NEAR-FIELD NOISE PREDICTIONS

OF AN AIRCRAFT IN CRUISE

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INTRODUCTION

The application of laminar-flow wing designs will offer significant drag reduction and fuel savings on large commercial transports. Traditionally, surface contamination, surface defects, vibration and turbulence have prevented practical application on commercial aircraft. These concerns are being overcome through innovative research.

Noise generated by the aircraft is now being investigated as a cause of premature transition of a laminar boundary layer. An acoustic disturbance with the correct frequency and intensity is known to cause transition of a laminar boundary layer under laboratory conditions. It is speculated that aerodynamic noise sources may have the correct characteristics to cause boundary-layer transition under flight conditions.

One important element in determining whether a laminar boundary layer will transition (due to the presence of an acoustic source) is an accurate prediction of the noise source and its characteristics. Predictions yield not only the total noise level, which can be verified by measurements, but also information concerning the characteristics of the individual noise sources. The prediction of the near-field noise environment of an aircraft in cruise has become an important element in the research and development of wing designs that can maintain laminar flow at a cruise speed of Mach 0.8.

CAUSES OF TRANSITION

- **Surface Contamination**
  - **Insect Residue**
  - **Ice Crystals**
- **Surface Defects**
- **Vibration**
- **Turbulence**
- **Noise**

LOCKHEED NEAR-FIELD NOISE PREDICTION PROGRAM

A computer program was developed by Lockheed-Georgia Company for the purpose of predicting the near-field acoustic environment of an aircraft in cruise (Refs. 1, 2, 3). This program is designed to compute the 1/3 octave band spectra and Overall Sound Pressure Level (OASPL) at a point on an aircraft operating at high altitude and high-speed conditions.

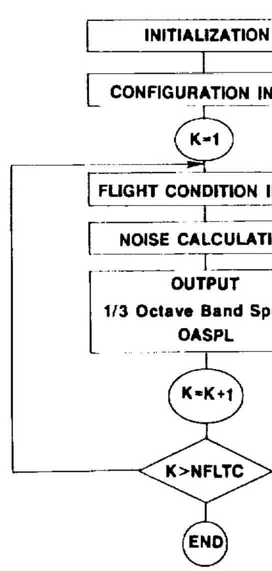
Noise sources predicted by the code can be divided into two categories: propulsion sources and airframe sources. The propulsion system of the aircraft is assumed to be a turbojet or turbofan engine. The components of the engine which produce noise are fan/compressor, combustor, turbine and jet. Acoustic suppression material may be used in the engine and is accounted for in the prediction procedure.

The airframe itself is also a producer of noise. The two airframe sources predicted by the code are trailing-edge noise and turbulent boundary-layer noise.

The noise source algorithms are based on empirical formulations derived from data at near sea level conditions with relatively low or no forward speed effects. Since the noise predictions are for high speed and high altitude, corrections for forward speed and altitude are required.

A forward speed correction is required to determine the correct emission angle and propagation distance at the time the sound is emitted. The correction is a function of the observed angle and distance at the time the sound is received. Forward speed corrections are also made to the OASPL to account for convective and dynamic amplifications. (A detailed discussion of these forward speed corrections can be found in Ref. 1.)

An altitude correction is made by adjusting the acoustic impedance to correspond to the ambient conditions at altitude. Other altitude corrections such as atmospheric attenuation and atmospheric absorption are assumed to be small in the near field.



NEAR-FIELD NOISE SOURCES

For the purpose of this report, the propulsion system will be a high-bypass turbofan engine. This propulsion system is widely used in large commercial transports where laminar-flow wing designs would be most beneficial. Noise prediction procedures are provided for the four basic jet engine components i.e., the fan/compressor, combustor, turbine and jet. With these basic components the noise generated by a high bypass turbofan can be modeled.

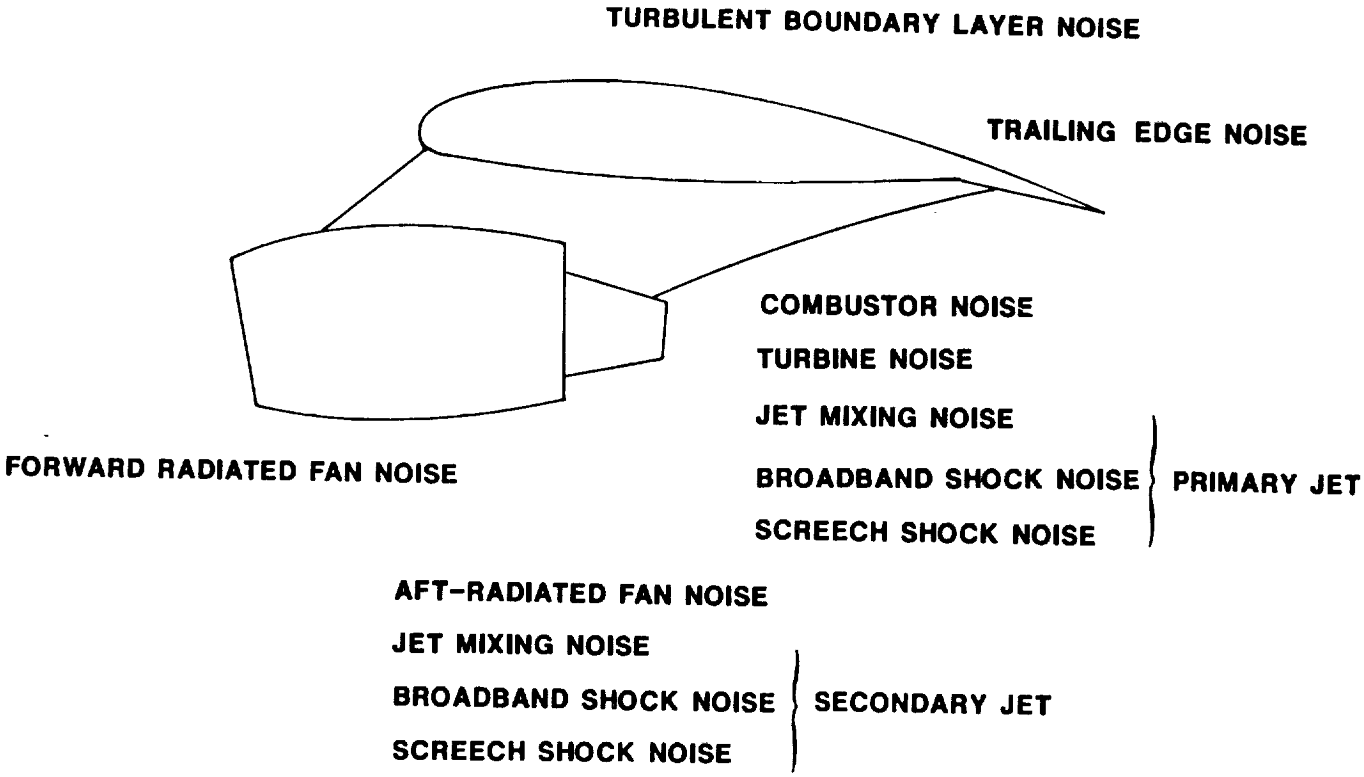
Fan noise is generated by the fan blade interacting with the incoming flow. Noise from the fan can radiate forward through the inlet and aft through the secondary jet nozzle. In addition to the broadband component of the noise spectra, discrete tones occur at the blade passing frequency and its harmonics. If the tip speed of the fan blade is supersonic, subharmonics of the blade passing frequency are also generated which only propagate forward. Compressor noise is predicted by the same method used to predict fan noise. However fan noise usually dominates compressor noise and is not considered in this report.

Combustor noise and turbine noise both propagate through the primary nozzle. Combustor noise is a low-frequency source while turbine noise is a high-frequency source. Like fan noise, turbine noise is composed of a broadband spectra and discrete tones occurring at the blade passing frequency and higher harmonics. Typically, the blade passing frequency of the turbine is so high that only the fundamental tone is included in the spectra.

Jet noise, which is made up of three components, propagates from both the primary nozzle and the secondary nozzle. The first component of jet noise is mixing noise. Mixing noise is always present in a jet and is the result of the jet interacting with the ambient air. The second and third components of jet noise are broadband shock and screech shock noise. Both broadband shock and screech shock occur only when the jet velocity exceeds the local speed of sound in the jet. The onset of broadband shock noise is predicted as soon as the jet flow conditions are supersonic. The onset of screech shock noise is not well defined and can usually be controlled with an appropriate nozzle design. Consequently screech shock noise is not considered in this report.

The two airframe sources, turbulent boundary-layer noise and trailing-edge noise are also included for study in this report.

NEAR-FIELD NOISE SOURCES



HIGH BYPASS TURBOFAN MODEL DESCRIPTION

Input parameters required for the noise prediction of a high bypass turbofan engine are obtained using estimated performance parameters from a full-scale high bypass turbofan with a maximum continuous thrust rating of 38,000 lb. Temperature and pressure ratios are known for the fan discharge, the combustor inlet and the low pressure turbine exhaust as a function of flight Mach number, altitude and thrust setting. The corrected rotational speeds of the fan and high pressure compressor, the corrected fan mass flow rate, the bypass ratio, and the fuel mass flow rate are also known. With this information, the necessary input data for a complete noise prediction of a high bypass turbofan are computed.

Predictions are made for two observer locations on a line parallel to the engine axis as shown.

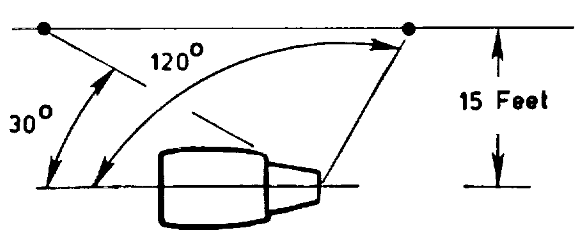
NOISE STUDY OF A FULL SCALE HIGH BYPASS TURBOFAN ENGINE IN CRUISE

Engine configured without acoustic suppression

Engine performance data given as a function of

- **Altitude**
- **% Thrust**
- **Flight Mach No.**

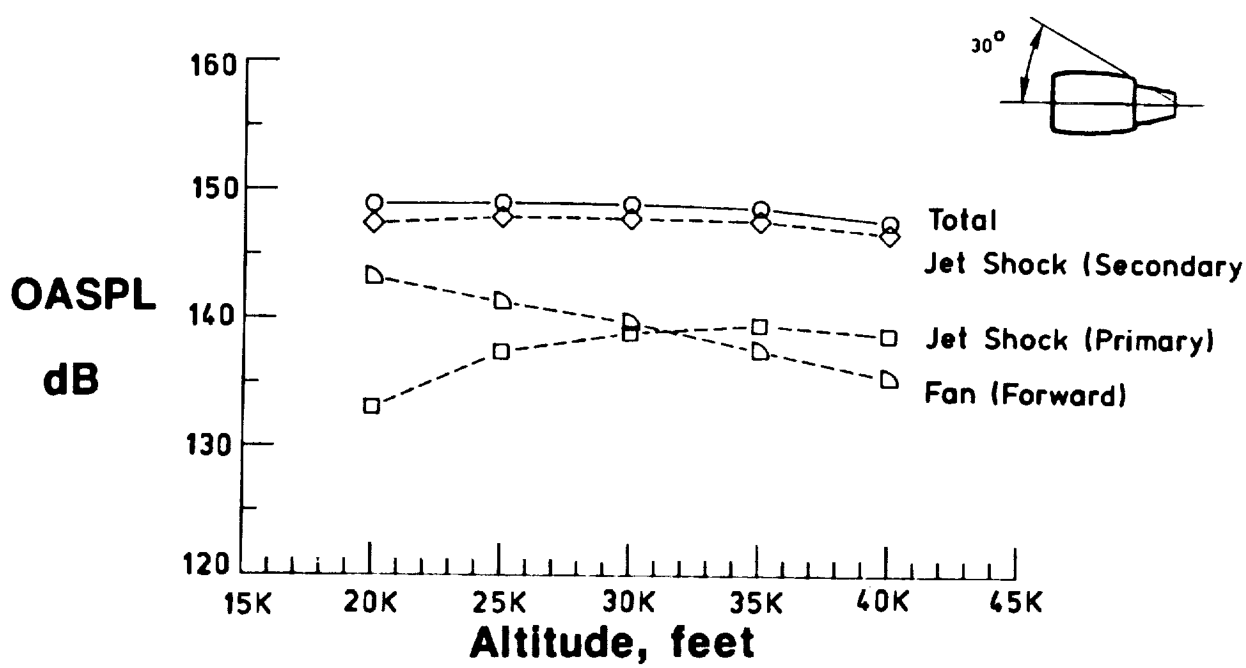
OBSERVER LOCATION



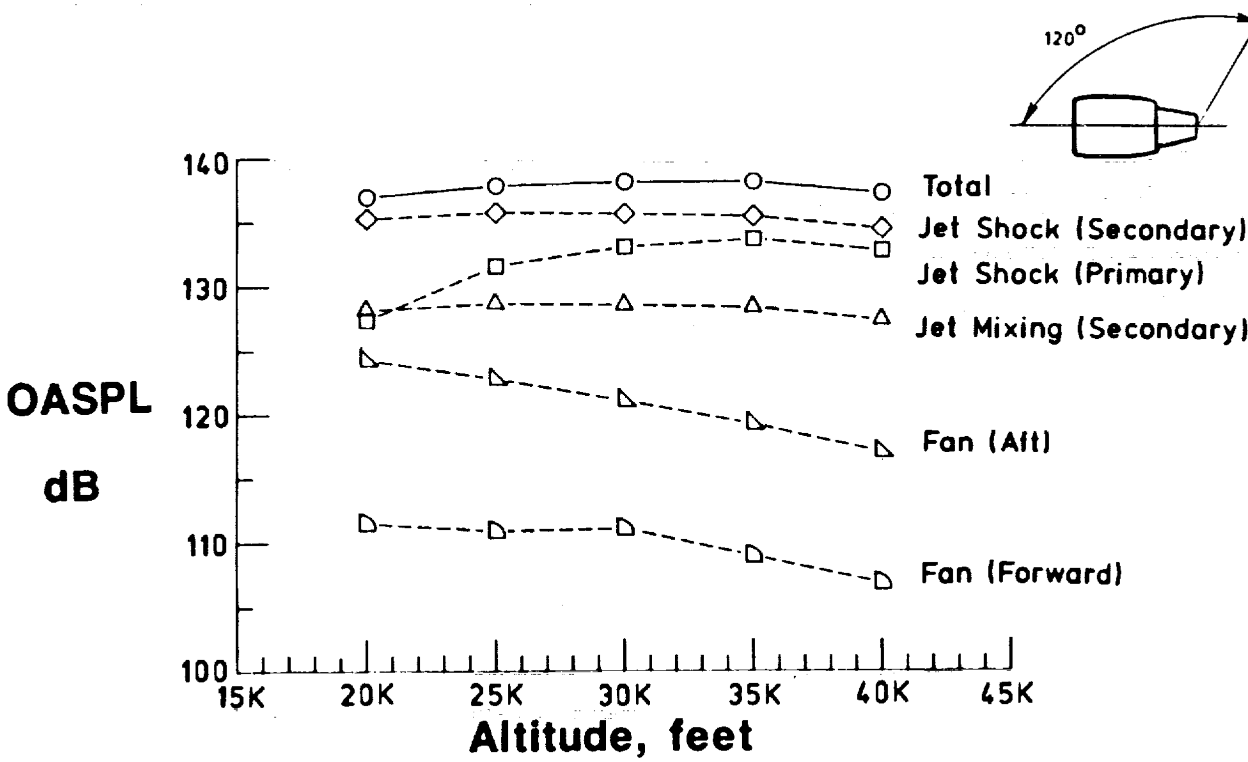
ALTITUDE VARIATION

Noise levels are investigated by varying the altitude from 20,000 feet to 40,000 feet while operating at maximum continuous thrust and a flight Mach number of 0.8. Parameters relevant to noise predictions and engine performance vary significantly with altitude. For example the mass flow rate required by the fan at 40,000 feet is 46% less than that required at 20,000 feet. Since fan noise correlates directly with the mass rate a reduction in the OASPL as a function of altitude is realized.

It would seem reasonable to expect total OASPL to also decrease with increasing altitude. However, this was not the case. Two offsetting factors contribute to this result. First, the acoustic impedance decreased with increasing altitude. Second, the intensity of the broadband shock noise, which is determined by the jet Mach number, increased as a function of altitude by about the same amount as the acoustic impedance decreased. This resulted in a constant OASPL as a function of altitude.

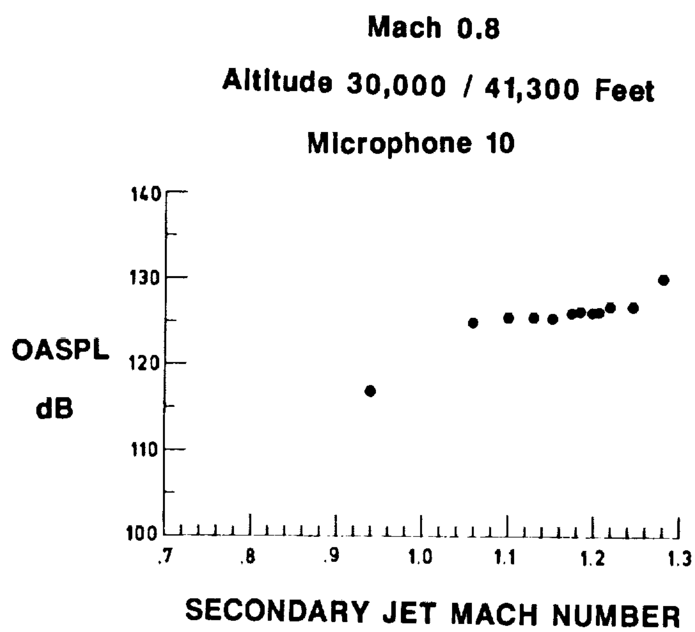


ALTITUDE VARIATION
Mach 0.8
100% Maximum Continuous Thrust

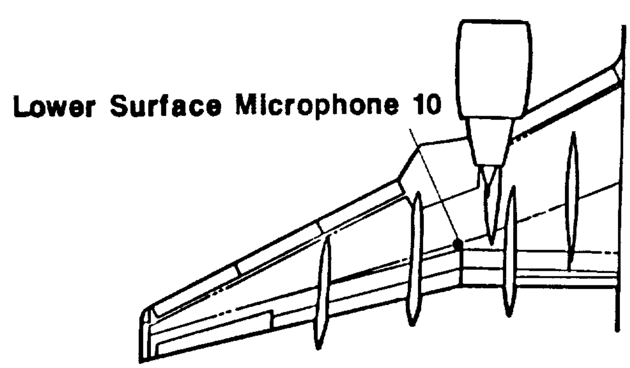


BOEING 757 GLOVE TEST DATA

During the Boeing 757 glove test, data were obtained over an altitude range of 30,000 feet to 41,300 feet. The OASPL is plotted as a function of the secondary jet Mach number as shown. In this figure, the OASPL maintains a level of 126 dB for secondary jet Mach numbers between 1.0 and 1.28. When the jet Mach number exceeds 1.0, broadband shock noise is present and follows the trend of constant noise level as a function of altitude. When the jet Mach number is less than 1.0, the noise level is reduced as would be expected since broadband shock noise is not present in the secondary jet.

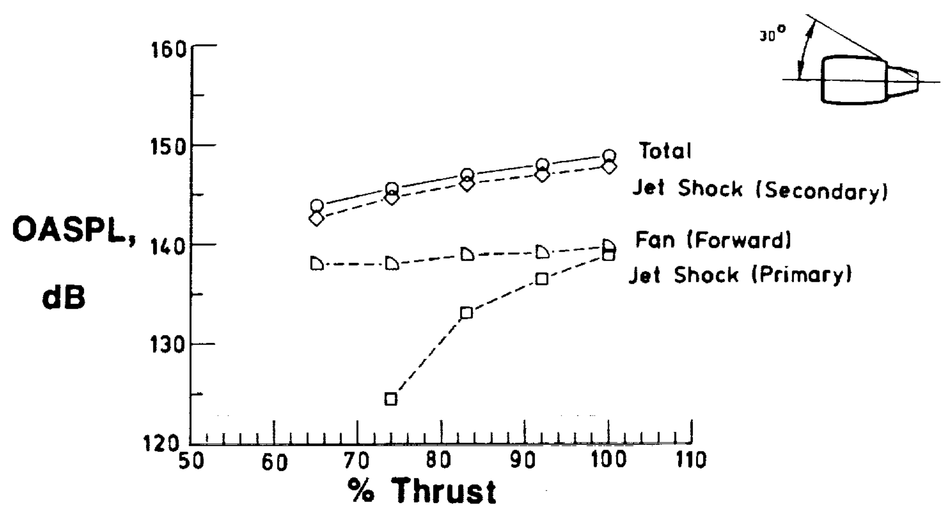


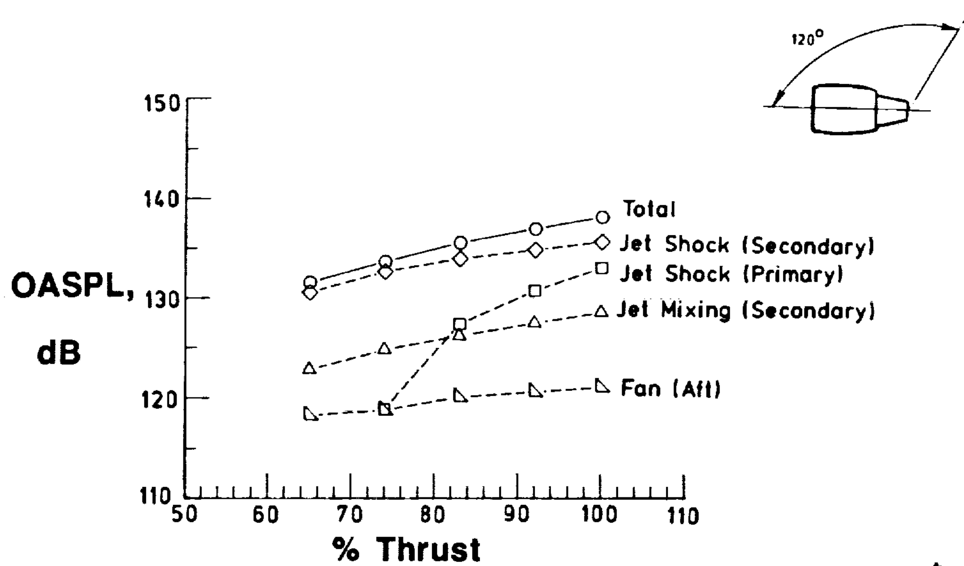
MICROPHONE LOCATION



THRUST VARIATION

Noise levels are also investigated by varying the thrust of the jet while operating at a flight Mach number of 0.8 and an altitude of 30,000 feet. As expected the total OASPL increases with increasing thrust. However the increase is not as great as might be expected. A reduction of 64% in thrust results in only a 5 dB decrease at 30° and 6 dB at 120°. The dominate noise source is again broadband shock noise from the secondary jet. In fact the remaining propulsion noise sources contribute very little to the total OASPL. Examination of the jet conditions indicates that additional thrust is generated by the primary jet with the jet Mach number increasing from .96 at 64% thrust to 1.17 at 100% thrust. The secondary jet conditions on the other hand increase from 1.11 at 64% thrust to 1.18 at 100% thrust. It is worth noting that the secondary jet conditions are supersonic even at low thrust accounting for the presence of broadband shock noise.





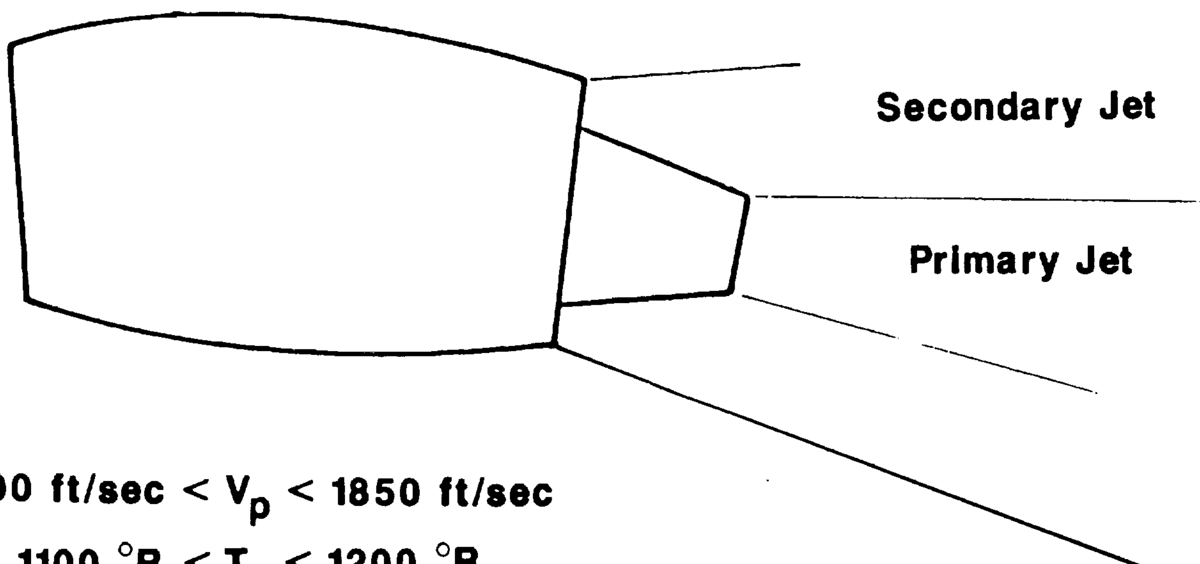
TYPICAL JET CONDITIONS DURING CRUISE

Broadband shock noise from the secondary jet has emerged as a very important noise source during cruise. Even though the secondary jet velocity at total temperatures is much lower than the primary jet, the Mach number in the secondary jet is typically supersonic when varying altitude and thrust. The supersonic conditions in the secondary jet are primarily the result of the low total temperature in the jet. Not only is broadband shock noise typically present in the secondary jet but the secondary flow acts as a shield to reduce the effect of the noise levels produced by the primary jet.

$1000 \text{ ft/sec} < V_s < 1200 \text{ ft/sec}$

$500\,^{\circ}R < T_s < 575\,^{\circ}R$

$1.00 < M_{js} < 1.15$



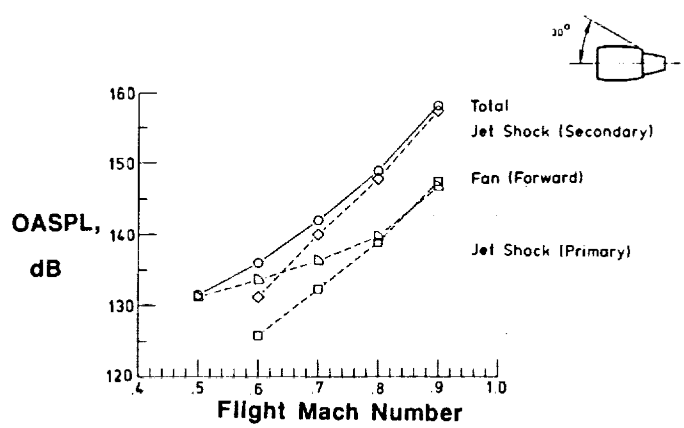
$1400 \text{ ft/sec} < V_p < 1850 \text{ ft/sec}$

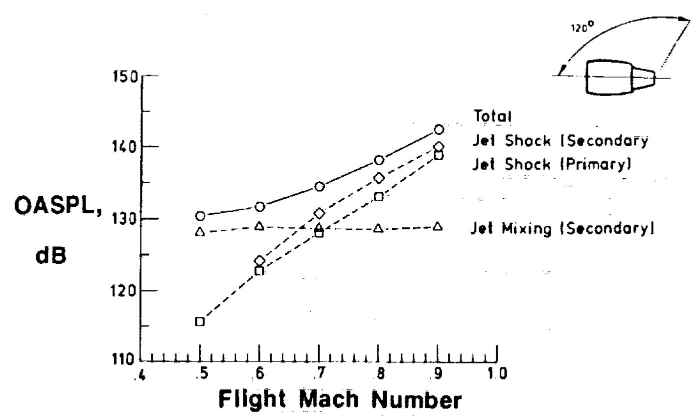
$1100\,^{\circ}R < T_p < 1200\,^{\circ}R$

$0.93 < M_{jp} < 1.25$

FLIGHT MACH NUMBER VARIATION

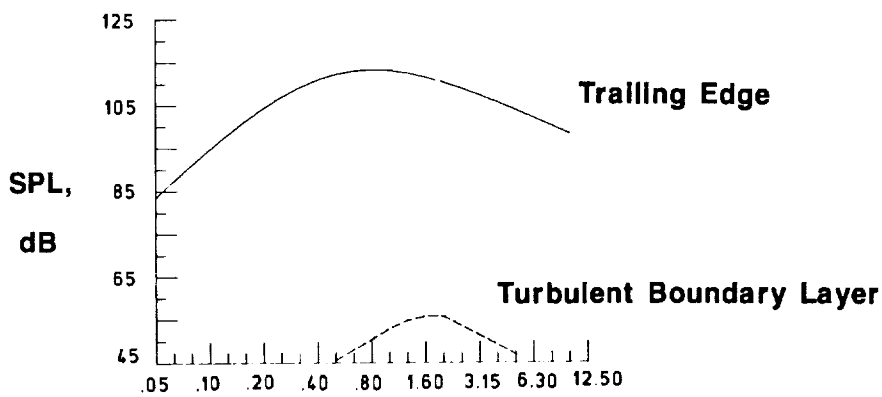
Finally noise levels are examined by varying the flight Mach number from 0.5 to 0.9 in 0.1 increments. Thrust and altitude are maintained at 100% and 30,000 feet, respectively. At a flight Mach number of 0.5, broadband shock noise is absent from both the primary and secondary jets. An increase in the flight Mach number to 0.9 dramatically increases the total OASPL at both observer locations. An increase of 26 dB is observed at 30° and an increase of 12 dB is observed at 120°. This increase in noise is the result of several factors. One factor is that the engine performance parameters are at higher levels as the flight Mach number increases; another is that the forward speed correction for the noise sources is larger as the flight Mach number increases.



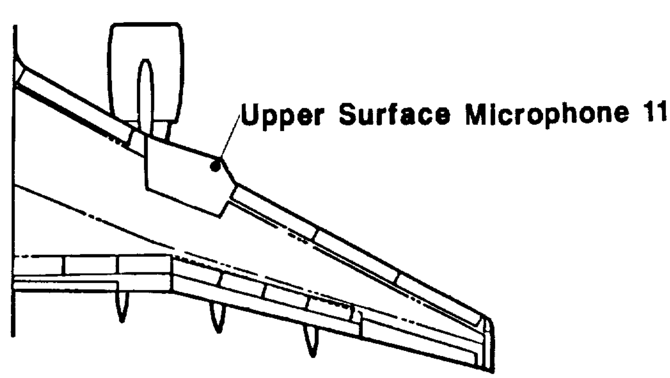


Airframe sources are important in determining the total OASPL especially in cases where a surface is shielded from the propulsion system. Recent measurements on the wing of a Boeing 757 showed that noise levels on the upper surface were unaffected by increases in the engine RPM which is mounted by a pylon from the wing lower surface. This spectrum shows the contributions of turbulent boundary-layer noise and trailing-edge noise at an upper surface point near the leading edge of a Boeing 757 wing. The turbulent boundary-layer noise levels predicted by this code are typically 10 to 15 dB lower than the trailing-edge noise levels as shown. Therefore turbulent boundary-layer noise does not contribute to the total OASPL.

Altitude 40,000 Feet; Mach 0.8; Mic 11

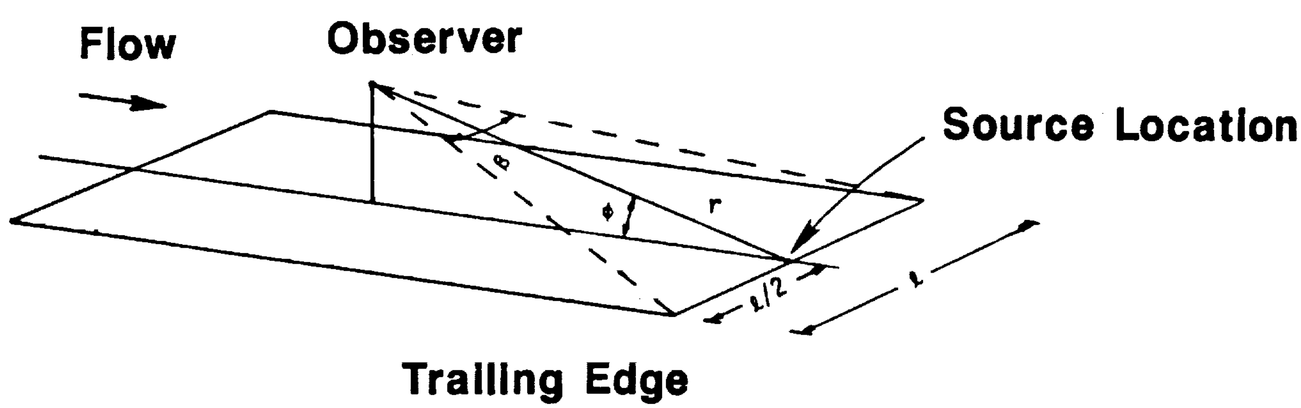


MICROPHONE LOCATION



Trailing-edge noise is the result of a sudden change in the pressure as a boundary layer is convected past a surface trailing edge. As the boundary layer approaches the trailing edge, the pressure differential between the upper and lower surface is forced to zero to satisfy the Kutta condition. This, in turn, results in an induced pressure field which propagates away from the trailing-edge region (Ref. 4).

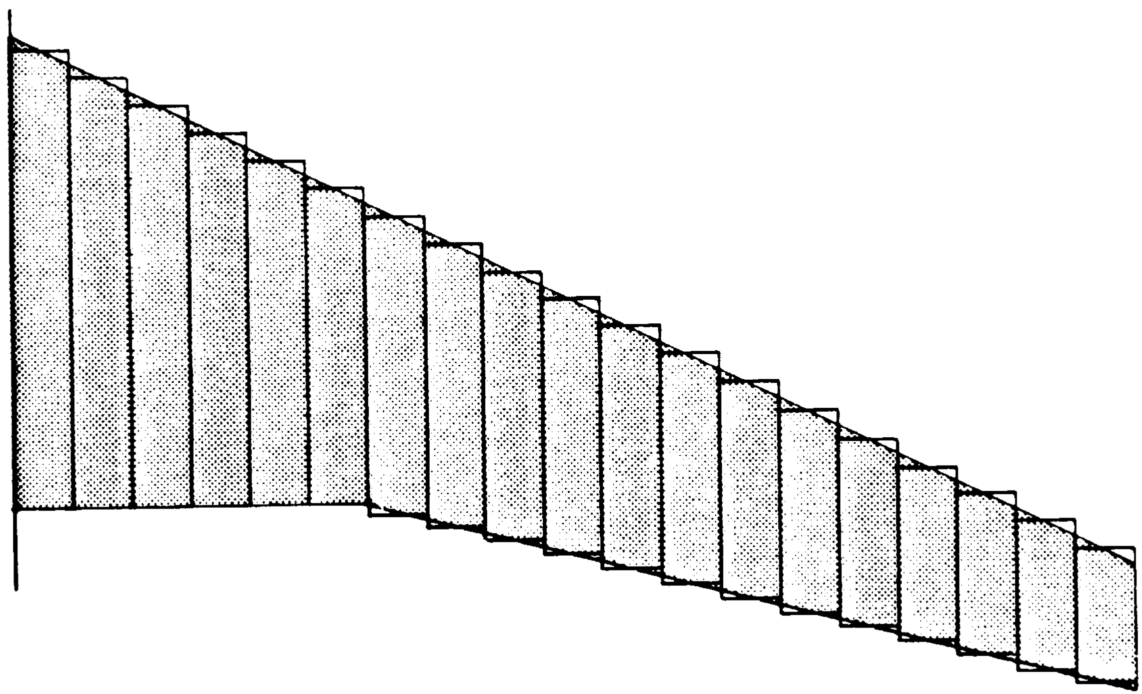
The algorithm for the prediction of trailing-edge noise is based on a flat plate analysis. The observer is restricted to be on the centerline of the plate and the flow must leave perpendicular to the trailing edge.



Source/Observer geometry for trailing edge noise

TRAILING-EDGE NOISE

Trailing-edge noise is a distributed source and not conducive to point source analysis. The wing of a Boeing 757 therefore is approximated as a series of adjacent flat plates. Contour levels are generated on a grid of 121 chordwise and 201 spanwise stations. This corresponds to a point every 3 inches in both the spanwise and chordwise directions and gives sufficient resolution for smooth contour levels.

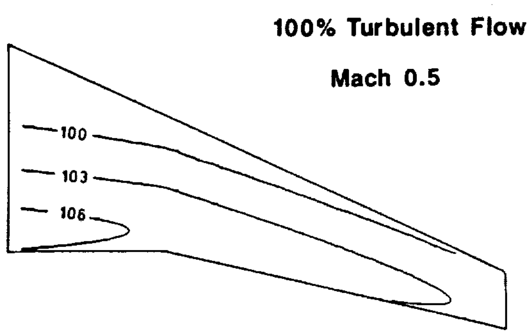


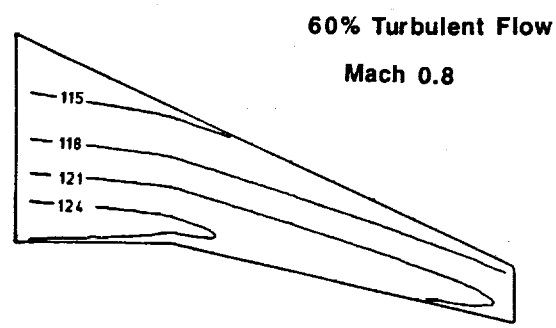
Flat plate approximation of a Boeing 757 wing

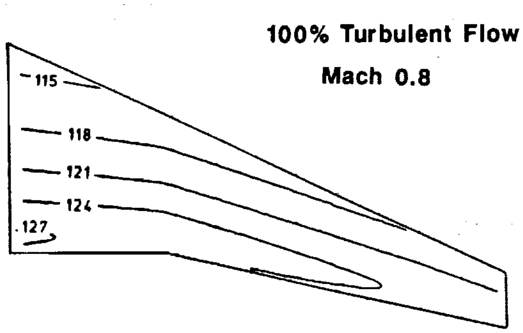
TRAILING-EDGE NOISE

Trailing-edge noise is a function of primarily two factors, the flight Mach number and the thickness of the turbulent boundary-layer at the trailing-edge. An increase in the flight Mach number significantly increases the noise levels. An increase in the flight Mach number from 0.5 to 0.8 for example will increase the peak Overall Sound Presure Level by 21 dB.

The effect of varying the turbulent boundary-layer thickness is perhaps of greater interest to laminar-flow studies, since a laminar boundary layer on the leading-edge portion of the wing will reduce the thickness of the turbulent boundary-layer thickness at the trailing edge. A laminar boundary layer is simulated over the first 40% of the wing by using a length scale of 60% of the chord to calculate the turbulent boundary-layer thickness. The resulting reduction in noise level is unfortunately not very significant. Peak noise levels are reduced by only 3 dB.

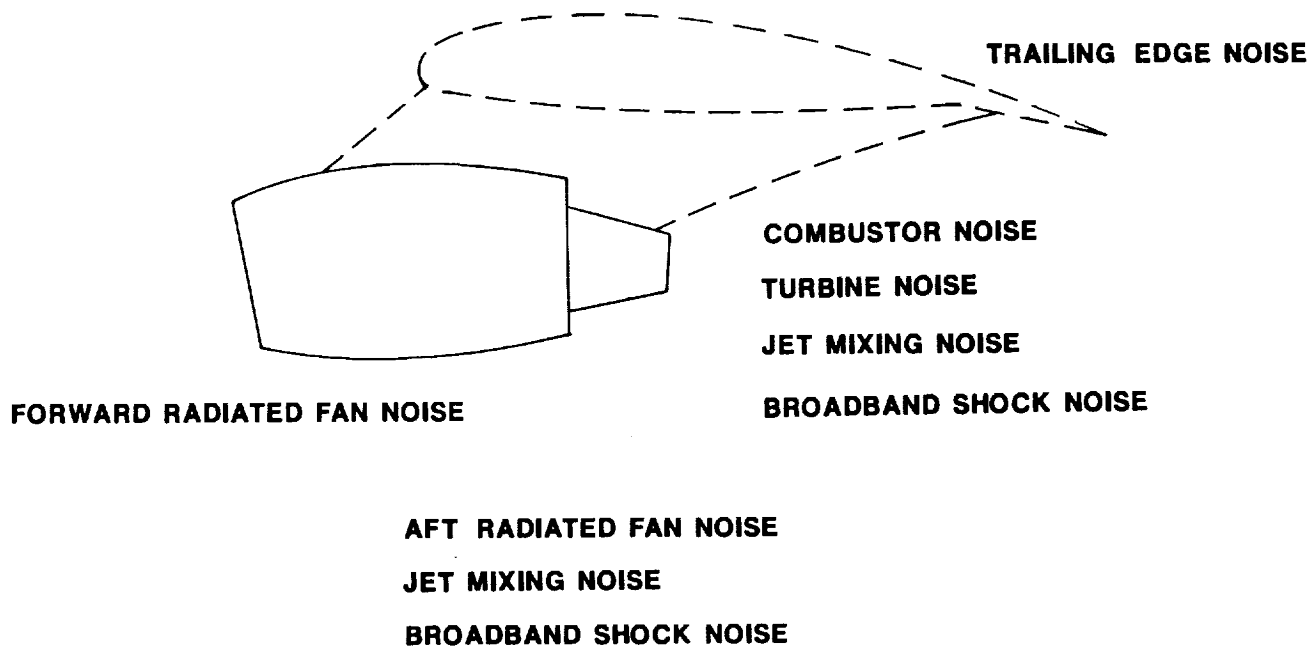






MODELING THE ACOUSTIC FIELD

The total noise at a point on the surface of the aircraft is computed by summing the contribution of the propulsion and airframe sources. In the case of the propulsion sources, the predictions are free-field so that the presence of a wing surface is not accounted for. The effect of shielding by a surface is also not predicted but can be simulated by judiciously choosing the noise sources to be predicted.

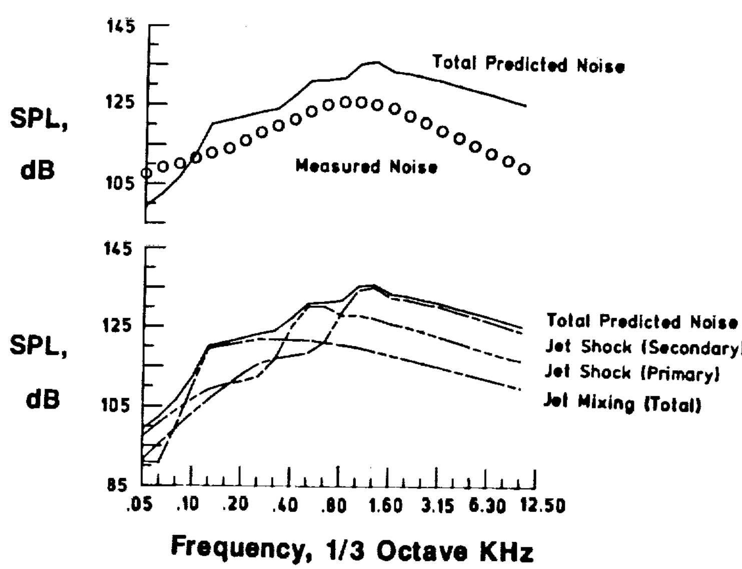


COMPARISON OF MEASURED VERSUS PREDICTED NOISE

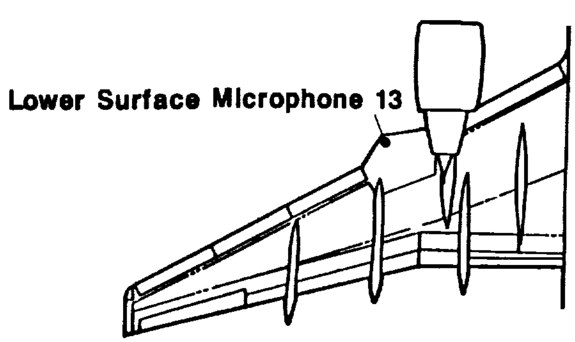
A noise prediction is made and compared with test data obtained on the wing of a Boeing 757 aircraft. The microphone is located on the lower surface of the wing near the leading edge of a test section designed for laminar flow. Three sources contribute to the total OASPL. They are jet mixing noise and broadband shock noise from the primary and secondary jets. In the low frequency range, .05 to .4 KHz, jet mixing noise is the dominate source. At higher frequencies, the spectra are dominated by broadband shock noise from the primary and secondary jets. Fan, combustor, turbine, and trailing-edge noise were included in the noise prediction but did not contribute to the total OASPL in this case.

Comparison of the total predicted noise and the measured noise shows levels are within 10 dB except for very high frequencies. It is believed that with sufficient test data, improvements to the code can be made especially in the area of forward flight corrections.

Altitude 40,000 Feet; Mach 0.8; Fan Speed 4100 RPM; Mic 13



MICROPHONE LOCATION



CONCLUSIONS

The physics of the coupling of sound waves with the boundary layer is not yet well understood. It is believed; however, that for effective coupling of the sound waves and instability waves in the boundary layer, a matching of both frequency and wave number must occur (Ref. 5). This requires that the sound field to be accurately defined in both space and time. Currently analytical prediction methods lack sufficient accuracy to predict the noise levels from components of a turbofan engine. Although empirical methods do not yield the detail required for an analysis of the receptivity of sound by a boundary layer, valuable insight can be gained as to the changes in noise levels that might be expected under various operating conditions and aircraft configurations.

Predictions

Noise levels remained unchanged with increasing altitude when flight Mach number and thrust are held constant at 0.8 and 100% respectively

Noise levels increase significantly with increasing flight Mach number

Noise levels increase moderately with increasing thrust

Flight Data

Limited flight data tend to support these conclusions although noise prediction program tends to over predict the total noise level

Significant noise sources

- **Jet Noise**
  - **Broadband Shock**
    - **Primary Jet**
    - **Secondary Jet**
  - **Jet Mixing**
    - **Primary Jet**
    - **Secondary Jet**
- **Forward Radiated Fan Noise**
- **Trailing Edge Noise**

Dominant noise sources dependent on flight Mach number

Under normal cruise conditions broadband shock noise can be expected to be present in the secondary jet

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