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A New Theory for Rapid Calculation of the Ground Pattern of the Incident Sound Intensity Produced by a Maneuvering Jet Airplane

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SUMMARY

An approximate method is described for computing the jet noise pattern of a maneuvering airplane. The method permits one to relate the noise pattern individually to the influences of airplane speed and acceleration, jet velocity and acceleration, and the flight-path curvature. The analytic formulation determines the ground pattern directly without interpolation and runs rapidly on a minicomputer. Calculated examples are presented including a climbing turn and a simple climb pattern with a gradual throttling back. For certain types of operation, the results differ significantly from those obtained by previous methods.

INTRODUCTION

Jet noise is a major problem associated with community-airport relations. The effort to reduce the level of noise experienced by residents near airports has included the study of airplane operations as they relate to the noise received in residential areas. One important factor in this study is the form of the constant-intensity ground pattern as a function of the airplane trajectory, its velocity variation, and its engine operation. The constant-decibel contours provide a graphical means of evaluating the potential benefit of varying these parameters.

At present, several different methods are used for computing the ground pattern of jet noise. The first is a strictly numerical approach. One can utilize a computer program, such as that of reference 1, for computing the sound pressure level at a fixed point due to a jet at a given location and orientation. For a given jet position, the noise level can be calculated over a range of ground grid points. Then the jet is moved to a new location and the calculation repeated for the same ground points. After such calculations have been performed for a number of jet locations, the ground-level constant-decibel line is determined by interpolation. This method possesses the advantage that many complexities (such as atmospheric attenuation) are included in the calculation. One of the disadvantages of the method is that it determines the ground pattern indirectly by interpolation and therefore requires calculations at many more points than a method that calculates the pattern directly. Because of the lengthy computer times, the ground-level observer points must be widely spaced, and accuracy is lost by interpolating in the resulting coarse grid. For the same reason, the discrete grid location increments along the flight path must be relatively large. Significant variations in the ground pattern can thereby be lost when the airplane direction or the jet velocity is varying because relatively gradual changes in these quantities can cause rapid variations in the constant-decibel envelope.

A second procedure currently in use is that of reference 2. This procedure utilizes the fact that the constant-decibel envelope is very nearly a cylinder for straight, steady flight. The intersection of this cylinder with the ground is an ellipse. The method of reference 2 approximates the flight path as a series of straight-line, constant-condition segments. The ground pattern is accordingly approximated by sections of ellipses. The advantage of this method is that it is fast and simple. Its principal difficulty is that the constant-decibel envelope is not well approximated by a cylinder either when the jet velocity varies or when the airplane turns.

A third method for computing the ground pattern is that of reference 3 or 4. This method utilizes experimental or calculated data for points located at known slant distances from an airplane in straight, level, steady flight. These data are then applied symmetrically on either side of the flight track at corresponding slant distances for an airplane with varying trajectory or engine parameters. One advantage of this method is that it is efficient in that the calculation is performed only at the necessary locations - the two ground contour points corresponding to each location of the airplane. Furthermore, it can avoid a number of theoretical uncertainties, such as atmospheric effects and the precise analytic form of the directivity function, through the use of empirical data. A possible disadvantage of the method is that, if the tabular input is based on experimental data, any error or anomaly due to the experimental conditions becomes locked into the calculation. A definite disadvantage results from the fact that the distances and inclination angles associated with a ground-level noise contour for an airplane with a variable direction or jet velocity do not correspond to those for straight, steady, level flight. In fact, if the airplane is turning, these points are not even symmetrically situated with respect to the local flight trajectory.

The procedure described in the present paper represents a different approach to computing the ground noise pattern. The method is based primarily on analytic, rather than numerical techniques, with the use of the envelope theory of differential geometry. The analytic formulation permits one to relate the noise pattern individually to the influences of airplane speed and acceleration, the jet velocity and acceleration, and the flight-path curvature. Conditions for which a specific constant-decibel envelope does not exist are determined. The running time for a single, complete take-off noise contour is a few seconds on a minicomputer with screen display of the contour and the ground track of the airplane trajectory.

In order to keep the analytical expressions tractable, several simplifying assumptions are made. The method is limited to calculating the overall sound pressure level or, equivalently, the intensity, whereas other existing methods include the capability of computing effective perceived noise levels. The jet axis is assumed to be aligned with the local flight direction. Effects of atmospheric attenuation and refraction are neglected. These effects are considered to be negligible for propagation distances of primary interest in take-off and landing situations. Finally, only the incident noise is considered, since only this noise can be related to the airplane operation. Sound impedance calculations for flat uniform surfaces are fundamentally inappropriate for predicting reflection effects in the presence of a heterogeneous distribution of structures, shrubs, trees, asphalt, etc.

SYMBOLS

$A(\tau)$	function defined by equation (4a), m
$\tilde{A}$	proportionality constant, m
a	speed of sound, m/sec
$B(\tau)$	$= M_c - \frac{M}{2}$
$\bar{b}$	unit vector defined by equation (5c)
c	constant of proportionality (eq. (1)), $W\text{-}m^4/kg^2$
D	airplane drag, N
d	jet exit diameter, m
I	sound intensity, W/m^2
I_s	sound intensity on a specific constant-intensity surface
M	flight Mach number
M_c	convection Mach number of jet eddies with respect to a_o
$\dot{m}_a$	mass flow of air in jet, kg/sec
$\dot{m}_f$	mass flow of fuel in jet, kg/sec
$\bar{n}$	unit vector at airplane location pointing in direction of local center of curvature of flight path (eq. (5b))
OASPL	overall sound pressure level
R	distance from jet exit to point on constant-intensity surface, m
R_τ	$= dR/d\tau$, m/sec
R'	$= dR/d\psi$, m
$\bar{r}$	vector to general point on constant-intensity surface
$\bar{r}_t$	position vector of airplane, m
SPL	sound pressure level
s	distance along flight path, m
T	thrust, N

$\bar{T}$ unit vector at airplane, pointing in local direction of flight (eq. (5a))

t torsion (out-of-plane curvature) of flight path, 1/m

V airplane speed, m/sec

V_j jet velocity, m/sec

W airplane weight, N

η exponent in equation (1)

κ local flight-path curvature, 1/m

ρ density, kg/m^3

τ time, sec

θ airplane climb angle, deg

ϕ angle between $\bar{r} - \bar{r}_t$, $\bar{T}$ plane and $\bar{T}$, $\bar{n}$ plane (see fig. 1(b))

ψ angle between $\bar{r} - \bar{r}_t$ and $\bar{T}$ (see fig. 1(b))

Superscript:

$-$ vector

Subscripts:

o free air conditions

j condition in jet

ANALYSIS

Basic Jet Noise Equations

The expression given in reference 5 for the intensity of noise from an axisymmetric jet is

$$I \approx \frac{\rho_j{}^2 V_j{}^8 d^2}{\rho_o a_o{}^5 R^2 (1 - M_c \cos \psi)^5}$$

where M_c is proportional to V_j/a_o with a proportionality factor that is assigned a value from 0.5 to 0.65 by various authors. The present analysis uses a value of 0.5 (consistent with ref. 6).

The noise associated with a moving jet is treated in reference 6. The sound intensity for a jet moving at Mach number M is

$$I = \frac{c\rho_j^{\,2} d^2 M_c^{\,4}\left(M_c - \frac{M}{2}\right)^4}{R^2\left[1 - \left(M_c - \frac{M}{2}\right)\cos\psi\right]^\eta} \tag{1}$$

where the exponent η is considered to be an empirical parameter. It is often taken to be 5. However, the experimentally measured form for this expression varies considerably when $M_c - \frac{M}{2}$ approaches 1. Various parameters in equation (1) can be altered to account for this distortion. In the present analysis, η is retained as an unspecified parameter, its value being assigned to correspond with M_c in accordance with the data of reference 6. Another possibility, suggested in reference 5, is to change the bracketed quantity to

$$\left\{\left[1 - \left(M_c - \frac{M}{2}\right)\cos\psi\right]^2 + 0.09\left(M_c - \frac{M}{2}\right)^2\right\}^{1/2}$$

This modification to equation (1) is required if $M_c - \frac{M}{2}$ actually attains the value of 1, for otherwise the denominator would vanish for $\psi = 0$. A third possibility is to weaken the fourth-power exponents in the numerator of equation (1). Either of the latter two variations would require corresponding adjustments in the following equations.

The jet that issues from the nozzle at a fixed time τ has associated with it a surface on which noise intensity attains the level I_s. The following equation for this axisymmetric surface can be obtained from equation (1):

$$R(\psi) = \sqrt{\frac{c\rho_j^{\,2} d^2}{I_s}}\ \frac{M_c^{\,2}\left(M_c - \frac{M}{2}\right)^2}{\left[1 - \left(M_c - \frac{M}{2}\right)\cos\psi\right]^{\eta/2}} \tag{2}$$

In this formula, ρ_j, M, M_c, and possibly even d may vary with time. Thus, R can be expressed as a function of ψ and τ in the form

$$R(\psi,\tau) = \frac{A(\tau)}{\left[1 - B(\tau)\cos\psi\right]^{\eta/2}} \tag{3}$$

where

$$A(\tau) \equiv \sqrt{\frac{c\rho_j{}^2 d^2}{I_s} M_c{}^2 B^2(\tau)} \tag{4a}$$

and

$$B(\tau) = M_c - \frac{M}{2} \tag{4b}$$

It is theoretically possible to calculate the noise distribution for an aircraft flight trajectory by calculating, for a specified intensity, the constant-intensity surfaces of equation (3) for small increments of time along the trajectory. However, it is more efficient to compute directly the envelope of all these surfaces for the entire trajectory. The following analysis provides a method for computing this envelope surface. It is based on the theory described in reference 7.

Envelope Equations

The position vector of the airplane at time τ is denoted by $\bar{r}_t$. The moving trihedral coordinate system is determined by a set of base vectors $\bar{T},\bar{n},\bar{b}$ (fig. 1(a)) obtained from the derivatives of $\bar{r}_t$ (see ref. 8)

$$\bar{T} = \frac{d\bar{r}_t}{ds} = \frac{1}{V}\frac{d\bar{r}_t}{d\tau} \tag{5a}$$

$$\bar{n} = \frac{1}{\kappa}\frac{d\bar{T}}{ds} \tag{5b}$$

$$\bar{b} = \bar{T} \times \bar{n} \tag{5c}$$

According to equation (5b), the local flight-path curvature is the magnitude of $d\bar{T}/ds$. Denote the generic vector of a point on the constant intensity surface by $\bar{r}$. Then the components of $\bar{r} - \bar{r}_t$ in the $\bar{T}$, $\bar{n}$, and $\bar{b}$ directions are readily determined from the diagram of figure 1(b). Thus $\bar{r}$ can be written

$$\bar{r} = \bar{r}_t - (R \cos \psi)\bar{T} + (R \sin \psi \cos \phi)\bar{n} + (R \sin \psi \sin \phi)\bar{b} \tag{6}$$

where all the vectors are functions of τ, and $R = R(\psi,\tau)$. For each value of τ there exists a surface on which $I = I_s$, and there also exists a characteristic line on the envelope of these $I = I_s$ surfaces. Each of these lines must satisfy both equation (6) and the equation

$$\frac{d\bar{r}}{d\psi} \cdot \frac{d\bar{r}}{d\phi} \times \frac{d\bar{r}}{d\tau} = 0 \tag{7}$$

(See ref. 7.) The set of all the characteristic lines constitute the envelope of the constant-decibel surfaces. The derivatives in equation (7) can be calculated from equation (6) with the use of the Frenet-Serret formulas (ref. 6, p. 18):

$$\frac{d\bar{r}}{d\psi} = (R \sin \psi - R' \cos \psi)\bar{T} + \cos \phi(R \cos \psi + R' \sin \psi)\bar{n}$$

$$+ \sin \phi(R \cos \psi + R' \sin \psi)\bar{b}$$

$$\frac{d\bar{r}}{d\phi} = 0 \cdot \bar{T} - (R \sin \psi \sin \phi)\bar{n} + (R \sin \psi \cos \phi)\bar{b}$$

$$\frac{d\bar{r}}{d\tau} = (V - R_\tau \cos \psi - V\kappa R \sin \psi \cos \phi)\bar{T}$$

$$+ [R_\tau \sin \psi \cos \phi - VR(\kappa \cos \psi + t \sin \psi \sin \phi)]\bar{n}$$

$$+ (R_\tau \sin \psi \sin \phi + tVR \sin \psi \cos \phi)\bar{b}$$

where R_τ is obtained by differentiating equation (3) with respect to time. Substituting these expressions into equation (7) and collecting terms (note that terms involving t subtract out) yield the following equation for the characteristic lines:

$$\cos \phi = \frac{1}{\kappa R}\left[\sin \psi + \frac{R}{R'}\left(\cos \psi - \frac{R_T}{V}\right)\right] \tag{8a}$$

which can also be written

$$\kappa R \cos \phi = \sin \psi + \frac{R}{R'}\left(\cos \psi - \frac{R_T}{V}\right) \tag{8b}$$

Both forms of the equation are important in the calculation of the characteristic lines, which, taken together, constitute the constant noise level envelope. If the local trajectory curvature κ is not too small, equation (8a) is used. First, ψ is varied in small increments and those values of ψ for which the absolute value of the right side of the equation is less than 1 yield values of $\cos \phi$ corresponding to points on the characteristic line. These points are computed from equation (6).

When κ is very small, small increments in ψ correspond to large increments in ϕ, and the procedure using equation (8a) consequently becomes less accurate. In this case the flight path is approximated as being straight. Equation (8b) is used and produces characteristic lines which are approximately the circles obtained by equating the left side of equation (8b) to zero for very small κ values. Each one is the individual parallel on a surface given by equation (3) that satisfies

$$\sin \psi + \frac{R}{R'}\left(\cos \psi - \frac{R_T}{V}\right) = 0 \tag{9}$$

Differentiating equation (3) with respect to ψ yields

$$R' = \frac{-\eta AB \sin \psi}{2(1 - B \cos \psi)^{\eta/2+1}}$$

and therefore

$$\frac{R}{R'} = -\frac{2}{\eta}\left(\frac{1 - B \cos \psi}{B \sin \psi}\right) \tag{10}$$

With equation (10) equation (9) becomes

$$B \sin^2 \psi = \frac{2}{\eta}(\cos \psi - B \cos^2 \psi) - \frac{2}{\eta} \frac{\dot{R}_T}{V}(1 - B \cos \psi) \tag{11}$$

which can be written as a quadratic equation for $\cos \psi$, with the solution

$$\cos \psi = \frac{-\left(1 + \frac{B\dot{R}_T}{V}\right) + \sqrt{\left(1 + \frac{B\dot{R}_T}{V}\right)^2 + B(\eta - 2)\left(B\eta + 2\frac{\dot{R}_T}{V}\right)}}{B(\eta - 2)} \tag{12}$$

In these equations, $\dot{R}_T$ is obtained by differentiating equations (3), (4a), and (4b) with respect to time. If $\dot{R}_T \neq 0$, the right side of equation (12) is a function of ψ. It is then solved by iteration.

The ground pattern is calculated by locating the intersections of the characteristic lines with the ground plane. However, it is sometimes advantageous to relate details of the ground pattern to specific variations in trajectory or jet velocity by a study of the full constant-decibel envelope.

DISCUSSION AND EXAMPLES

Equation (8a) and its approximation for low-curvature flight paths (eq. (12)) are, in many respects, rather remarkable relationships. When they are combined with equations (1) to (5) and (10), they provide, in relatively simple algebraic form, the essential information for predicting the effects of each of the flight and engine parameters on the constant-intensity ground pattern.

The Problem of Existence of the Envelope

It is of interest to examine the conditions for which an envelope of the constant-decibel surfaces may fail to exist. This problem corresponds mathematically to determining the existence of solutions to equation (8b) or equation (12). It should be borne in mind that these equations would have a somewhat different form if equation (1) were modified to permit values of B near or exceeding 1.

Equation (8a) has a solution when the absolute value of the right side does not exceed 1. When intensity levels are considered that correspond to distances of the order of the flight-path curvature, then κR approaches 1, and a solution is virtually assured except for $\dot{R}_T/V$ extremely large, as might occur with the switching on or off of an afterburner.

If κR is small, equation (12) is applicable, and the ratio $\dot{R}_T/V$ becomes the primary quantity that determines the existance of solutions. When this ratio is positive, its limiting value is 1, since in this case the right side of equation (12) is exactly 1 regardless of the values assumed for B or η. The physical interpretation of this situation is that the extreme axial point on the constant-decibel surface is moving away from the airplane at exactly the same speed as the airplane speed so that this point is fixed in space, while the successive constant-decibel surfaces are increasing in overall size. Thus, each one encloses the previous one with no common points except that at $\psi = 0$.

When the ratio R_T/V is negative (decreasing the value of $V_j - V$) the limiting condition for the existence of a solution to equation (12) is determined by that value of the ratio that causes the expression under the radical to become negative. In this case, the constant-decibel surfaces are collapsing so rapidly that each one is enclosed by the previous one and, therefore, no envelope points exist.

Basic Examples

For the sake of simplicity in formulating illustrative examples, variations in airplane speed and direction will be taken to be gradual in nature so that the quasi-equilibrium theory of reference 9 is applicable for determining the airplane flight parameters. According to this theory, the required thrust is the sum of the airplane drag and the component of weight in the flight direction. Thus for a simple climb pattern,

$$T = D + W \sin \theta \tag{13a}$$

For a fan jet,

$$T = (\dot{m}_a + \dot{m}_f)(V_j - V) \tag{13b}$$

Combining equations (13a) and (13b) yields, for the jet velocity,

$$V_j = V + \frac{1}{\dot{m}_a + \dot{m}_f} D + W \sin \theta \tag{14}$$

The engine mass flow is approximately proportional to $\rho_j M_c$ and it may be maintained nearly constant under quasi-equilibrium conditions. If this assumption is made, equation (14) provides a simple expression for jet velocity in terms of climb angle, and equation (2) can be written approximately as

$$R = \frac{\tilde{A} M_c B^2}{(1 - B \cos \psi)^{\eta/2}}$$

where $\tilde{A} = \rho_j M_c d \sqrt{\frac{c}{I_s}}$. The following conditions, representative of a heavy fighter-bomber airplane, are assumed for purposes of illustrations:

$D = 75$ kN

$W = 336$ kN

$V = 91.0$ m/sec

$\dot{m}_a + \dot{m}_f = 438$ kg/sec

$\tilde{A} = 1.585$ m

$\eta = 5.0$

$I_s = 75$ dB, based on reference value of 10^{-12} W/m^2

Then, for the climb profile shown in figure 2(a), the ground pattern shown in figure 2(b) results. The form of this ground pattern may be compared with that of the second example, illustrated in figure 3, for which the climb angle is nearly constant (fig. 3(a)). In the latter constant-thrust case, the envelope of the constant-intensity region is approximately a cylinder and, consequently, its intersection with the ground is nearly elliptical. The effect of the cutback in thrust by about one-third is evident in figure 2(b). The constant-decibel region on the ground contracts rapidly as the airplane levels off, although the flight is much lower than at the corresponding time in the example of figure 3.

For the third example, shown in figure 4, the same conditions are assumed as for the example of figure 3 except that the airplane turns as it climbs. The ground track of the airplane is shown in figure 4, along with the 75-dB ground pattern. The directional nature of the jet noise is apparent in this figure, resulting in a bulge in the constant-decibel contour toward the outside of the turn. It is apparent from the figure, however, that noise at this intensity level is experienced over a greater length of time on the inside of the turn.

Comparison With Other Methods

In an attempt to illustrate how the computer program of reference 1 might be used to estimate a ground pattern of incident noise intensity, the constant-decibel regions were computed for the airplane at four discrete locations along a straight climb path inclined at an angle of 14.04°. Other flight parameters typical of a military jet trainer were

Jet velocity, m/sec	562
Aircraft velocity, m/sec	95
Climb angle, deg	14.04
Jet mass flow, kg/sec	33

The four corresponding constant-decibel lines are shown in figure 5 along with the elliptical line computed by the present method. No attempt was made to estimate an envelope of the four regions calculated by the method of reference 1, inasmuch as the coarse grid resulted in polygon contours of irregular shape such that a tangent fairing to these contours could not be performed in a unique manner.

One assumption of the method of reference 2 may lead to difficulties when jet or airplane velocity is varied rapidly. As was mentioned in the Introduction, the method of reference 2 assumes that the flight path consists of constant-condition segments for each of which the envelope is a cylinder and that the ground pattern is a segment of an ellipse. Consider the situation for which the flight direction is constant, but some other parameter (such as flight speed or jet velocity) is varying. Thus, the approximating cylinders for each of the different segments of the flight path have different radii. If the segments were made shorter and shorter, then the approximating cylinders would approach circles, with the radii varying continuously with the flight parameters. In this limit, these circles would be approximately the same as the characteristic lines used in the present method, and consequently the results for the two methods would be very similar (provided that an envelope actually did exist for the assumed conditions). Of course, such a continuously varying procedure would defeat the purpose of reference 2, which assumed constant-condition segments for the purpose of reducing computer time. Furthermore, the assumption of these constant conditions leads to results that depart radically from those of the present method when the jet velocity varies at even a moderate rate. This difference in results is due to the extreme sensitivity (approximately fourth power) of the size of the constant-decibel region to the jet velocity, which causes a rapid variation in the radii of the characteristic circles corresponding to a gradual variation in the jet velocity. Thus, the shape of the envelope predicted by the present method would differ significantly from the cylinders predicted by reference 2.

Another difference between previous methods and the present work is illustrated in figure 6. Consider the limiting condition for which the cylinders become essentially circles, one obtains for the intersection of each circle with the ground plane two points symmetrically situated on either side of the ground track. If atmospheric attenuation and refraction effects are negligible, these points would be located at approximately the same slant distance as the sideline points used as a basis for the calculation in references 3 and 4. Thus, if the airplane were climbing at a constant angle, but turning out of a vertical plane, the methods of reference 2 (using very short, straight-line segments) and of references 3 and 4, would yield similar results - a pattern consisting of points symmetrically disposed on either side of the ground track and resembling somewhat an ellipse "bent" around the ground track as a center line. However, the ground pattern calculated by the present method differs significantly from such a shape, as is illustrated by the comparison shown in figure 6. This difference results from the fact that, for a turning maneuver, the characteristic lines are no longer circles but more elongated figures that stretch out the envelope in the direction of the jet exhaust, thereby displaying the full directivity of the jet noise.

CONCLUDING REMARKS

A method for calculating the constant-intensity noise level surface resulting from the jet engine of a maneuvering airplane has been presented. The method differs from other procedures both in approach and in the resulting ground pattern shapes. The capability of the method to treat the effect of continuously variable jet velocity was demonstrated by an example of an airplane performing a simple climb pattern. Another example, for a climbing turn, demonstrated that the noise intensity pattern displayed an asymmetry with respect to the ground track that is not apparent in simpler treatments. The analytic form of the equations permits one to relate the noise pattern individually to the effects of airplane speed and acceleration, flight-path curvature, and jet velocity and acceleration, and also to determine explicitly conditions for which a constant-decibel envelope does not exist.

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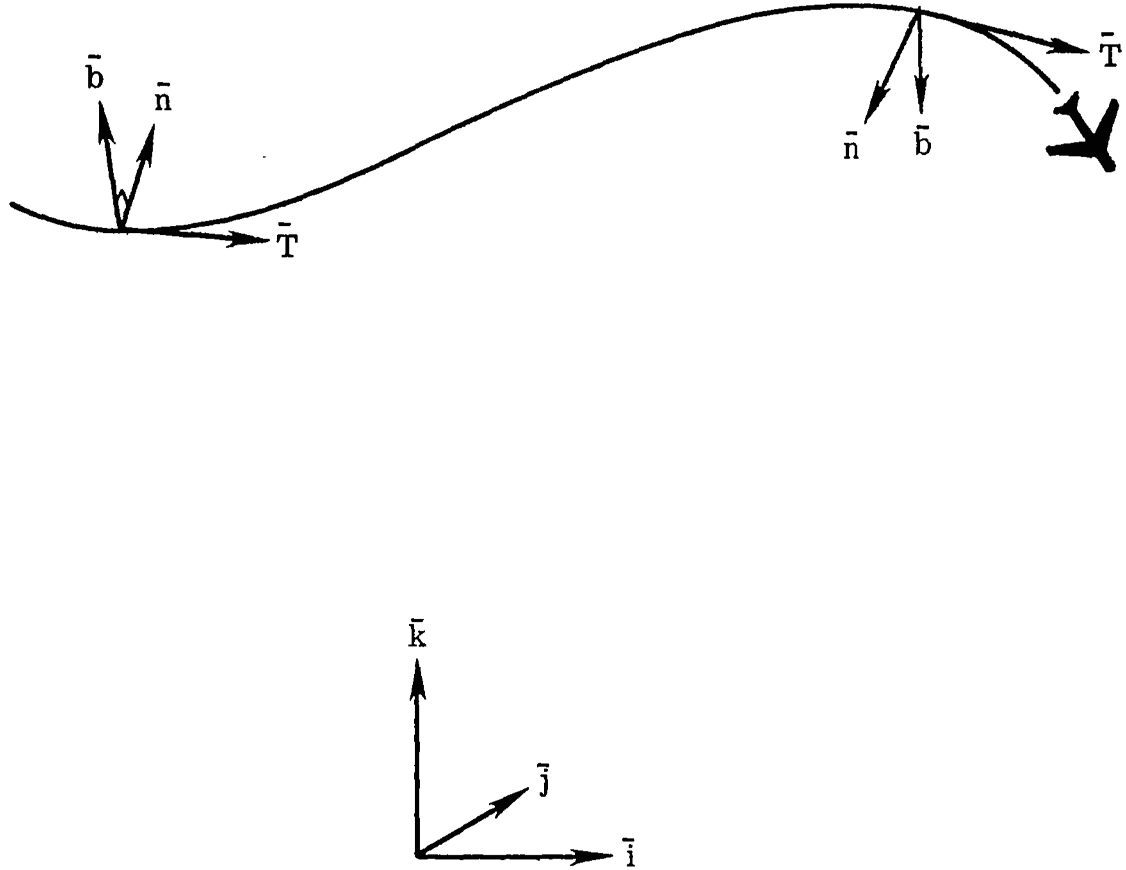
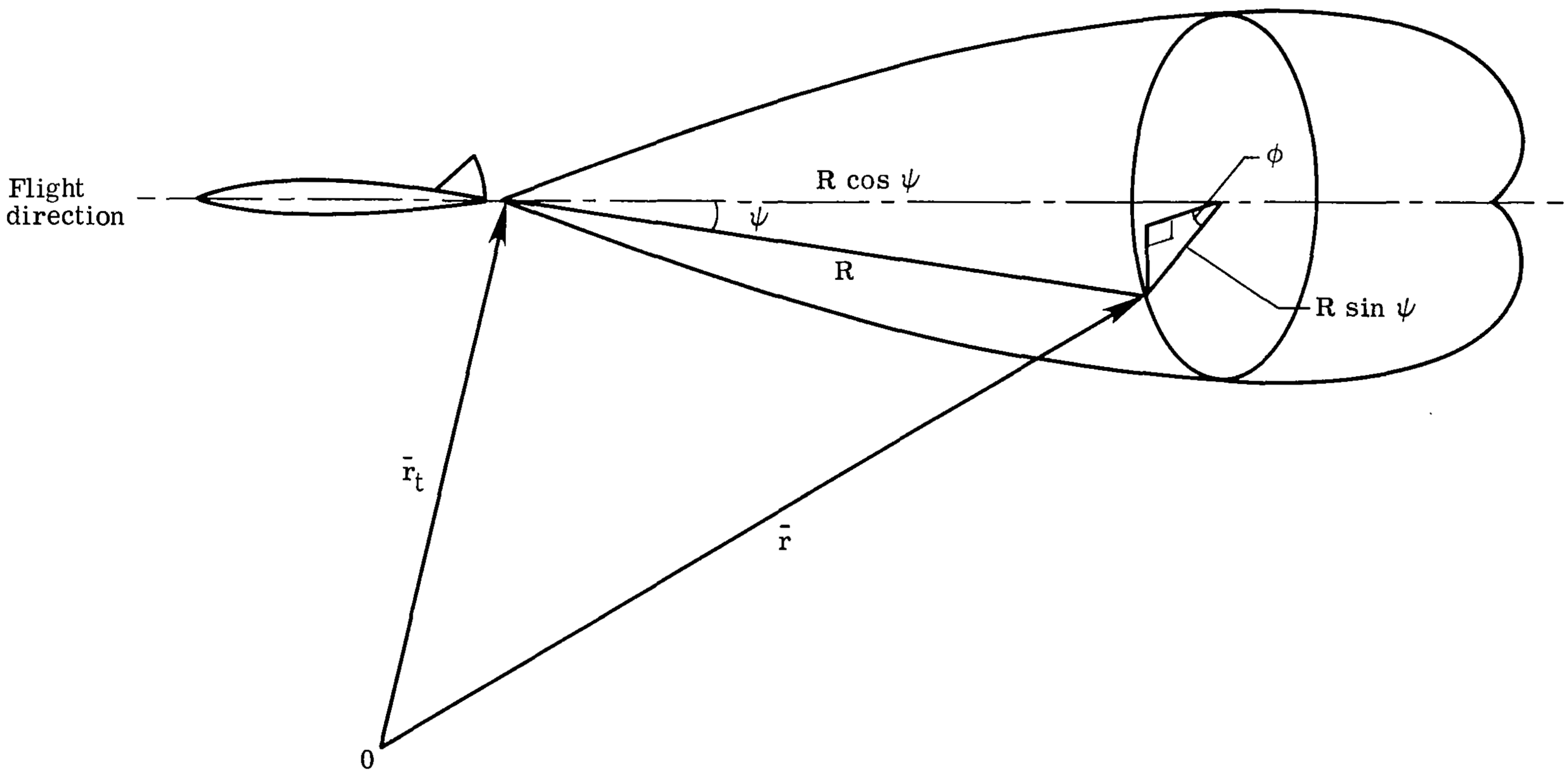


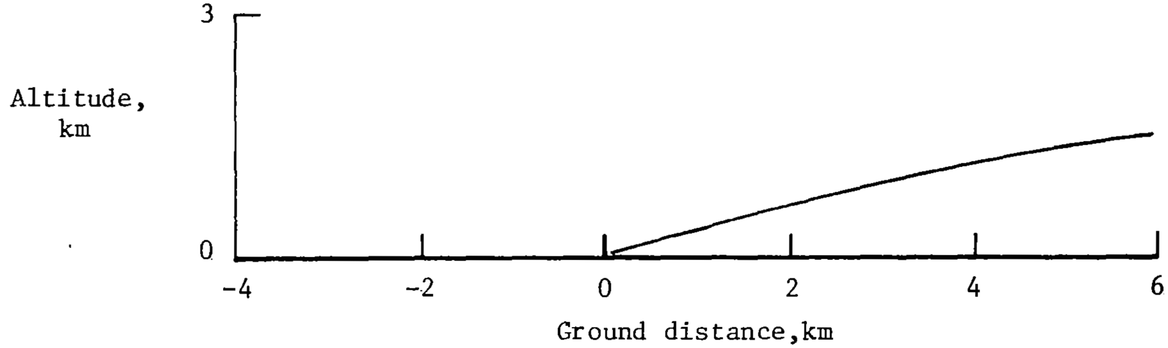
(a) Fixed ($\bar{i}, \bar{j}, \bar{k}$) and moving ($\bar{T}, \bar{n}, \bar{b}$) coordinate systems.

Figure 1.- Geometry for vector relations.

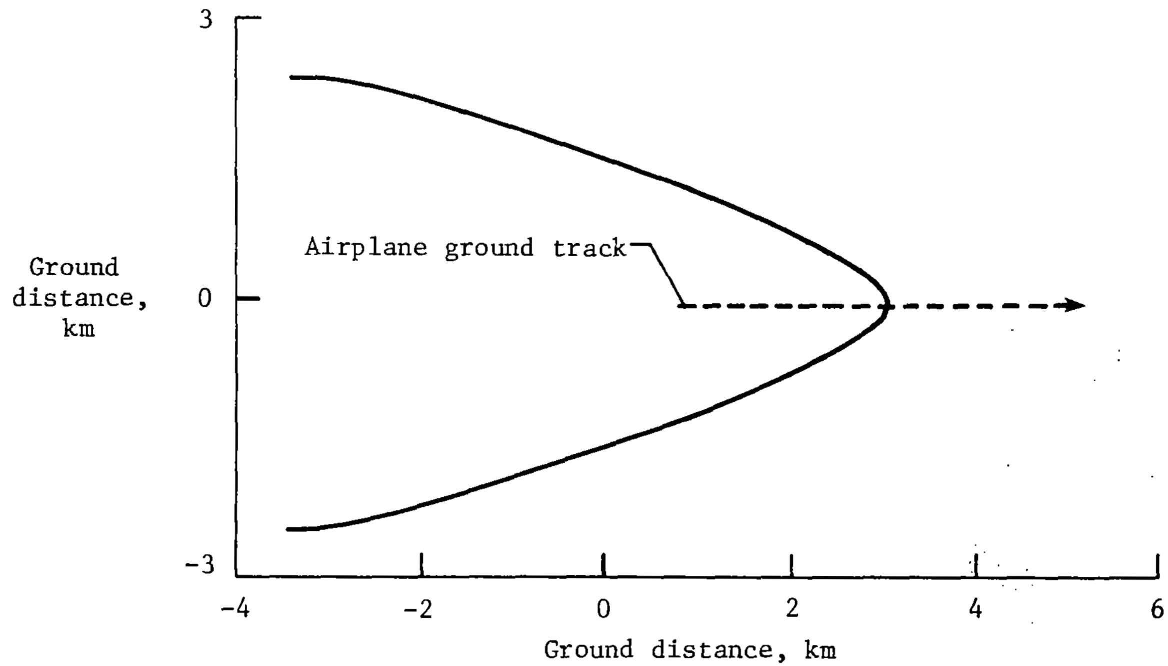


(b) Geometry of constant-intensity surface.

Figure 1.- Concluded.

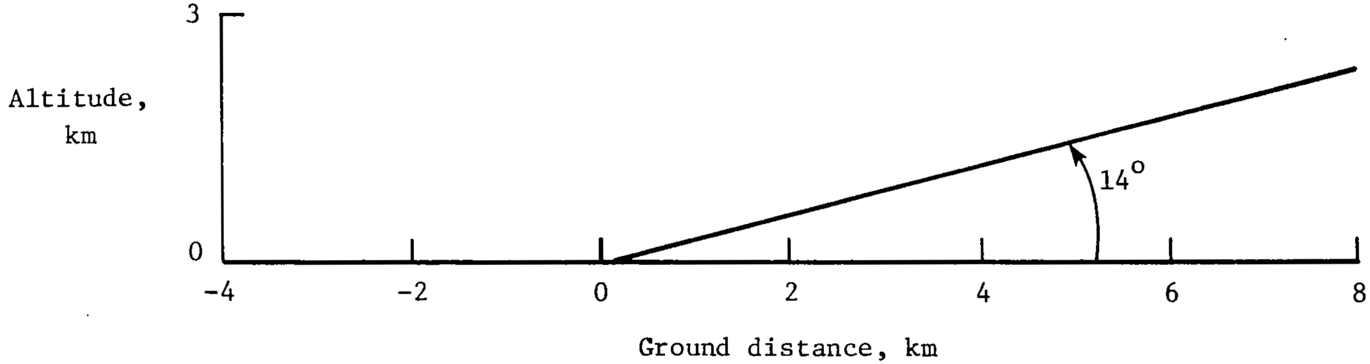


(a) Climb profile.

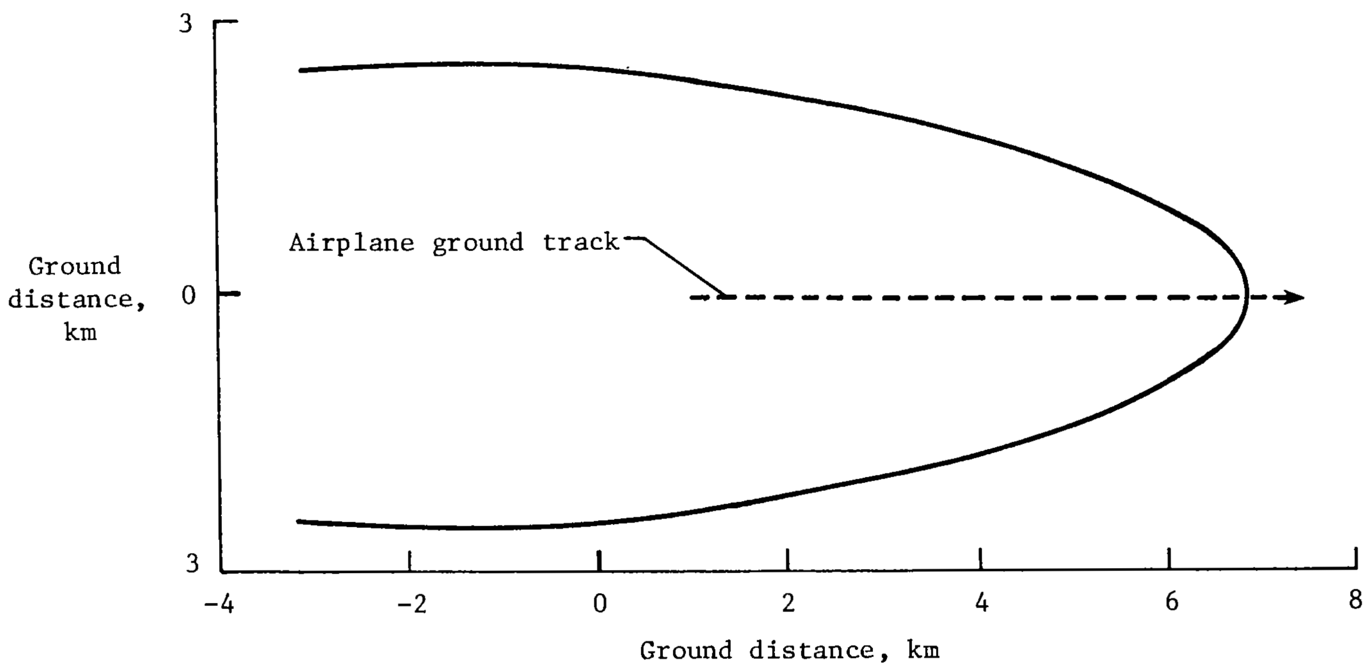


(b) Ground noise pattern.

Figure 2.- Example 1. Climb profile and 75-dB ground noise pattern.



(a) Climb profile.



(b) Ground noise pattern.

Figure 3.- Example 2. Climb profile and 75-dB ground noise pattern.

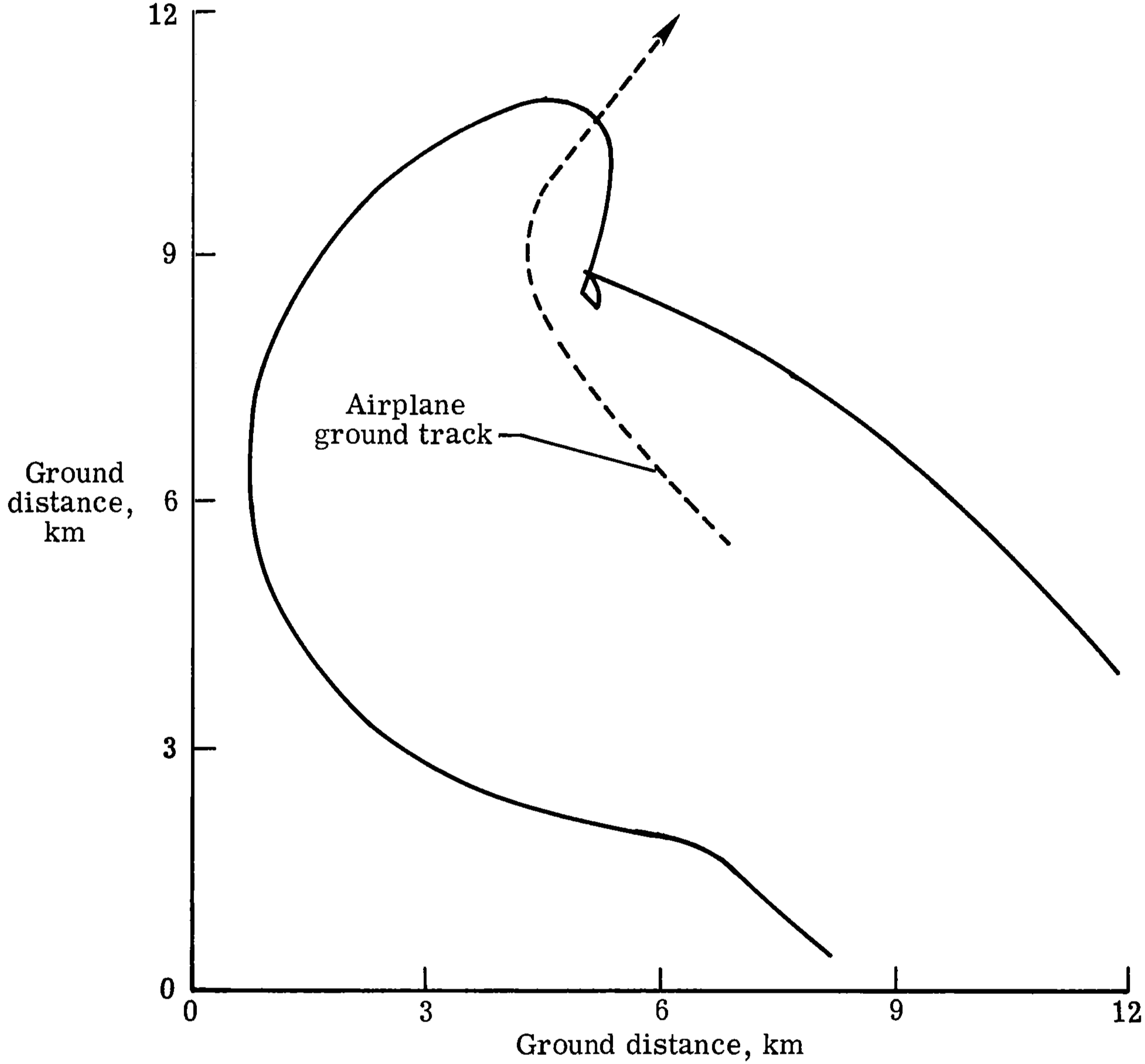


Figure 4.- Example 3. 75-dB ground noise pattern for turn-climb trajectory. Climb profile same as in figure 3.

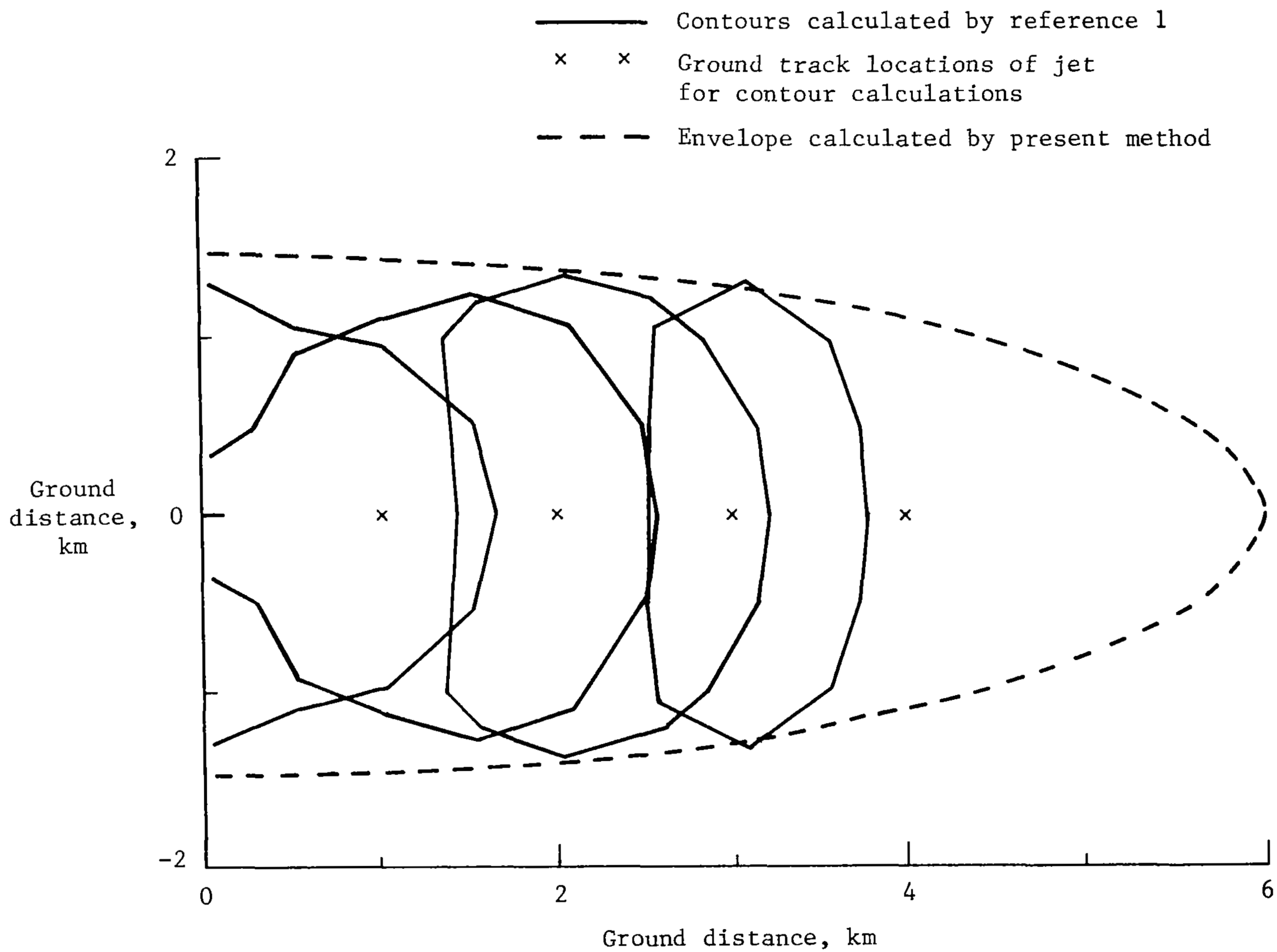


Figure 5.- Four 80-dB SPL contours calculated by method of reference 1 and envelope calculated by present method for example of straight, steady climb at 14°.

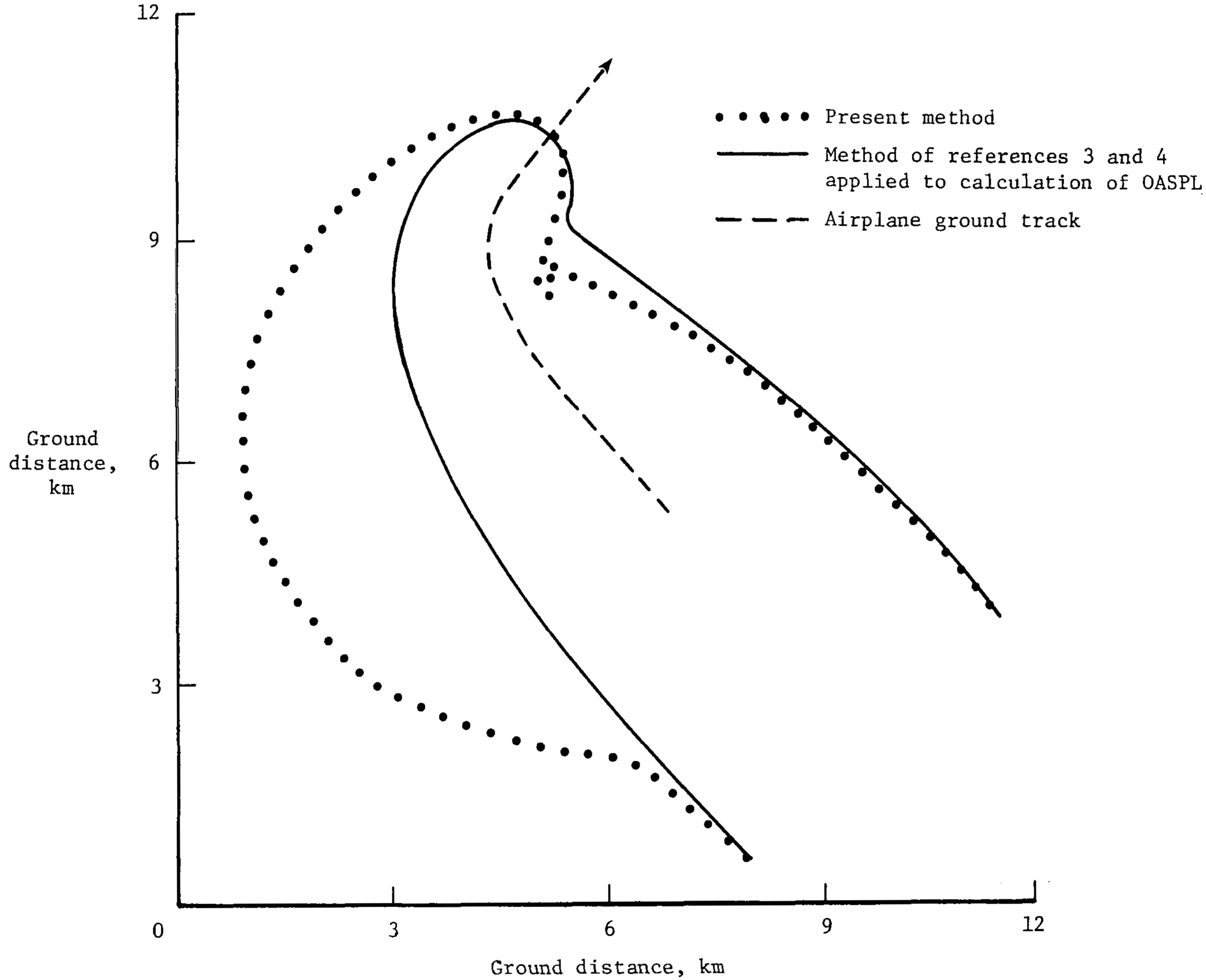


Figure 6.- Comparison of present method with that of references 3 and 4 for calculation of ground pattern for climbing turn. 75-dB noise intensity level; 14° climb profile.

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16. Abstract

An approximate method is described for computing the jet noise pattern of a maneuvering airplane. The method permits one to relate the noise pattern individually to the influences of airplane speed and acceleration, jet velocity and acceleration, and the flight-path curvature. The analytic formulation determines the ground pattern directly without interpolation and runs rapidly on a minicomputer. Calculated examples are presented including a climbing turn and a simple climb pattern with a gradual throttling back. For certain types of operation, the results differ significantly from those obtained by previous methods.

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