NOISE PREDICTION TECHNOLOGY FOR CTOL AIRCRAFT

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SUMMARY

The application of a new aircraft noise prediction program (ANOPP) to CTOL noise prediction is outlined. Noise prediction is based on semi-empirical methods for each of the propulsive system noise sources, such as the fan, the combustor, the turbine, and jet mixing, with noise-critical parameter values derived from the thermodynamic cycle of the engine. Comparisons of measured and predicted noise levels for existing CTOL aircraft indicate an acceptable level of accuracy.

INTRODUCTION

The noise produced by jet-powered aircraft has become an increasingly important consideration since their introduction to the commercial fleet in the late 1950's. The noise of aircraft operating near airports seriously affects over six million people in the United States alone. Aircraft noise has, therefore, become, as indicated in figure 1, an important consideration in the design of CTOL aircraft. Consequently, methods for calculating, with known accuracy, the environmental noise that a proposed new aircraft will produce are being developed. Although not indicated in figure 1, noise minimization is at odds with other design considerations such as weight minimization, propulsion plant efficiency, and direct operating cost minimization and thus increases the number of interactions to be juggled by the preliminary design team for a new aircraft.

In order to predict the noise that an aircraft will produce, the specifics of its aerodynamic and propulsion cycle characteristics must be known and values of the noise-critical parameters supplied as input data to the noise prediction algorithms. Furthermore, the computer implementation of the noise prediction algorithms must be compatible with the requirements mandated by the preliminary design activity; namely, it must be complete, responsive, and accurate.

The purpose of this paper is to describe a state-of-the-art aircraft noise prediction program (ANOPP) recently developed by NASA. This program is presently being used by NASA's supersonic cruise aircraft research (SCAR) project and by NASA in an international study to determine expected noise levels of future supersonic cruise aircraft.

SYMBOLS AND ABBREVIATIONS

A	atmospheric absorption factor
c_a	ambient speed of sound
D	drag
$D(\theta)$	directivity factor
f	frequency
G	ground effects factor
g	gravitational acceleration
h	altitude (see fig. 2)
I	source noise intensity
L	lift
M	aircraft Mach number
$\dot{m}$	mass flow rate
$m(\theta)$	forward speed exponent
$\overline{p_o^2}$	mean-squared pressure at observer
R	gas constant
$R(t)$	aircraft position vector
$r(t)$	observer position vector relative to aircraft
r_o	reference distance
S	entropy
$S(f)$	frequency factor
T	temperature
T_a	ambient temperature
$T(h,V,\Omega_c)$	engine thrust
t	time

U	universal power function for jet noise
V	aircraft velocity
$\dot{V}$	aircraft acceleration
W	aircraft weight
x,y	reference coordinates (see fig. 2)
α	coefficient of absorption
Γ	reflected wave factor
γ	thrust angle
θ,ϕ	aircraft orientation angles
Π	acoustic power
ρ	density
ρ_a	ambient air density
Ω_c	corrected engine rotor speed
ω	density exponent
EPNL	effective perceived noise level
PNL	perceived noise level
PNLT	tone-corrected perceived noise level
OASPL	overall sound pressure level
SPL	sound pressure level

NOISE PREDICTION METHODOLOGY: ANOPP

The essential ingredients to aircraft noise prediction (see fig. 2) are (1) the source intensity I, (2) the aircraft position given by the vector R(t), (3) the aircraft orientation given by θ and ϕ, and (4) the location of the observer given by the vector r(t). In addition, the atmospheric and ground-impedance characteristics indicated by A and G must be specified. The source intensity I is the sum of the individual noise sources and their associated directivity $D_i(\theta,\phi)$ and spectral $S_i(f)$ factors:

$$I = \sum_{i=1}^{\substack{\text{All}\\\text{Sources}}} \frac{\Pi_i}{4\pi r_o^2} D_i(\theta,\phi)\, S_i(f) \tag{1}$$

The mean-squared pressure at the observer is given by

$$\overline{p_o^2} = \rho_a\, c_a\, A|G|^2 \frac{I}{(r/r_o)^2} \tag{2}$$

where A accounts for atmospheric absorption and G accounts for ground effects. When the source intensity is specified as the mean-squared pressure in, say, 1/3-octave frequency bands, the resulting mean-squared pressure at an observer in these same frequency bands can then be calculated and converted to sound pressure level (SPL) in decibels. Subsequent computation of perceived noise level (PNL), tone-corrected perceived noise level (PNLT), effective perceived noise level (EPNL), or some other logarithmic noise scale may then be accomplished (ref. 1).

Generation of Noise-Critical Parameters

Aircraft flyover noise depends on the aircraft flight trajectory and on the throttle setting (thermodynamic state of the engine) during flight. The noise prediction algorithms implemented in ANOPP require as input data, values of specific propulsion cycle parameters together with the resulting flight trajectory of the aircraft.

Propulsion cycle. - The noise generated by aircraft engines is related to the thermodynamic state of the engine during the flight. For example, the combustion noise depends on pressures and temperatures at the combustor inlet and exit stations, and the fan noise is correlated with the total temperature rise across the fan. These variables are obtained from a temperature-entropy diagram for the engine cycle, as shown in figure 3 (ref. 2). This diagram represents the thermodynamic state of the engine and contains the information which is necessary for the prediction of propulsion noise. Presently, ANOPP accepts data from an externally generated T-S diagram as input; however, since the aircraft trajectory also depends on these data, a capability is being added for computing the engine cycle within the ANOPP system.

Flight dynamics and aircraft trajectory. - Noise prediction requires a knowledge of the position of both the aircraft and the observer. Since ANOPP accounts for directivity effects, the aircraft orientation must also be known. For the purpose of this paper, a simple two-degree-of-freedom analysis of the trajectory is adequate. Figure 4 shows typical flight-path segments for a take-off and for a landing maneuver. The take-off has a ground roll, a lift-off, an acceleration, and a pull-up segment; the landing has approach, flare, and roll-out segments.

The basic equations controlling the trajectory are the conditions of dynamic equilibrium tangent to and normal to the flight path. The tangential equation is

$$\frac{W}{g} \dot{V} = -W \sin \gamma + T - D \qquad (3)$$

where W is the aircraft weight; T, the thrust, which is a function of altitude, aircraft velocity, and corrected rotor speed; D, the aerodynamic drag; V, the aircraft velocity; and γ, the thrust angle. The normal equation is

$$L = W \cos \gamma \qquad (4)$$

where L is the aerodynamic lift. Combining these equations gives

$$\frac{\dot{V}}{g} = \frac{T}{W} - \frac{\cos \gamma}{(L/D)} - \sin \gamma \qquad (5)$$

Note that different aircraft may have the same trajectories if the similarity parameters T/W and L/D in equation (5) are equal and if the aircraft are operated in the same fashion.

Component Noise Sources: Jet Noise

Typical noise-generating components of a fan jet engine are indicated in figure 5. The ANOPP library of prediction modules contains methods for computing the acoustic power Π for most of the significant component noise sources on modern jet-powered CTOL aircraft, including jet noise (refs. 3 and 4), fan and compressor noise (ref. 5), combustion noise (ref. 6), turbine noise (ref. 7), and airframe noise (refs. 8 and 9). The procedure for predicting the acoustic power of a propulsion noise source using parameter values from the engine cycle is outlined below for jet noise. The procedures for other propulsion noise sources are similar and are described by Zorumski (ref. 10).

The noise from a single circular jet (see fig. 6) is predicted by using the semiempirical formulae proposed by the Society of Automotive Engineers aircraft noise standards committee (ref. 3). The SAE procedure gives the total acoustic power from the jet as

$$\Pi_{JET} = 6.67 \times 10^{-5}\ \dot{m}c_a^2 \left(\frac{\rho_{JET}}{\rho_a}\right)^{\omega - 1} U\left(\frac{V_{JET}}{c_a}\right) \tag{6}$$

where $U\left(\frac{V_{JET}}{c_a}\right)$ is the universal power curve for jet noise, which follows approximately a V_{JET}^7 law in the velocity range up to $\frac{V_{JET}}{c_a} = 2$ and a lower exponential value at higher velocities. The density exponent ω varies from -1 at low jet velocities to +2 at high jet velocities. The intensity of a static jet noise source is given by

$$I_{STATIC} = \frac{\Pi_{JET}\ D(\theta)\ S(f)}{4\pi r_o^2} \tag{7}$$

where $D(\theta)$ and $S(f)$ are directivity and frequency factors peculiar to jet noise, and directivity dependence on the angle ϕ has been dropped. The intensity of a moving jet noise source is given by

$$I_{FLIGHT} = (1 - M\cos\theta)^{-1} \left[(V_{JET} - V)/V_{JET}\right]^{m(\theta)} I_{STATIC} \tag{8}$$

where the additional terms account for observed effects for an aircraft in forward flight.

Finally, the mean-squared pressure at an observer location is calculated using

$$\overline{p_o^2} = \rho_a\ c_a\ A|G|^2\ I_{FLIGHT} \tag{9}$$

The jet noise prediction procedure is summarized in figure 7.

CTOL NOISE PREDICTION

The ANOPP flow chart for a typical CTOL noise prediction is given in figure 8. The aircraft performance section of the program consists of subprograms for the engine cycle analysis and for the aircraft trajectory analysis. The engine cycle analysis is used to predict the thermodynamic state of the engine, that is, pressures, temperatures, and flows at points within the engine, from engine component data. These data are necessary inputs to the noise source prediction modules of ANOPP. The aircraft trajectory subprogram predicts the distance, altitude, and pitch of the aircraft as functions of time from an input of the thrust setting and angle-of-attack scheduling, the aerodynamic data, and the weight of the aircraft. Alternately, the cycle and trajectory data may be input as time-dependent tables. Once the cycle and trajectory computations are complete, the source noise power Π, directivity D, and spectrum S are evaluated for each noise source. Shielding effects may then be introduced by modifying the directivity. The noise from different sources is then added and the effects of spherical spreading and atmospheric attenuation are introduced to obtain the time history of the acoustic spectrum at a selected observer position. With this spectrum history, the subjective effects of the noise, such as perceived noise level (PNL) and effective perceived noise level (EPNL), may be computed.

ANOPP ARCHITECTURE

ANOPP architecture provides for the efficient generation, handling, and storage of the large quantities of data required by the aircraft noise prediction process through an extremely flexible data base management scheme. Noise prediction methodologies are implemented in independent functional modules that are scheduled by the executive system at execution time in accordance with simple control instructions provided by the user. Job progress may be inspected or protected from computer failure by a checkpoint-restart provision. A typical CTOL noise prediction including trajectory analysis, atmospheric modeling, propagation and ground effects, and calculation of component and total noise levels at selected observer positions can all be accomplished in one computer run with turnaround time on the order of an hour or two.

ANOPP VALIDATION STATUS

Validation of ANOPP commences at the module level. The circular jet noise module, for example, implements the equations of reference 2, which are the result of correlation with a data base of approximately 30 000 measurements. The inverted flow (coannular) jet noise equations implemented in a separate module have been correlated against nearly 200 000 measurements on subscale model jets. Prediction methodologies for other component noise sources are to a lesser degree also validated at the module level but far less high-quality data are available. In particular, much more data are required for turbomachinery noise sources, which can dominate or contribute significantly to aircraft noise levels for certain operating conditions. Although ANOPP incorporates the best available prediction technology, much work is required in order to achieve the highest possible level of confidence in each component noise source prediction method.

Measured aircraft flyover data together with the required values of engine cycle parameters have recently become available which permit comparison with predicted noise levels. In figure 9 measured data for a Learjet airplane in level flight at an altitude of 122 m (400 ft) are compared with ANOPP predicted levels. The ANOPP computations were made using only jet, shock cell, and combustion noise, since contributions from other sources were judged to be negligible (see fig. 8). The predicted perceived noise level as a function of angle to engine inlet averaged about 3 dB low. The spectrum at $\theta = 120°$ was, however, well predicted.

In figure 10 measured data for a Concorde aircraft in level flight at an altitude of 300 m (1000 ft) are compared with ANOPP predicted levels, again using only the jet, shock cell, and combustion noise modules. The predicted perceived noise level agreement with data is good as is the spectrum agreement at $\theta = 130°$. The difference between measured and predicted levels for the spectrum at frequencies above 2000 Hz may be due to contributions of turbomachinery noise sources, which were not included in the ANOPP prediction. For both these examples the measured and predicted effective perceived noise levels (EPNL) were in excellent agreement.

In a recent informal study which involved measured data for several aircraft with each operating at power settings corresponding to both take-off and landing, the ANOPP results, which included predictions for turbomachinery and airframe noise, averaged 2 to 3 dB below the measured perceived noise levels. The accuracy of ANOPP predictions was generally good and indicated that ANOPP is a viable system and acceptable for use in the preliminary design process.

Present validation plans call for detailed comparison of measured and predicted noise levels for high-bypass-ratio, wide-body aircraft. Every attempt will be made to identify component noise sources through spectral analysis and other techniques. Data for low power settings for which jet noise is not the dominant source will be included in order to validate turbomachinery, combustion, and airframe noise prediction methods.

CONCLUDING REMARKS

A comprehensive, efficient, user-oriented aircraft noise prediction program (ANOPP) developed by NASA has been described. The program implements semiempirical methods for predicting aircraft noise from a knowledge of the trajectory and the thermodynamic cycle of an existing or proposed aircraft. Comparisons of measured and predicted noise levels for existing CTOL aircraft indicate an acceptable level of accuracy. Other comparisons, not presented in this paper, also corroborate this conclusion. Further validation studies involving high-bypass-ratio propulsion systems together with continued improvements and application of the ANOPP system to NASA projects are anticipated.

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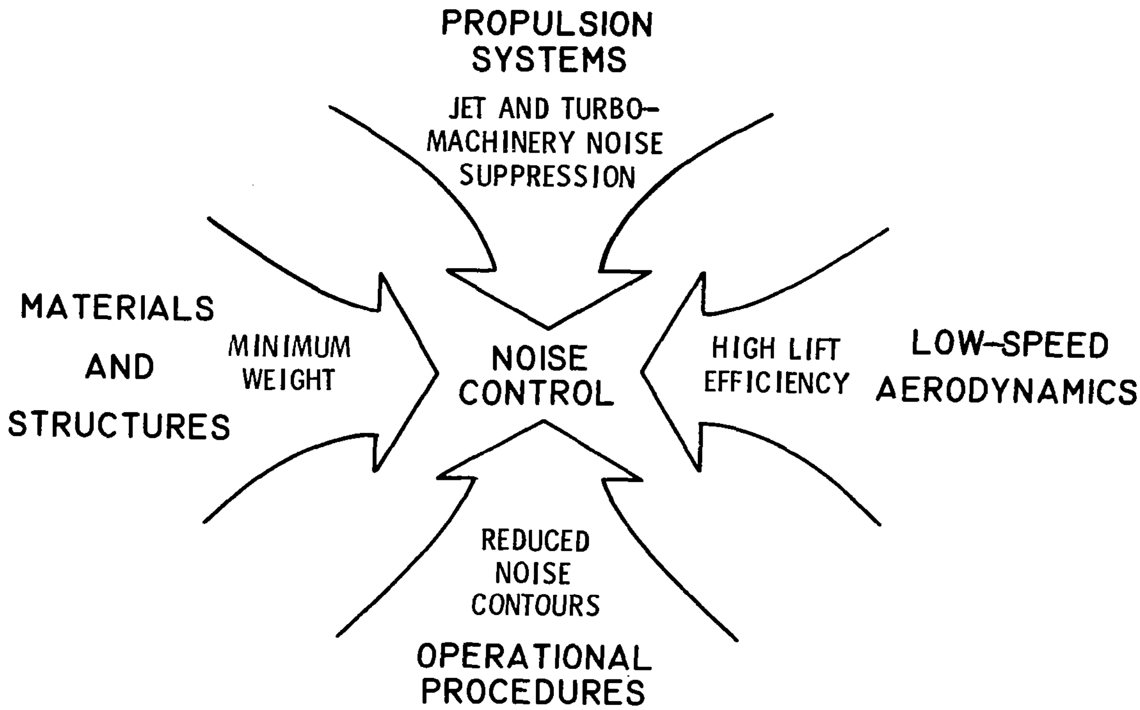

Figure 1.- Noise is an aircraft design constraint.

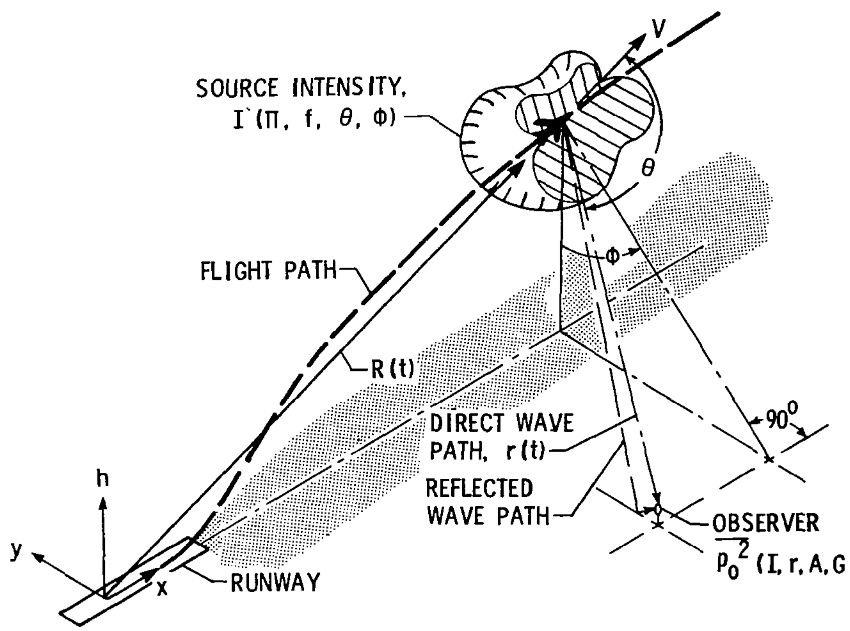

Figure 2.- Required ingredients for aircraft noise prediction.

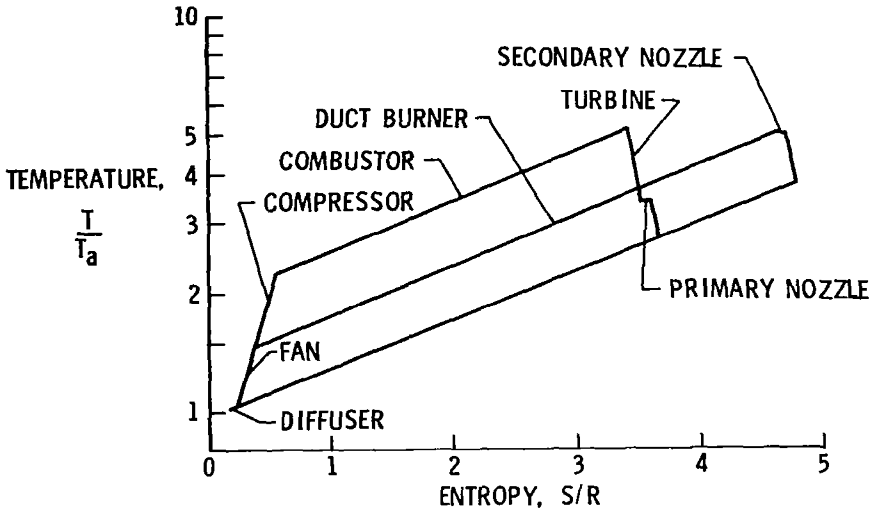

Figure 3.- Representative propulsion cycle.

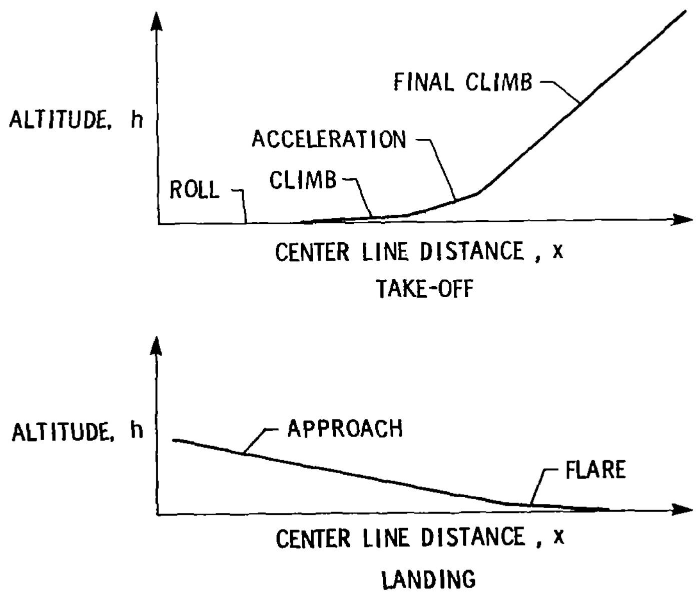

Figure 4.- Flight trajectories.

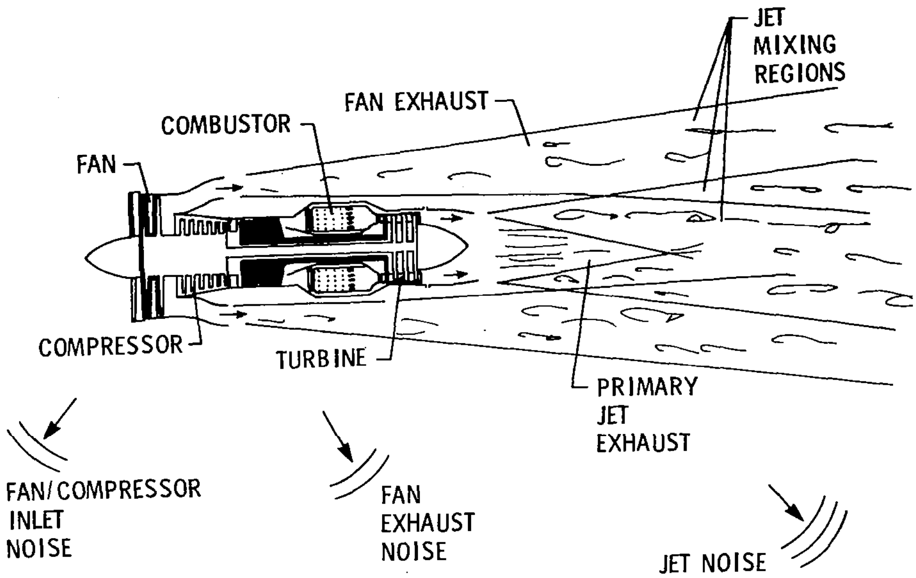

Figure 5.- Propulsion noise sources.

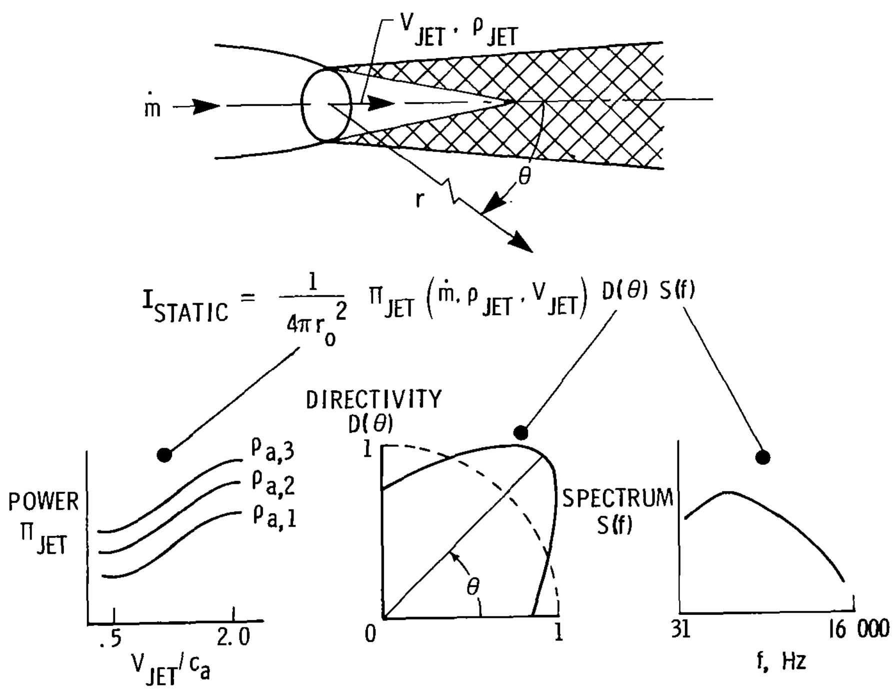

Figure 6.- Jet noise.

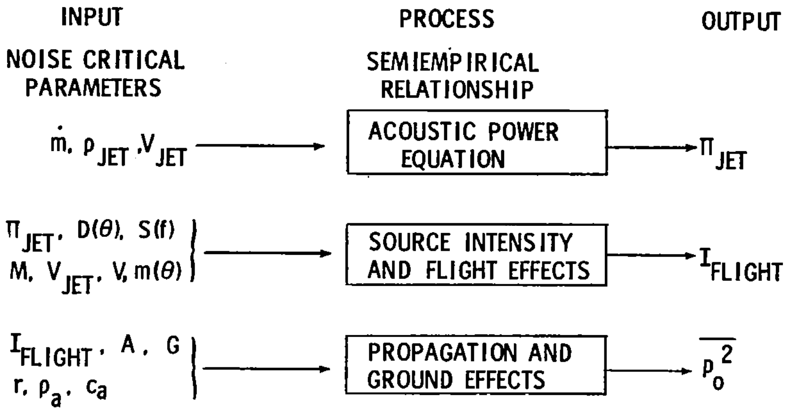

Figure 7.- Jet noise prediction procedure.

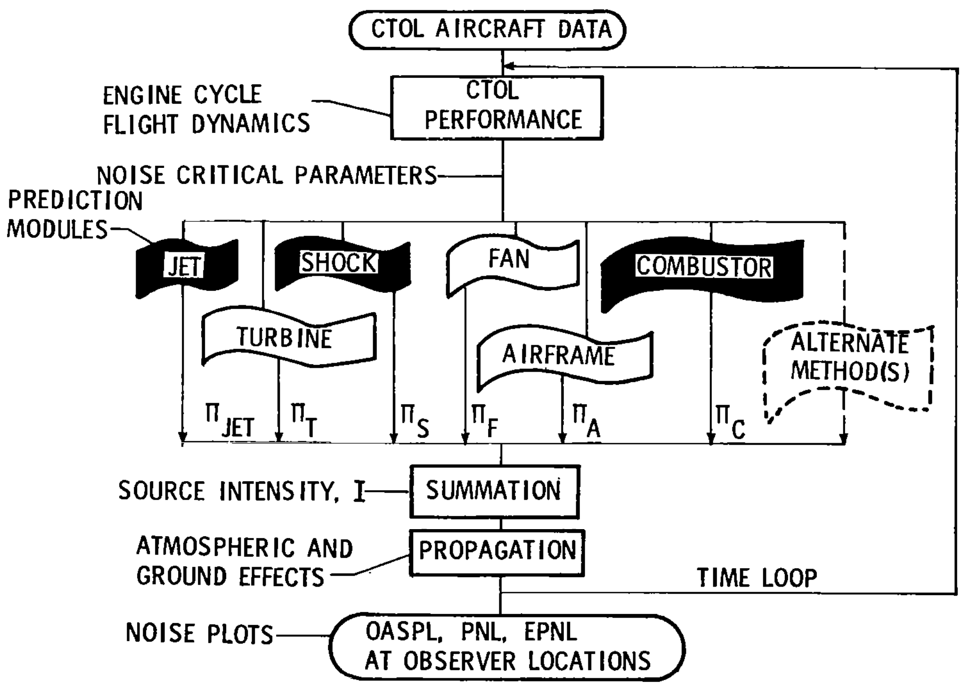

Figure 8.- CTOL noise prediction. (Highlighted prediction modules were used for calculations shown in figs. 9 and 10.)

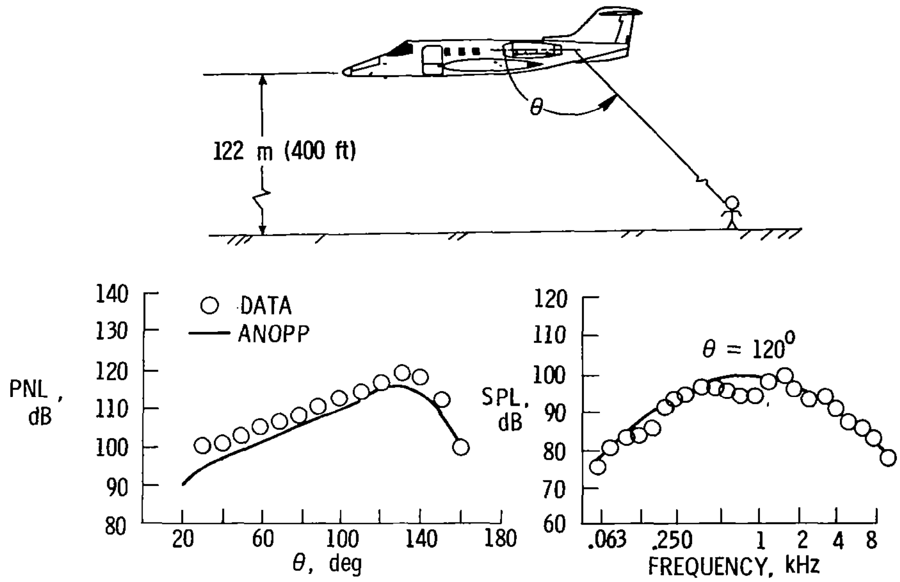

Figure 9.- ANOPP flyover noise validation — Learjet.

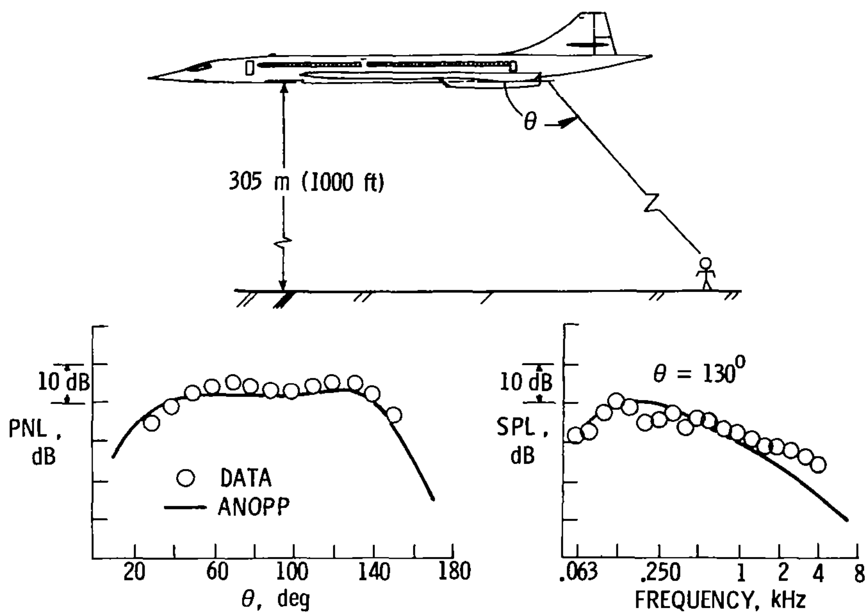

Figure 10.- ANOPP flyover noise validation — Concorde.