)$	1/3-octave-band sound pressure levels, for each of the j frequency bands, when the airplane is at Q_{ri} at time t_{ri} on the initial reference flight path over K_r; or when the airplane is at Q_i at time t_i on the average test flight path for measurements at K_T
$L_{pr}(ri,j,k)$	1/3-octave-band sound pressure levels at time t_{ri}, for each of the j frequency bands, when the airplane is at Q_{ri} on any reference flight path over K_r except the initial reference path
$L_{Ar}(t_{ri})$	A-frequency-weighted sound level at reference microphone location K_r at time t_{ri} when the airplane is at Q_{ri} on the reference flight path
L_{AEr}	A-frequency-weighted sound exposure level at reference microphone location K_r for an airplane on a reference flight path at minimum distance d_{rm}
M_o	mean molecular weight of air; 28.9644 kg/kmol
Q_i	a point on the average test flight path where the airplane was at time t_i associated with the middle of the time-averaging period for a sample of airplane noise signal recorded at K_T
Q_{ei}	the point on the average test flight path at the time t_{ei} where the airplane was when it emitted the noise signal associated with sound-emission angle θ_{ei}
Q_{ri}	a point on a reference flight path where the airplane was at time t_{ri} and with the same sound-emission angle between the flight path and the sound-propagation path to K_r as for time t_i on the average test flight path
Q_{rei}	the point on a reference flight path at time t_{rei} where the airplane was when it emitted the noise signal associated with sound-emission angle $\theta_{rei} = \theta_{ei}$
R^*	gas constant: 8314.32 N-m/(kmol-K)
$R_r;R_T$	the point on the reference (or average test) flight path at the time of closest approach to point K_r (or K_T)

B.7 (Continued)

$t_i;t_{ei}$	time, relative to an arbitrary starting time, at the middle of the averaging time period for any set of measured 1/3-octave-band sound pressure levels and also the time when the airplane was at Q_i on the average test flight path; time when the airplane was at sound-emission point Q_{ei} on the average test flight path
t_{Tm}	time, relative to the same starting time as for time t_i, when the airplane was at R_T on the average test flight path
$t_{ri};t_{rei}$	time, relative to an arbitrary starting time, when the airplane was at Q_{ri} on a reference flight path; or when the airplane was at sound-emission point Q_{rei} on a reference flight path
$T_A;T_S$	absolute temperature of the air at the height of the test airplane on the test flight path; or near the ground surface in the vicinity of measurement point K_T
$V_r;V_T$	reference true airspeed of the airplane along the reference flight path (160 knots); or average true airspeed of the test airplane along the average test flight path
X,Y,Z	coordinates of a point relative to a reference origin
X_{ei},Y_{ei},Z_{ei}	coordinates of a point Q_{ei} on the average test flight path
X_{rM},Y_{rM},Z_{rM}	coordinates of reference microphone location K_r ($Y_{rM} = Z_{rM} = 0$)
X_{TM},Y_{TM},Z_{TM}	coordinates of test microphone location K_T ($Z_{TM} = 0$)
X_{RT},Y_{RT},Z_{RT}	coordinates of minimum-distance point R_T on the average test flight path
γ^*	ratio of specific heats: 1.4
γ_r	inclination angle of the reference flight path to the horizontal, positive upwards
$\theta_{ei};\theta_{rei}$	sound-emission angle, at Q_{ei}, from the average test flight path to the sound-propagation path for measurement point K_r; or, at point Q_{rei}, from the reference flight path to the sound-propagation path for reference point K_r

B.7 (Continued)

Δt_{rpi}; Δt_{Tpi} — sound-propagation time at speed c_r along the reference sound-propagation path from Q_{rei} to K_r; or at speed c_T along the test-day sound-propagation path from Q_{ei} to K_T

Δt_{ri} — difference between times $t_{r(i+1)}$ and t_{ri} at successive airplane-position locations on a reference flight path corresponding to the same sound-emission angles relative to the test flight path at times $t_{(i+1)}$ and t_i

δt_{ri} — average of time differences t_{ri} and $t_{r(i-1)}$ and also the average period of time for a sample of A-weighted mean-square sound pressure in a calculation of A-weighted sound exposure level

B.8 References:

B-1 Anon., "Aircraft Noise," International Standards and Recommended Practices, Annex 16 to the Convention of International Civil Aviation, International Civil Aviation Organization, Amendment 2 (1985).

B-2 Anon., "Noise Standards: Aircraft Type and Airworthiness Certification," Part 36 of the Federal Aviation Regulations (Part 36 was first published 1 December 1969; includes changes 1 to 16 with change 16 effective 13 September 1982).

B-3 Appendix A to the report on Agenda Item 3 "Outline of a Standard Method of Computing Noise Exposure Contours," ICAO Committee on Aircraft Noise Seventh Meeting, CAN/7-WP/59, May 1983, Montreal.

B-4 "Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity," Aerospace Recommended Practice ARP 866A, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096 (1975).

B-5 "Sound Level Meters," IEC Standard, Publication 651, International Electro-technical Commission, Geneva, Switzerland (First Edition 1979).

B-6 "American National Standard Specification for Sound Level Meters," ANSI S1.4-1983, Standards Secretariat, Acoustical Society of America, New York, NY.

B-7 "Prediction Method for Lateral Attenuation of Airplane Noise During Takeoff and Landing," Aerospace Information Report AIR 1751, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096 (1981).

TABLE B1.

ATTENUATION COEFFICIENTS
FOR EXTRAPOLATION OF DURATION
ADJUSTMENTS TO SOUND EXPOSURE LEVEL
(Reference B-3)

CENTER FREQUENCY OF 1/3-OCTAVE BAND, Hz	ATTENUATION COEFFICIENT, DECIBELS PER 100 METERS
50	.033
63	.033
80	.033
100	.066
125	.066
160	.098
200	.131
250	.131
315	.197
400	.229
500	.295
630	.361
800	.459
1,000	.590
1,250	.754
1,600	.983
2,000	1.311
2,500	1.705
3,150	2.295
4,000	3.115
5,000	3.607
6,300	5.245
8,000	7.213
10,000	9.836

AIRPLANE: ____________________ LOCATION: Under the Flight Path

ENGINES: ____________________ AIR TEMP: Referenced to Attenuation Rates

REL. HUM: Defined in Table B1

AIRSPEED: 160 Knots

MINIMUM DISTANCE, METERS	SOUND EXPOSURE LEVEL, SEL, dB THRUST-RELATED ENGINE-POWER PARAMETER APPROACH	INTERMEDIATE	TAKEOFF
80			
100			
125			
160			
200			
250			
315			
400			
500			
630			
800			
1000			
1250			
1600			
2000			
2500			
3150			
4000			
5000			
6300			
8000			

NOTE: The number of power settings for which data are to be tabulated depends on the airplane type, except that at least two (approach and takeoff) are required.

TABLE B2. PREFERRED FORMAT FOR PRESENTATION OF SOUND EXPOSURE LEVEL DATA

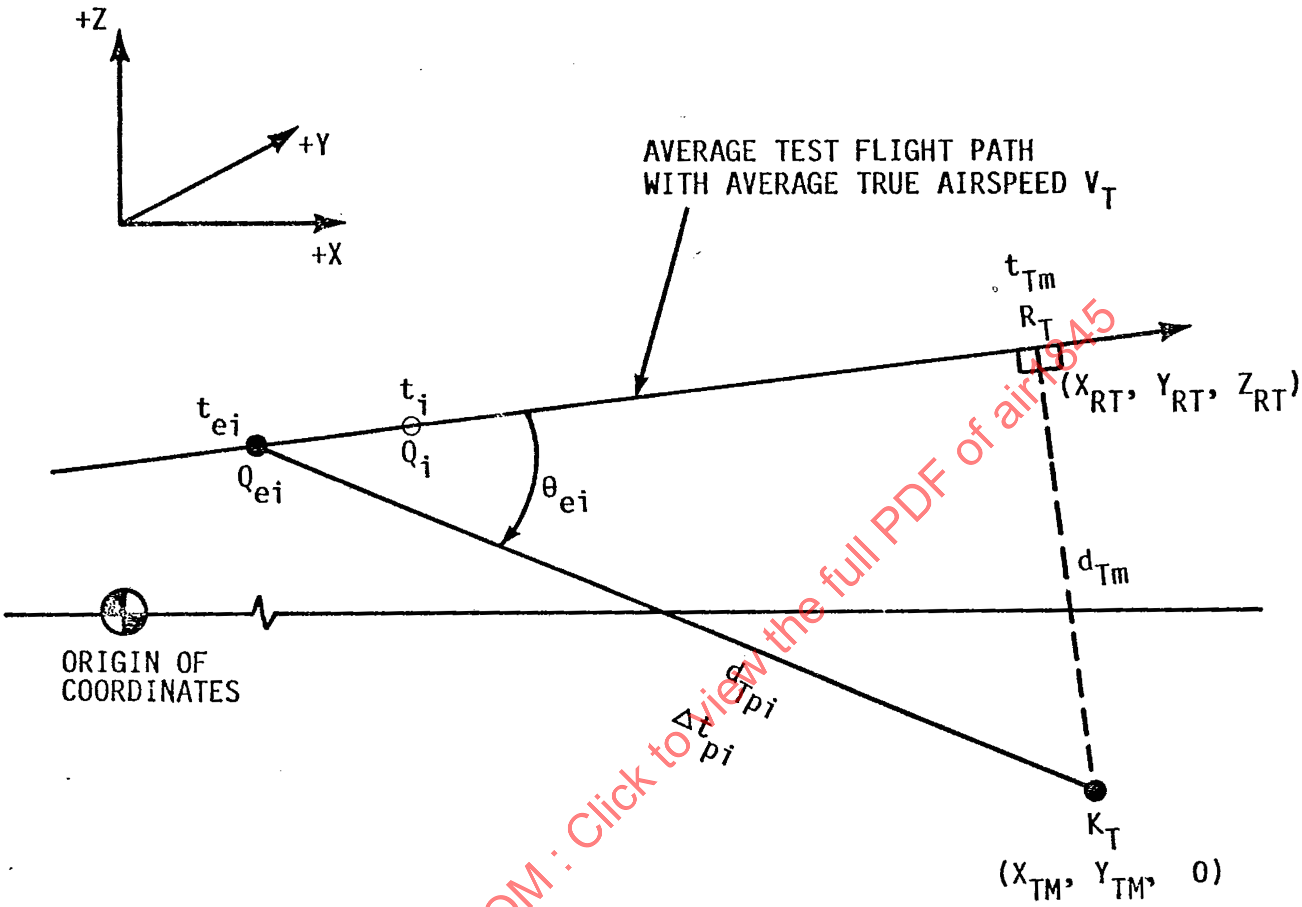


Fig. B1 GEOMETRY FOR TEST MEASUREMENT CONDITIONS USED IN INTEGRATED PROCEDURE.

Note: Sound-propagation distance d_{Tpi} is from sound-emission point Q_{ei}, on the average test flight path at time t_{ei}, to the test-time location of the microphone in the X-Y plane at point K_T. Sound is received at K_T at time t_i when the airplane is at point Q_i. The minimun distance to the flight path, d_{TM}, occurs when the airplane is at point R_T at time t_{Tm}. Sound-propagation time is Δt_{pi} at average sound speed c_T.

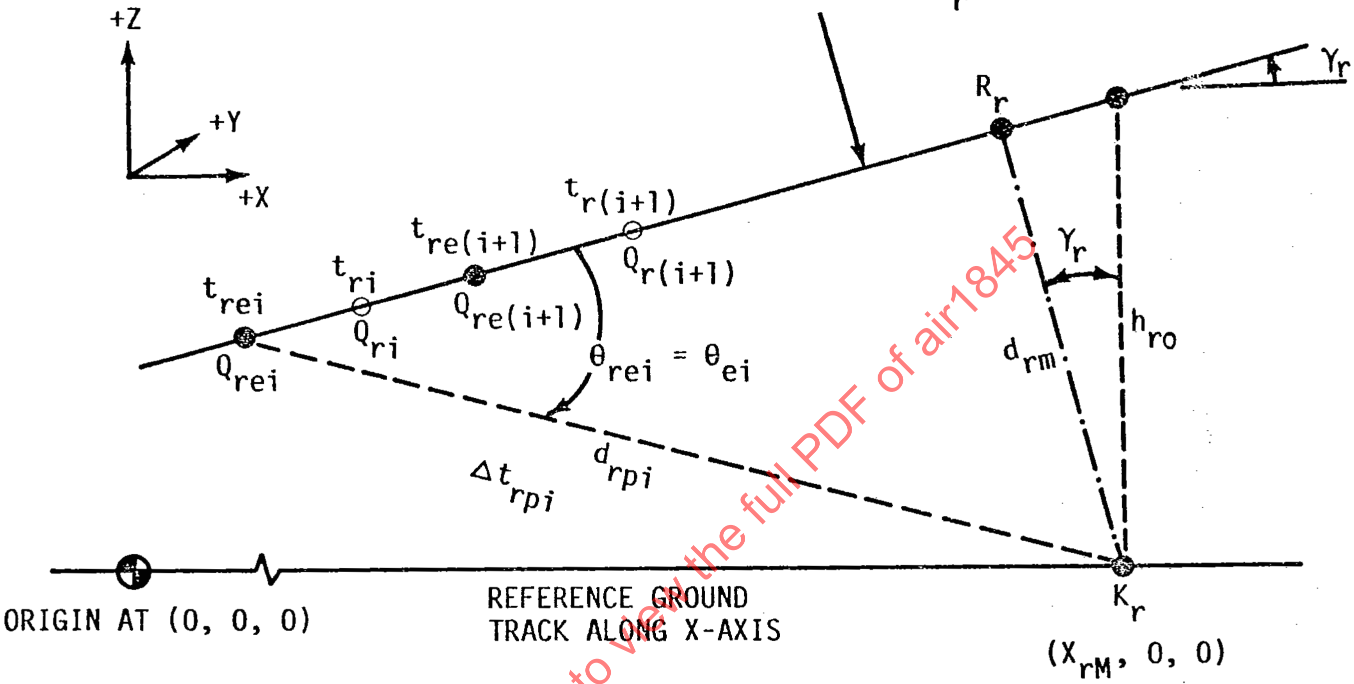


Fig. B2 GEOMETRY FOR FLIGHT REFERENCE CONDITIONS USED IN INTEGRATED PROCEDURE.

Note: Reference microphone location at K_r on reference ground track under reference flight path.

APPENDIX C

DURATION ADJUSTMENT FOR CURVED FLIGHT PATHS

C.1 Introduction: When the airplane's flight path includes a turn, it may be desirable to adjust the noise values derived per the procedures in Appendix B for the change in duration that occurs as a result of the turn. This duration adjustment, Δ_ϕ, to the SEL value accounts for the differences between a straight flight path and a curved flight path for an observer located on the ground and is defined by:

$$\Delta_\phi = 10 \lg(t'/t) \qquad (C1)$$

where t and t' are duration times (corresponding to the times when the sound level is 10 dB less than L_{Amx}) for straight and curved flight paths, respectively. From the above equation a doubling of duration corresponds to an increase of 3 dB in sound exposure level. Procedures to estimate the effect on the duration time, (Refs. C-1 and C-2), and hence on the sound exposure levels, of curved flight paths are often based on approximations derived using equivalent straight line flight paths. One of the approximations is outlined below.

C.2 Circular Segment Approximation of Curved Flight Paths by Straight Line Segments: Circular portions of a ground track may be replaced by an even number of straight line segments, selected so that the length of the segments when summed equals the arc length of the curved flight track. It is desirable to select the arc segments such that no segment exceeds an angle of 30° to limit position error. With this constraint, the maximum position error is 0.02 times the radius of the track, or 180 ft for a radius of 9000 ft. When the equivalent straight line segments are defined, geometric relationships are developed which identify the corresponding coordinates of the curved flight path. The contribution of each segment to the change in duration time and therefore to the sound exposure level is estimated by computing the sound exposure fraction of the segment. The sound exposure fraction for a straight line segment is defined as the sound exposure at an observation position attributed to an aircraft's flight on a finite straight segment divided by the sound exposure that would be observed at the position if the straight segment had infinite length. Its derivation is based on a 90° dipole model which identifies the time history of the sound received at an observation position for the linear segment relative to that received from an airplane flyby on a straight segment of infinite length. The fractional sound exposure increments are then summed yielding values representative of the change in sound exposure level resulting from the flight path curvature. Representative calculations indicate that the duration adjustment, Δ_ϕ, at lateral locations is of the order of 0.5 dB or less for typical operational turns by civil jet transports within approximately 25 percent of the turn radius from the flight track.

C.3 References:

C-1 K. M. Eldred and R. L. Miller, "Analysis of Selected Topics in the Methodology of the Integrated Noise Model," BBN Report No. 4413, June 1980.

C-2 R. E. Cadoux, "Results for the Effect of Turning Flight Tracks on Duration Correction," British Aerospace Acoustic Memo 781, March 1985.

APPENDIX D

CUMULATIVE SOUND LEVEL MEASURE

Compatibility of various land uses with a noise environment is determined by the cumulative effect of the different noise sources contributing to the noise environment. Consistent with American National Standard S3.23-1980, "Sound Level Descriptors for Determination of Compatible Land Use," this AIR recommends day-night average sound level as the acoustical measure for assessing land use compatibility with respect to noise. Since land uses are generally of a long-term, continuing nature the yearly average, day-night average sound level is considered to be an appropriate quantity for planning purposes.

Day-night average sound level, with abbreviation DNL and symbol L_{dn}, is a 24-hour average, obtained after adding 10 decibels to sound levels occurring between 2200 hours and 0700 hours. Although day-night average sound level is use for assessing community noise by all U.S. Federal agencies concerned with airport noise, some state and local agencies may use other forms of average sound level, with different or no adjustments for evening or nighttime operations. Because of the fundamental similarity, the procedures of this AIR may be used for computation of any cumulative measure based on sound exposure level by application of appropriate adjustments for time-of-day.

By definition, average sound level* is the level, in decibels, of the mean-square A-weighted sound pressure during a stated time period, with reference to the square of the standard reference sound pressure of 20 micropascals. Where a noise environment is caused by a number of identifiable noise events, such as a series of airplane operations, average sound level may be calculated from the sound exposure levels of the individual events occurring within a time period T:

$$L_T = 10 \lg \left[(1/T) \sum_{i=1}^{n} 10^{0.1 L_{AE}(i)} \right] \qquad \text{(D1)}$$

where $L_{AE}(i)$ is the sound exposure level of the i^{th} event, in a series of n events in time period T, in seconds.

For an individual event, time-average sound level and sound exposure level are related by:

$$L_T = L_{AE} - 10 \lg (T/t_o) \qquad \text{(D2)}$$

*In the literature, average sound level has also been called "equivalent sound level" or "equivalent continuous sound level" with the alternative letter symbol of L_{eqT}.

When T is 86,400 seconds or 24 hours, representing a daily average sound level, Eq. (D1) becomes:

$$L_{24h} = 10 \lg \left[\sum_{i=1}^{n} 10^{0.1 L_{AE}(i)} \right] - 49.4 \qquad \text{(D3)}$$

where the constant term is from 10 lg (1/86,400).

Equation (D3) is modified to account for the time of day weighting associated with m nighttime flights and n daytime flights in the day-night average sound level calculation as:

$$L_{dn} = 10 \lg \left[\sum_{i=1}^{n} 10^{0.1 L_{AE}(i)} + \sum_{j=1}^{m} 10^{0.1[10+L_{AE}(j)]} \right] - 49.4 \qquad \text{(D4)}$$

Yearly day-night average sound level is defined as:

$$L_{dny} = 10 \lg \left[(1/365) \sum_{i=1}^{365} 10^{0.1 L_{dn}(i)} \right] \qquad \text{(D5)}$$

where L_{dn} (i) is the day-night average sound level for the i^{th} day out of one year. An equivalent alternative computation that is convenient for airport operations is to calculate the yearly-day-night average sound level from Eq. (D4) making use of annual average numbers of airplane operations per daytime and nighttime periods of each airplane type, in the summations.

APPENDIX E

EXAMPLE CALCULATION OF SOUND EXPOSURE LEVEL DURING A TAKEOFF OPERATION

This Appendix provides an example of the calculation of airplane performance and noise. The departure operation of a two engine jet airplane is used for the example calculation of sound exposure levels for four representative community locations; behind brake release, adjacent to ground roll during departure, directly under the flight path during climbout, and lateral to the ground track after liftoff.

Calculation procedures for sound exposure levels during approach operation are similar to those used during the airborne part of the takeoff operation. Calculation of noise adjacent to the runway during ground roll after touchdown is not considered in this AIR.

E.1 Performance Calculation: The aircraft used in this example has a maximum takeoff weight of 32,205 kg (71,000 lb) and is powered by two low-bypass-ratio jet engines. Aircraft performance data are to be assembled as shown in Figure E1 for the selected departure operation. (Thrust and flap management details for both takeoff and approach operations are supplied as input data.) The selected takeoff operational weight equal to the maximum for the example case is based upon the mission range of the aircraft. Local airport conditions in this example are assumed to correspond to the computational reference conditions of Section 2.3 of the AIR.

Airplane aerodynamic and engine data were developed according to Appendix A for each of the different configurations of the aircraft involved in the operation (see Figure E2. Note, coefficient H equals zero for the example engine).

Departure Procedure: Climb at 6° flap with takeoff thrust to 1000 feet;

At 1000 feet altitude reduce rate of climb to 1000 ft/min and accelerate to 180 knots while retracting flaps; reduce thrust to climb power;

Continue climb to 3000 feet. At 3000 ft altitude accelerate to 250 knots while maintaining 1000 ft/min rate of climb.

Development of the departure performance profile (shown in Figure E1) proceeds as follows:

E.2 Initial Climb Speed:

From Eq. (A7)

$$V_c = C \sqrt{W}$$

where:

$$C = 0.574 \text{ (see Figure E2)}$$

$$V_c = 0.574 \sqrt{71{,}000} = 152.9 \text{ knots}$$

E.3 Equivalent Takeoff Ground Roll:

From Eq. (A6)

$$s_g = B\theta_{am}(W/\delta_{am})^2/[N(F_n/\delta_{am})]$$

where:

$B = 0.0149$ (see Figure E2)

$\theta_{am} = 1.0$ (Ref. temperature, 15°C)

$\delta_{am} = 1.0$ (Ref. altitude, sea level)

$N = 2$ (Number of Engines)

$F_n/\delta_{am} = 9605 - 7.10V_c + 0.0828\ h = 9605 - 1086 + 0 = 8519$ lb (from Eq. (A1) for thrust corresponding to 152.9 knots, sea level and 15°C)

Therefore:

$$s_g = \frac{1.0\ (0.0149)\ (71000)^2}{2\ (8520)} = 4408 \text{ ft}$$

E.4 Initial Climb (Sea Level to 1000 ft):

From Eq. (A8)

$$\gamma = \arcsin(1.01 \left\{ [N(F_n/\delta_{am})_{avg}/(W/\delta_{am})_{avg}] - R \right\})$$

where:

$$R = 0.0753 \text{ (see Figure E2)}$$

E.4 (Continued)

and at the average altitude of 500 feet:

$\delta_{am} = 0.982$

$(F_n/\delta_{am})_{500} = 9605 - 7.1(152.9) + 0.0828(500)$

$= 9605 - 1086 + 41 = 8560 \text{ lb}$

Therefore:

$$\sin\gamma = (1.01)\left\{[2(8562)/(71{,}000/0.982)] - 0.0753\right\}$$

and

$\gamma = 9.39°$

From Eq. (A9)

$$s_c = \frac{1000}{\tan\gamma} = \frac{1000}{0.1654} = 6046 \text{ ft}$$

E.5 Acceleration and Flap Retraction:

From Eq. (A10) for s_a in feet, V in knots and V_{tz} in ft/min

$$s_a = (1/2g)(0.95)(V_{tb}^2 - V_{ta}^2) \Bigg/ \left\{\frac{N(F_n/\delta_{am})_{avg}}{(W/\delta_{am})_{avg}} - R_{avg} - \frac{V_{tz}}{101.3\ V_{tavg}}\right\}$$

An estimate of 1250 feet will be used as the altitude at the end of acceleration and flap retraction, i.e., point b.

Then:

$(\sigma_{am})_{1000} = 0.971$

$(\sigma_{am})_{1250} = 0.965$

V_a = 152.9 knots calibrated airspeed (CAS)

V_b = 180 knots CAS

V_{ta} knots true airspeed (TAS) $= \dfrac{152.9}{\sqrt{(\sigma_{am})_{1000}}} = 155.1$ knots TAS

$V_{tavg} = 169.2$ knots

V_{tb} knots TAS $= \dfrac{180}{\sqrt{(\sigma_{am})_{1250}}} = 183.2$ knots TAS

E.5 (Continued)

V_{tz} = 1000 ft/min

$R_{FLAP\ 6°}$ = 0.0753

$R_{FLAPS\ UP}$ = 0.0783

$\Big\}$ R_{avg} = 0.0768

$(\delta_{am})_{avg} = \delta_{am}(1125) = 0.960$

$(W/\delta_{am})_{avg}$ = 73,958 lb

$(F_n/\delta_{am})_{1250} = 9605 - 7.1(180) + 0.0828(1250) = 8430$ lb

$(F_n/\delta_{am})_{1000'} = 9605 - 7.1(152.9) + 0.0828(1000) = 8602$ lb

$(F_n/\delta_{am})_{avg}$ = 8516 lb

Therefore:

$$s_a = \frac{0.0421(183.2^2 - 155.1^2)}{\left\{\frac{(2)(8517)}{73{,}958} - 0.0768 - \frac{1000}{(101.3)(169.2)}\right\}} = 4204 \text{ ft}$$

$$\gamma = \sin^{-1}\frac{V_{tz}}{101.3\ V_{tavg}} = \sin^{-1}\frac{1000}{101.3(169.2)} = 3.34°$$

$\Delta h = (s_a \tan \gamma)/0.95 = 4204(\tan 3.34°) = 259$ ft

h = 1259 ft

NOTE: The difference between the computed altitude gain and the initial estimate of 250 ft (for obtaining altitude related parameters) is within 10 percent and a second iteration is not required.

E.6 <u>Continued Climb: 1259 Feet to 3000 Feet:</u> Thrust will now be reduced to the climb rating (specified in Figure E2).

Average altitude = 2130 ft = (1259 + 3000)/2

$(\delta_{am})_{avg}$ = 0.925

$(W/\delta_{am})_{avg}$ = 76,757 lb

$R_{FLAPS\ UP}$ = 0.0783 (see Figure E2)

V = 180 knots CAS

E.6 (Continued)

$$(F_n/\delta_{am})_{2130} = 8574 - 4.202(180) + 0.0967(2130) = 8024 \text{ lb}$$

And from Eq. (A12)

$$\sin \gamma = (0.95)\frac{2(8024)}{76,757} - 0.0783 = 0.1242$$

$$\gamma = 7.13°$$

From Eq. (A9) with $\Delta h = 3000 - 1259 = 1741$ ft

$$s_c = \frac{\Delta h}{\tan \gamma} = \frac{1755}{\tan 7.13} = 13906 \text{ ft}$$

E.7 <u>Acceleration to 250 Knot Climb Speed:</u> Equations A10 and A11 are used again to calculate this segment of the flight profile.

An initial estimate of 3500 feet will be used as the pressure altitude at the end of the acceleration.

Then:

$$(\sigma_{am})_{3000} = 0.915$$

$$(\sigma_{am})_{3500} = 0.902$$

$$V_{ta} = \frac{180 \text{ kts CAS}}{\sqrt{(\sigma_{am})_{3000}}} = 188.2 \text{ knots TAS}$$

$$V_{tb} = \frac{250 \text{ kts CAS}}{\sqrt{(\sigma_{am})_{3500}}} = 263.2 \text{ knots TAS}$$

$$V_{tavg} = 225.7 \text{ knots}$$

$$V_{tz} = 1000 \text{ ft/min}$$

$$(\delta_{am})_{avg} = \delta_{am}(3250) = 0.888$$

$$(W/\delta_{am})_{avg} = 79,955 \text{ lb}$$

$$(F_n/\delta_{am})_{3500} = 8574 - 4.202(250) + 0.0967(3500) = 7862 \text{ lb}$$

$$(F_n/\delta_{am})_{3000} = 8574 - 4.202(180) + 0.0967(3000) = 8108 \text{ lb}$$

$$(F_n/\delta_{am})_{avg} = 7985 \text{ lb}$$

E.7 (Continued)

Therefore:

$$s_a = \frac{0.0421(263.2^2 - 188.2^2)}{\left\{\frac{(2)(7985)}{79,955} - 0.0783 - \frac{1000}{(101.3)(225.7)}\right\}} = 18.343 \text{ ft}$$

$$\gamma = \sin^{-1} \frac{V_{tz}}{(101.3)\ V_{tavg}} = \sin^{-1} \frac{1000}{101.3(225.7)} = 2.51°$$

$$\Delta h = (s_a \tan \gamma)/0.95 = 18,343(\tan 2.51°) = 845 \text{ ft}$$

and

$$h = 3845 \text{ ft}$$

This end altitude gain is 345 feet higher than the initial height gain estimate of 500 ft, and is not within 10 percent of the estimate. For many purposes this initial result will be sufficiently accurate since the effect on altitude related parameters is small. A second iteration should be made using 3845 feet as the estimated end altitude. This second computation results in an altitude of 3870 feet, an increase of 25 feet, and the distance from brake release would increase by 595 feet to 47,502 feet, which is within 10 percent of the revised estimated height gain of 845 feet.

The entire profile to the 250 knot end speed is tabulated and displayed on Figure E1 including a second iteration for the height gained in the final segment.

E.8 Noise Calculation: The representative airplane has Noise-Power-Distance (NPD) data relating SEL to power setting and minimum slant distance as shown in Figure E3. These data were developed as described in Appendix B for each power setting, i.e., for each noted power setting acoustical measurements were made and the recorded data were normalized to reference atmospheric attenuation rates and then adjusted to other distances to provide the Noise-Power Distance data of Figure E3. With aircraft performance (Figure E1) and noise data (Figure E3) established, the calculation of SEL for any point P (x,y), can now be accomplished. This Appendix calculates noise levels at four representative locations. Sound exposure level contours at 90 and 100 dB are shown on Figure E4 for noise at the start of takeoff roll, acceleration, and climbout.

E.9 Representative Locations: Consider three locations, P_1, P_2, and P_3 which are 610 m (2000 feet) to the side of the takeoff ground track and a fourth point P_4 underneath the flight path. Location P_1 is behind brake release, P_2 is lateral to the runway and P_3 is at a point after liftoff has occurred. P_4 is the under the flight path location where a sound exposure level of 90 dB occurs.

E.9 (Continued)

In accordance with Section 3.3.1 of the AIR an x,y coordinate system is chosen with the origin (0,0) at the brake release point, and the x axis along the runway centerline. The coordinates for the example calculations with distances in feet, are: P_1 (-1500,2000); P_2 (1500,2000); P_3 (7000,2000); and P_4 (closure of the 90 dB SEL contour) to be determined by iteration.

NOTE: NPD data from Fig. E3 provide the initial estimate for all noise calculations, but adjustments are required for over-ground effects, directivity effects, and flight conditions, as described in Section 3.1 of the AIR.

E.10 <u>Sound Exposure Level at P_1 (-1500,2000):</u> Sound exposure level at P_1 is dependent upon the airplane-to-observer radial distance at the start of roll, the directivity angle, and the takeoff power (see Section 3.3.1). From equation 3.4.1

$$L_{AE}(P_1) = L_{AE}(P,d) + \Delta_V - \Lambda(0,r) + \Delta_L$$

The magnitude of the radial vector is $\sqrt{1500^2 + 2000^2} = 2500$ feet and the angle to the runway is $[180^\circ - \tan^{-1}(2000/1500)] = 127^\circ$.

From the airplane performance data in Section E.3 and Figure E1 the corrected net thrust per engine at lift-off is 8519 lb.

By interpolation using equations (3.7) and (3.8) a base noise level, $L_{AE}(P,d)$ corresponding to a distance of 2500 feet (762 m) and 8519 lb thrust of 97.4 dB is obtained from Figure E3.

The speed adjustment for duration,

$$\Delta_V = 10\ \lg(160/32) = 7.0\ \text{dB}$$

Lateral attenuation is computed using equation (3.10) for 0° elevation and a distance of 2500 feet (762 m)

$$\Lambda(0,r) = 15.09\ (1 - e^{-2.088}) = 13.2\ \text{dB}$$

The directivity adjustment factor is determined from equation (3.2) for an angle of 127°.

$$\Delta_L = 1.9\ \text{dB}$$

$$L_{AE}(P_1) = 97.4 + 7.0 - 13.2 + 1.9 = 93.1\ \text{dB}$$

E.11 SEL At P_2 (1500, 2000): Sound Exposure Level at P_2 is determined by adjusting the reference level, corresponding to takeoff power, for velocity and lateral attenuation, Eq. (3.4.2)

$$L_{AE}(P_2) = L_{AE}(P,d) + \Delta_V - \Lambda(0,d)$$

From the airplane performance data in Section E.3 and Figure E1 the corrected net thrust per engine at lift-off is 8519 lb. By interpolation, a base noise level, $L_{AE}(P,d)$, corresponding to a distance of 2000 feet (610 m) and 8519 lb thrust, of 99.1 dB is obtained from Figure E3.

Airplane speed at 1500 feet from the point of brake release is computed by the method described in Section 3.3.2 for an initial liftoff speed of 152.9 knots and an equivalent takeoff ground roll of 4,408 feet (see Sections E.2 and E.3 for performance calculations).

$$V = \sqrt{32^2 + (152.9^2 - 32^2)\ (1500/4408)} = 92.9 \text{ knots}$$

The speed adjustment for duration,

$$\Delta_V = 10 \text{ lg } (152.9/92.9) = 2.2 \text{ dB}$$

Lateral attenuation is computed using equation (3.10) for 0° elevation and a distance of 2000 feet (610 m)

$$\Lambda\ (0,d) = 15.09\ (1-e^{-1.67}) = 12.3 \text{ dB}$$

$$L_{AE}(P_2) = 99.1 + 2.2 - 12.3 = 89.0 \text{ dB}$$

E.12 SEL at P_3 (7000,2000): Since P_3 is beyond the point of liftoff and the ground track is "straight," there are only two adjustment factors; speed and lateral attenuation. Performance data from Fig. E1 are used to determine the height and airspeed of the aircraft as it passes by P_3, i.e., closest approach distance. From Eq. (3.1) and Section 3.4

$$L_{AE}(P_3) = L_{AE}(P,d) + \Delta_V - \Lambda(\beta,\ell)$$

Conditions 7000 feet from brake release: Height = 429 feet
Speed = 154 knots TAS
F_n/δ_{am} = 8555 lb

Minimum distance Eq. (3.5) $= [2000^2 + 429^2 \cos^2 9.39]^{1/2}$

$= \underline{2044 \text{ ft}}$ (623 m)

Elevation Angle, β, Eq. (3.6) $= \cos^{-1}$ (2000/2044) = 11.9°