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CORRELATION OF TOTAL SOUND POWER AND PEAK SIDELINE OASPL FROM JET EXHAUSTS

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CORRELATION OF TOTAL SOUND POWER AND PEAK SIDELINE OASPL FROM JET EXHAUSTS

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Abstract

An empirical analysis of jet noise is made for convergent exhaust nozzles. This study, conducted at the Lewis Research Center, presents an engineering approach to the correlation of total sound power and maximum sideline OASPL (at 200 ft) for both subsonic and supersonic jets based on available data. Data correlation for subsonic jets shows no dependency of total sound power and maximum sideline OASPL on jet density. The analysis for supersonic jets results in a correlation parameter for jet total sound power consisting of the conventional Lighthill parameter modified by considerations of jet Mach number and jet acoustic velocity. Similar parameters also correlate the maximum sideline OASPL for supersonic jets.

Introduction

The noise from aircraft jet exhausts represents one of the more important acoustic pollution sources. It is a cause of community annoyance particularly for transports using local urban landing sites. Although a great deal of effort has been expended in the past 20 years in attempting to determine the basic mechanisms of jet noise, and much has been learned, the mechanisms are even now not properly or fully understood.

Recent data[1] obtained over a wide range of jet total temperatures (up to 2460° R) and jet Mach numbers (up to nearly 2.0) and using both convergent and convergent-divergent nozzles, together with recent unpublished NASA data for large convergent nozzles permit a re-examination of empirical approaches to the correlation of jet noise data.

The acoustic performance of convergent and convergent-divergent nozzles[2] is illustrated schematically in Fig. 1 for a low jet total temperature. With a convergent nozzle, the sound power increases above that predicted by an extension of the subsonic curve. This increase in noise level is attributed to broadband shock noise.[1] The shock noise has a pronounced influence on cold jet noise levels but has lessening effects with increasing jet temperatures. With a convergent-divergent (C/D) nozzle the sound power increase in the transonic region lags that of the convergent nozzle but then attains or even surpasses it[1] as the typical shock cell structure is formed. As the design pressure ratio of the C/D nozzle is approached, the sound power decreases to that predicted by an extension of the subsonic curve. Thereafter, with increasing pressure ratio, the sound power increases and again approaches or even exceeds that of the convergent nozzle. Data in Ref. 1 indicate that with increasing jet temperature (higher jet velocities) while maintaining the same pressure ratio, the sound power differences between a convergent nozzle and a C/D nozzle become negligible. The jet temperatures at which this occurs are those over 2000° R.

It could be argued that the low temperature supersonic jet is of no interest for jet powered aircraft because of the high temperatures common to most jet engines. For certain STOL aircraft, however, the introduction of bypass fan-jet engines (low fan jet temperatures) with pressure ratios greater than choking, the added noise caused by a low temperature supersonic jet could be a critical noise factor leading to rejection of an airplane or propulsion design concept.

This paper presents an engineering approach to the correlation of total sound power and peak sideline overall sound pressure level ($OASPL_{ps}$) for both subsonic and supersonic jets based on the available new data and the preceding considerations.

Data

The data used herein were taken from published reports by NACA-NASA, Lockheed Aircraft Corporation and The Boeing Company. In addition unpublished data from the NASA Lewis Hot Jet Facility is presented. In brief, this facility, shown in Fig. 2 uses pressurized air from the Center's central air supply. A muffler is located downstream of the supply line butterfly valve to remove internally generated valve and upstream noise. Downstream of the muffler is a preheater consisting of 5 annular combustors capable of producing heated air to 1850° R. The final section of the rig includes a thrust stand on which is mounted a J-85 afterburner section with an adjustable nozzle. The afterburner is capable of heating the air to 3850° R. The nozzle can be removed and replaced with other test nozzles.

Total Sound Power

Background

Subsonic jets. The total sound power measured with subsonic jets from Refs. 1 to 6 and unpublished NASA data is plotted in Fig. 3 as a function of the Lighthill parameter, $\rho_o A_e U_j^8 a_o^{-5}$. It should be noted that for the annular nozzle (fan exhaust) data,[6] the area term in the Lighthill parameter should be modified for a noncircular nozzle. The Lighthill parameter is derived as a function of D^2 for circular nozzles. For such nozzles the D^2-term has been interpreted as the nozzle exhaust area. An analogous analysis shows that for a simple annular nozzle with a long centerbody (as in Ref. 6) the D^2-term in the Lighthill parameter is actually $D_o(D_o - D_i)$. For an annular nozzle the effective area then can be written as the flow area multiplied by $(1 + D_i/D_o)^{-1}$. In general, the data are in a band identified by a constant vary-

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ing from 3×10^{-5} to 6×10^{-5}, with the data taken two decades ago of Ref. 2 identified with the lower constant while much of the more recent data shows a constant near 4×10^{-5}. The data spread between the several investigators are believed to be caused by differences in: (1) measuring equipment, (2) internal rig or engine noise, and (3) jet turbulence levels. In the present study the constant used with the Lighthill parameter is 3×10^{-5}; however, use of a larger constant will be discussed later herein. It should also be noted that at high subsonic jet velocities, the total power deviates from the Lighthill 8-power velocity law and approaches a 3-power velocity law.[7] This deviation from the 8-power velocity law occurs at different Lighthill parameters depending on the size of the jet, with jets of increasing size deviating at increasingly higher values of the Lighthill parameter.

Considering the wide range of jet total temperatures, from ambient to 2460° R, included in the data shown in Fig. 3, it is apparent that the total sound power for subsonic jets is independent of jet density.

Supersonic jets. The total sound power for supersonic jets is shown in Fig. 4 as a function of the Lighthill parameter. It should be noted that the effective area for supersonic jets is the fully expanded jet area. Deviations of the data to both sides of the Lighthill curve (constant of 3×10^{-5}) are evident. The data show trends with both jet total temperature and jet Mach number. A significant portion of the temperature and Mach number trends are contributed by shock noise that, as stated before, has most significance at cold jet total temperatures and is of increasingly secondary importance at high jet total temperatures (see also Ref. 1).

Correlation

As a first step in the correlation of total sound power, the data are plotted in terms of the following two parameters:

$$\frac{W}{\rho_o A_e a_o^3 M_j^3} = f\left[\left(\frac{U_j}{a_o}\right)^8 M_j^{-3}\right] \quad . \tag{1}$$

This equation represents a simple rearrangement of the Lighthill parameter and, in addition, includes a jet Mach number correlation term obtained from an analysis of the data shown previously in Fig. 4. In rearranging the Lighthill parameter to that shown in Eq. (1), the left hand portion of the equation can be shown to consist of the ratio of the acoustic power-to-jet power with modifying ratios of jet acoustic velocity to ambient acoustic velocity, $(a_j/a_o)^3$ and density ratio (ρ_j/ρ_o).

Correlation of the supersonic total sound power data and selected subsonic data are shown in Fig. 5 in terms of Eq. (1). It is apparent that the shock noise has not been correlated by Eq. (1). However, the subsonic data of Ref. 1 and unpublished NASA data are in good agreement and a single subsonic correlation curve can be plotted as shown by the solid curve in Fig. 5.

In order to correlate the shock noise, an additional term must be included in the left hand portion of Eq. (1). This shock-noise term, F, was determined empirically and is given by:

$$F = \left(1 + \left\{\frac{12.5(M_j - 1)^3}{\left[0.04 + (M_j - 1)^3\right]\left[1 + 2(M_j - 1)^4\right]\left[1 + 0.05\left(\frac{U_j}{a_o}\right)^8 M_j^{-3}\right]}\right\}\right) \tag{2}$$

Eq. (1) is then rewritten to include F as follows:

$$\frac{W}{\rho_o A_e a_o^3 M_j^3 F} = f\left[\left(\frac{U_j}{a_o}\right)^8 M_j^{-3}\right] \tag{3}$$

The shock-noise parameter is used only for supersonic jets and is omitted for subsonic jets.

The correlation of total acoustic power data for supersonic jets is shown in Fig. 6 in terms of Eq. (3) together with representative subsonic jet data. The data include several points for engines (solid symbols) taken from Ref. 2. The curve through the data in Fig. 6 is given by the following relation:

$$\frac{W}{\rho_o A_e a_o^3 M_j^3 F} = 3.5\times10^{-3}\left[\frac{\left(\frac{U_j}{a_o}\right)^8 M_j^{-3}}{116.7 + \left(\frac{U_j}{a_o}\right)^8 M_j^{-3}}\right] \tag{4}$$

or

$$W = 3.5\times10^{-3}\, L_o F\left[\frac{1}{116.7 + \left(\frac{U_j}{a_o}\right)^8 M_j^{-3}}\right] \tag{5}$$

If the constant for the Lighthill parameter had been selected as 4×10^{-5} instead of 3×10^{-5}, the constant 116.7 in Eq. (5) would be 87.5, the other terms remaining the same.

Maximum Sideline OASPL

Background

Jet exhaust noise is frequently estimated using the maximum sideline overall sound pressure level, $OASPL_{ps}$. According to Ref. 8, this value of $OASPL_{ps}$ is referenced to 200 feet. Furthermore, Ref. 8 assumes a jet density effect (ρ_j^2) to exist and does not attempt to sort out internal noise from the exhaust noise nor account for shock noise.

Because the $OASPL_{ps}$ of a jet is closely related to the sound power for a jet, it should follow that a similar data correlation exists. It can be surmised then that the $OASPL_{ps}$ is a function of substantially the same parameters as those for the total power provided internal rig or engine noise has been eliminated.

Subsonic jet. In Fig. 7, the $OASPL_{ps}$ per unit nozzle exhaust area for subsonic jets is shown as a function jet velocity for a range of nozzles sizes ranging from 2.06-in. to a fan with a 72-in. outside diameter. (The effects of a_o and ρ_o are, for the present, assumed constant and negligible to the discussion.) The jet total temperature range covered is from ambient to 2460° T. No effect of jet density is apparent. At the lower jet velocities the relation between $OASPL_{ps}$ and velocity follows about an 8-power velocity law. At higher jet velocities (>1500 ft/s), a 3-power velocity law is approached as in the case of the total sound power.

Supersonic jets. A plot of $OASPL_{ps}$ data for supersonic jets is shown in Fig. 8 as a function of the jet velocity. Also shown for comparison is a faired curve for the subsonic data from Fig. 7. It is apparent that jet total temperature and jet Mach number trends similar to those noted for total sound power are evident. These deviations from the subsonic curve are again caused by shock noise and the other factors discussed previously.

Correlation

In order to correlate the jet Mach number trend, a M_j^3-term is added to both the ordinate and abscissa of Fig. 8 in a manner similar to that for the total sound power correlation and also the jet velocity is divided by the ambient air acoustic velocity, a_o. The result is shown in Fig. 9. It is evident that the shock noise, shown by the data above the subsonic curve, again requires a correlating parameter. On the basis of the available data, this parameter, F', is given by:

$$F' = \left(1 + \left\{\frac{7.5(M_j - 1)^3}{\left[0.0135 + (M_j - 1)^3\right]\left[1 + 2(M_j - 1)^4\right]\left[1 + 0.05\left(\frac{U_j}{a_o}\right)^8 M_j^{-3}\right]}\right\}\right) \qquad (6)$$

Note that Eqs. (6) and (2) are identical except for two constants.

The correlated $OASPL_{ps}$, including the shock noise parameter, is shown in Fig. 10 as a function of $(U_j/a_o)^8 M_j^{-3}$. Also shown in Fig. 10, for comparison, are selected values of $OASPL_{ps}$ for subsonic jets. It is apparent that correlation techniques for $OASPL_{ps}$ and total sound power are similar for both subsonic and supersonic jets.

In order to account properly for changes in the ambient air acoustic velocity, a_o, and ambient density, ρ_o, the ordinate in Fig. 10 must include these parameters in the form of the subtractive terms $10 \log a_o^3$ and $10 \log \rho_o$. Inclusion of these terms does not change the correlation of the data shown in Fig. 10 but does, of course, change the absolute value of the ordinate.

Concluding Remarks

When cold flow supersonic jets are used (as in internally blown augmentor wing STOL systems), on-design C/D nozzles can be used to reduce the total sound power level compared with simple convergent nozzles. However, the useful range of lower sound power levels is very limited, centering about the design Mach number. Consequently, precise nozzle geometry must be maintained in fabrication and operation to achieve the desired results.

A delay in the rise of the added sound power caused by shock noise for a C/D nozzle operating at an overexpanded condition[1] can perhaps be taken advantage of for some applications. For example, a C/D nozzle designed for a cold-flow jet Mach number of 1.8 yields substantially subsonic sound power values (based on the U_j) up to about a jet Mach number of about 1.4. (Such operation, of course, may cause undesirable or unacceptable thrust losses.) A brief examination of the C/D nozzle sound power data in Ref. 1 shows that the delay in the rise of the sound power level for C/D nozzles can be grossly estimated by the square root of the C/D nozzle design jet Mach number. Thus, a C/D nozzle design for $M_j = 1.8$ follows the subsonic total sound power curve until a jet velocity given by $\sqrt{1.8}$ is reached.

On the basis of available data presented herein indicating that the total sound power and peak-sideline sound pressure level for subsonic jets are independent of jet density, it is recommended that the SAE[8] noise prediction techniques (predicated on a ρ_j^2 dependency) be re-examined.

Results and Conclusions

The present analysis of experimental jet-exhaust total sound power and maximum sideline OASPL data has led to the following results and conclusions:

1. An empirical relation has been developed that correlates jet total sound power for convergent nozzles in terms of the conventional Lighthill parameter modified by jet temperature (acoustic velocity of jet) and jet Mach number parameters.

2. At high subsonic jet velocities (greater than 1500 ft/sec) the jet sound power asymptotically approaches a constant acoustic efficiency parameter. This results in a variation of jet sound power with jet velocity to the 3-power velocity law. For subsonic jets the total sound power is independent of jet density.

3. For low supersonic jets operating at low jet temperatures (near ambient), shock noise is an additive term to the usual turbulent interaction (shear layer) jet noise. On-design operation of convergent-divergent nozzles eliminates shock noise.

4. Supersonic jets at high jet temperatures show trends similar to those for high speed subsonic jets; however, the jet total sound power level increases with increasing jet Mach number. Shock noise becomes increasingly less significant at high jet velocities and temperatures.

5. Correlation of the maximum sideline OASPL can be achieved by using similar parameters to those used to correlate total sound power.

6. For subsonic velocities the maximum side-

line OASPL also is independent of jet density.

Symbols

(All nomenclature in English units)

A_e	effective nozzle exhaust area
a_o	ambient speed of sound
D_i	inner nozzle diameter
D_o	outer nozzle diameter
F,F'	shock noise parameters (defined in text)
L_o	Lighthill parameter, $\rho_o A_e U_j^8 a_o^{-5}$
M_j	jet Mach number
$OASPL_{ps}$	peak sideline sound pressure level at 200 ft
T_j	jet total temperature
U_j	jet velocity
W	total sound power
ρ_j	jet density
ρ_o	ambient density

References

1. Simcox, C. D., "Effect of Temperature and Shock Structure on Choked Jet Noise Characteristics," Paper 71-582, June 1971, AIAA, New York, N.Y.

2. Callaghan, E. E., and Coles, W. D., "Far Noise Field of Air Jet Engines," Rept. 1329, 1957, NACA, Cleveland, Ohio.

3. Dorsch, R. G., Kreim, W. J., and Olsen, W. A., "Externally-Blown-Flap Noise," Paper 72-129, Jan. 1972, AIAA, New York, N.Y.

4. Olsen, W. A., Dorsch, R. G., and Miles, J. H., "Noise Produced by a Small-Scale, Externally Blown Flap," TN D-6636, 1972, NASA, Cleveland, Ohio.

5. Plumblee, H. E., Wynne, G. A., and Zinn, B. T., "Effect of Jet Temperature on Jet and Pure Tone Noise Radiation," CR-1472, 1969, NASA, Washington, D.C.

6. Minner, G. L., and Feiler, C. E., "Low-Speed Jet Noise From a 1.83-Meter (6-Ft) Fan for Turbofan Engines," Paper 71-586, June 1971, AIAA, New York, N.Y.

7. Ffowcs Williams, J. E., "The Noise From Turbulence Convected at High Speed," Philosophical Transactions of the Royal Society of London, Ser. A, Vol. 255, No. 1061, Apr. 18, 1963, pp. 469-503.

8. Anon., "Jet Noise Prediction," AIR-876, July 1965, SAE, New York, N.Y.

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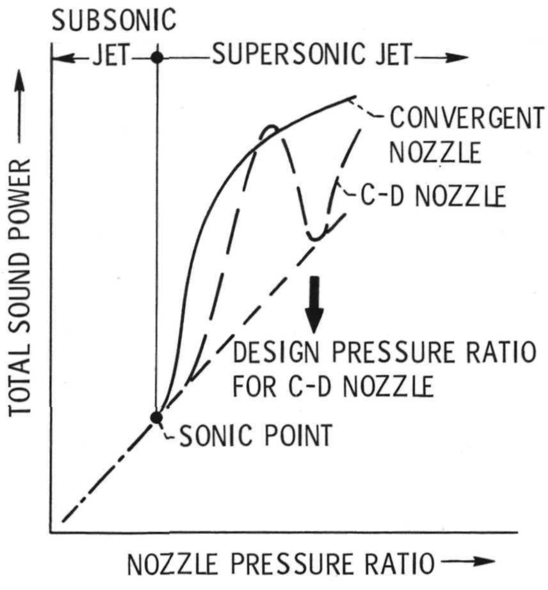

Figure 1. - Jet sound-power characteristics for convergent and convergent-divergent nozzles.

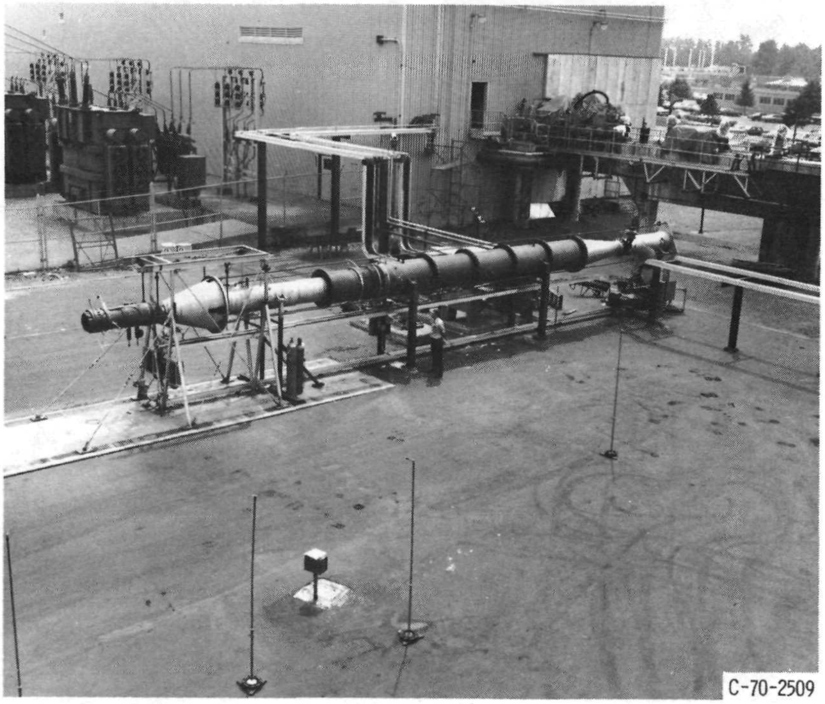

Figure 2. - NASA Lewis hot jet facility.

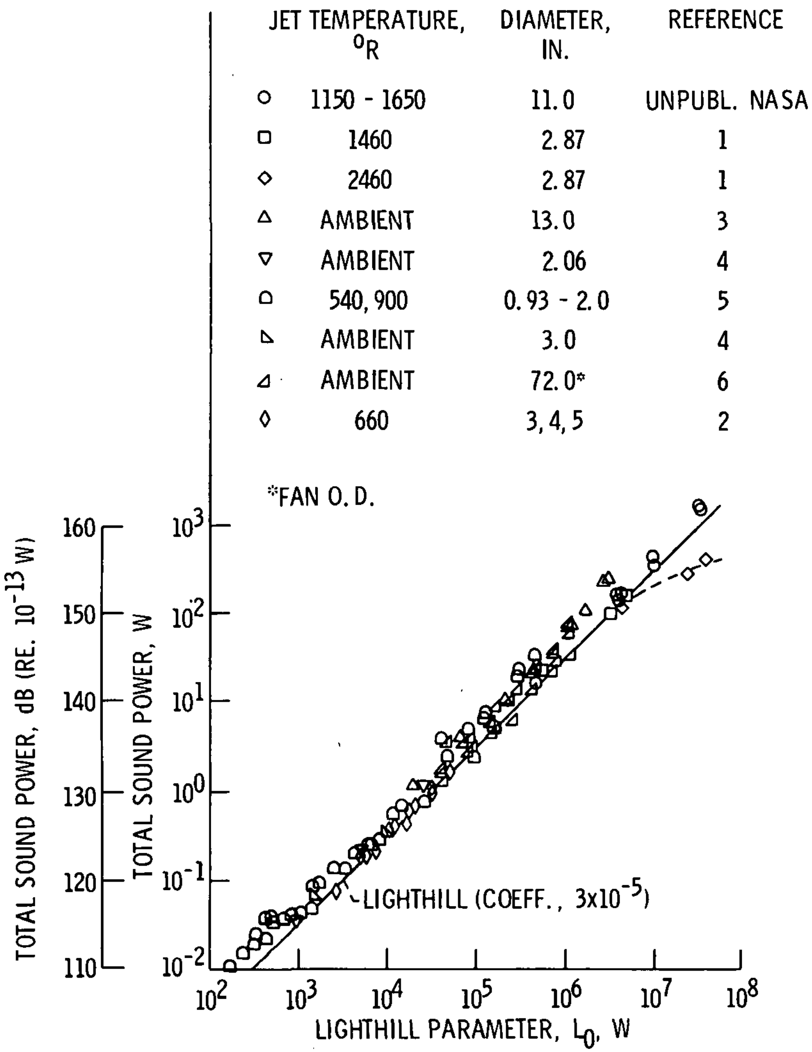

Figure 3. - Subsonic jet sound power variation with Lighthill parameter.

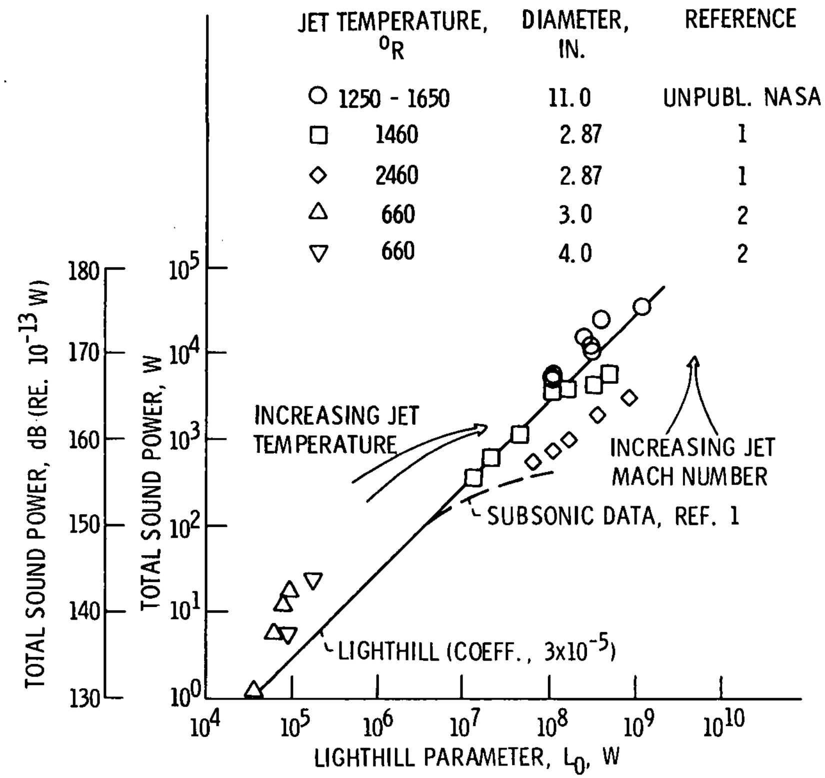

Figure 4. - Supersonic jet sound power variation with Lighthill parameter.

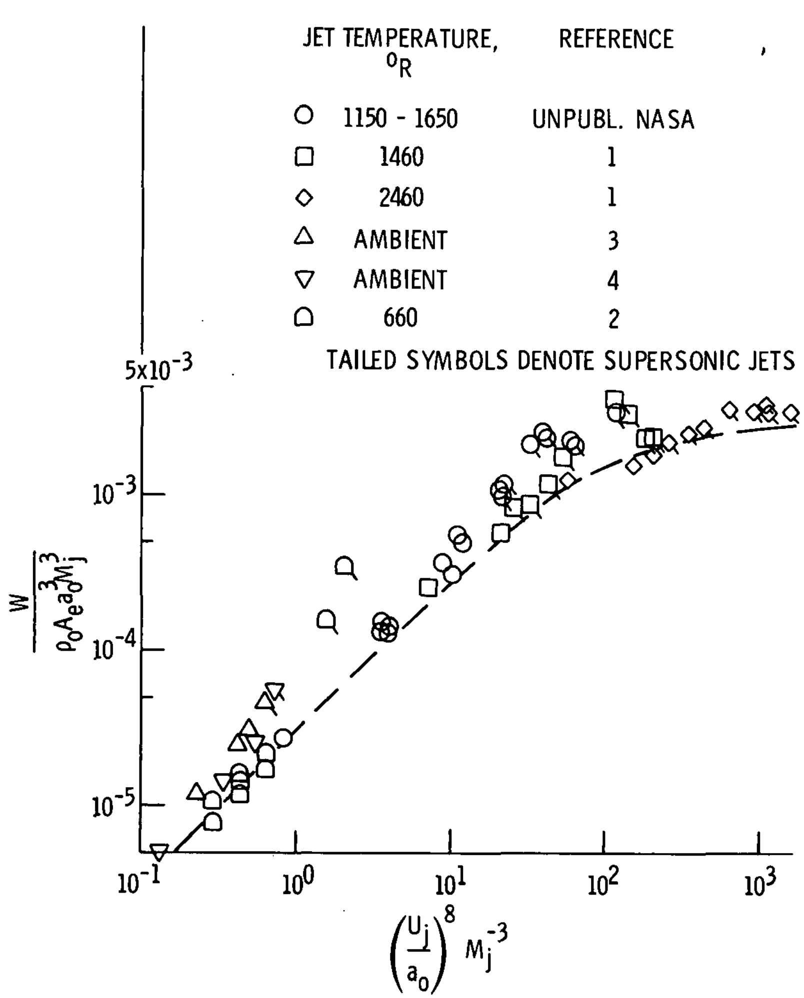

Figure 5. - Sound power correlation for jet Mach number.

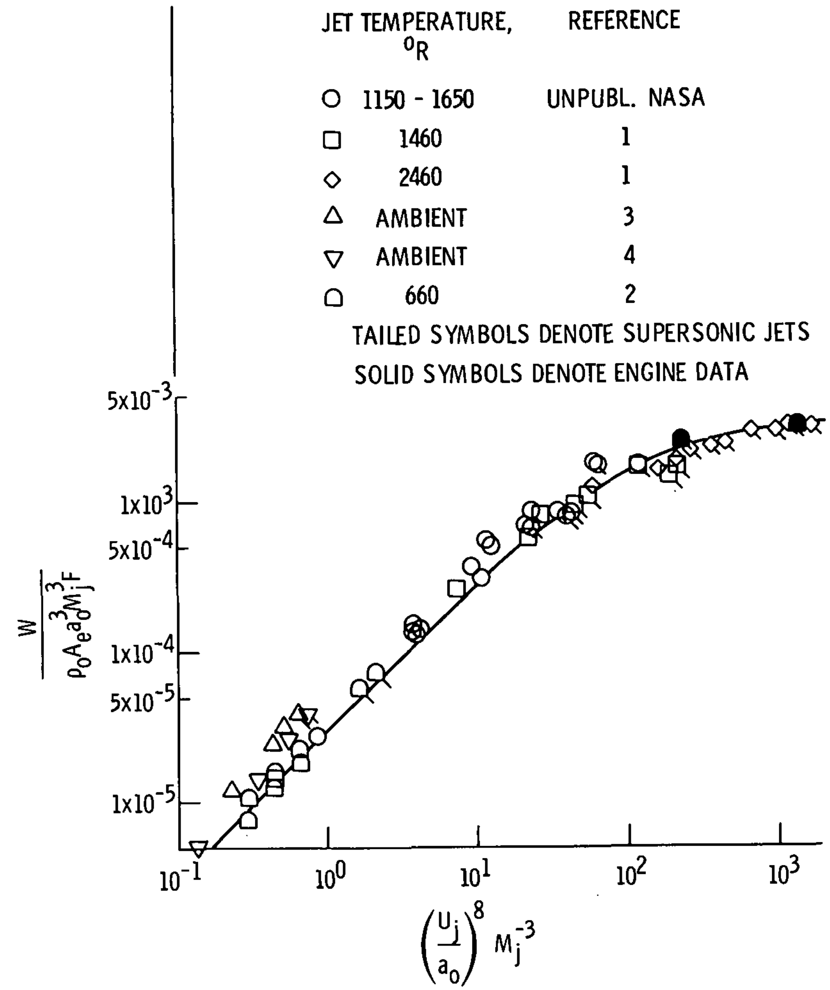

Figure 6. - Correlation of total sound power including shock noise.

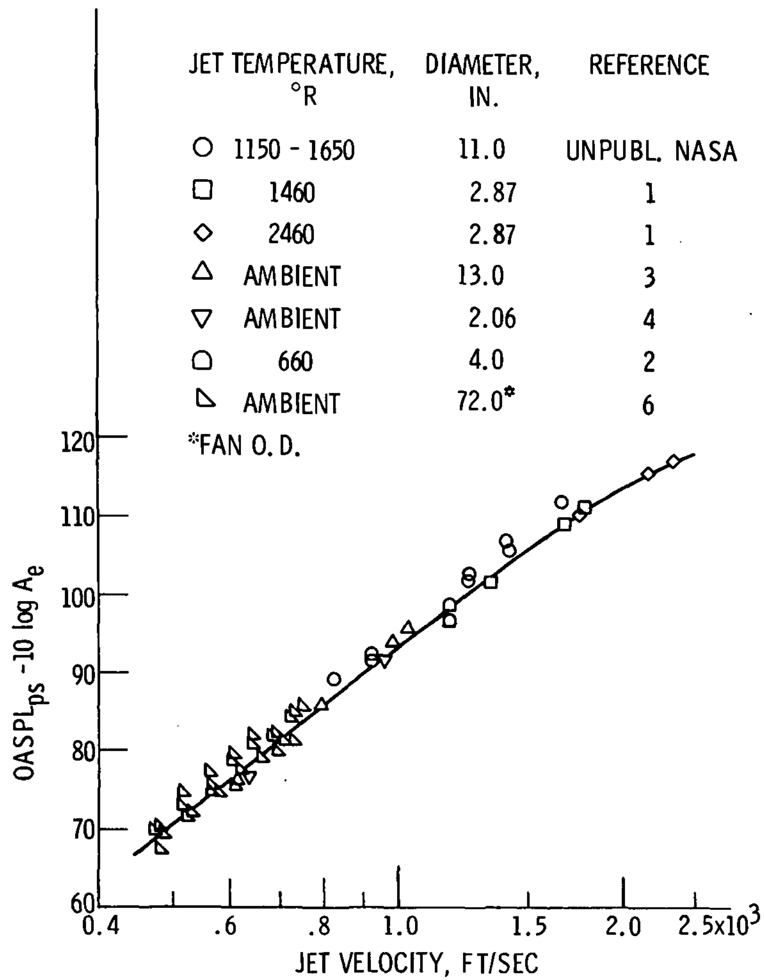

Figure 7. - Subsonic jet peak-sideline OASPL variation with jet velocity.

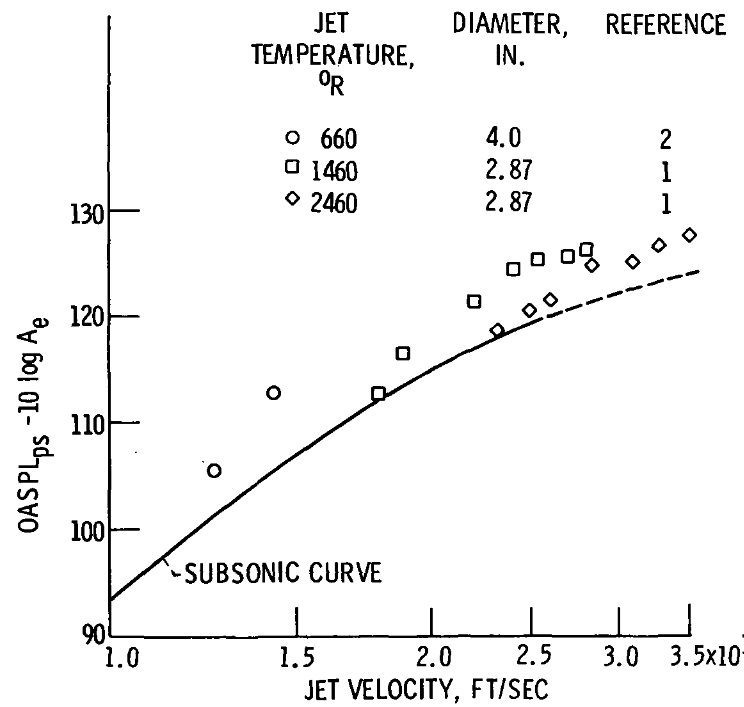

Figure 8. - Supersonic jet peak-sideline OASPL variation with jet velocity.

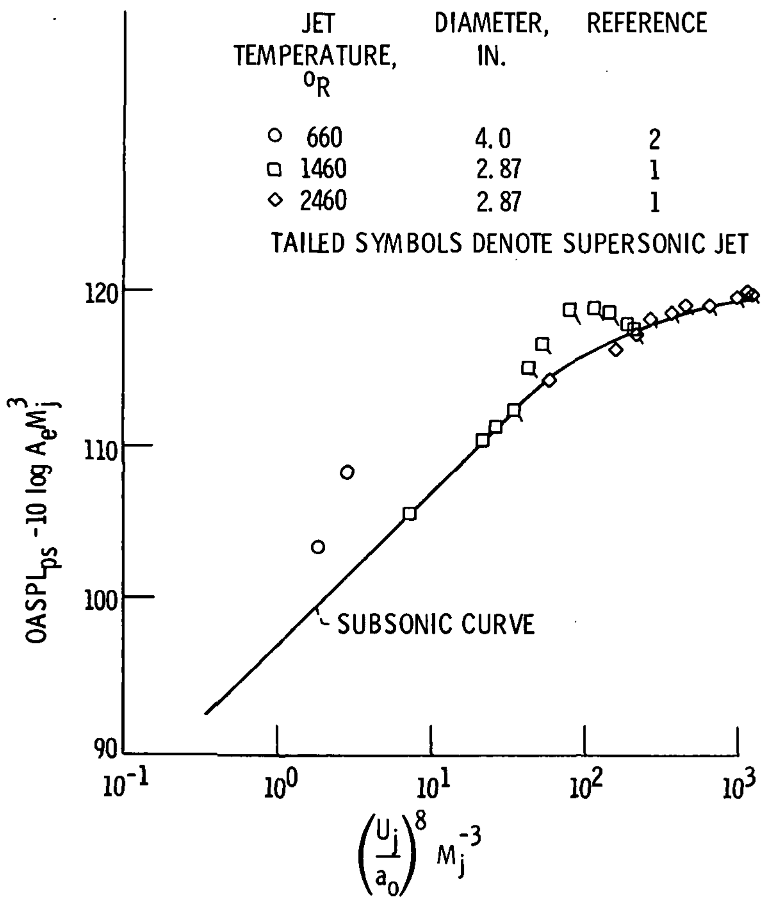

Figure 9. - Peak-sideline OASPL correlation for jet Mach number.

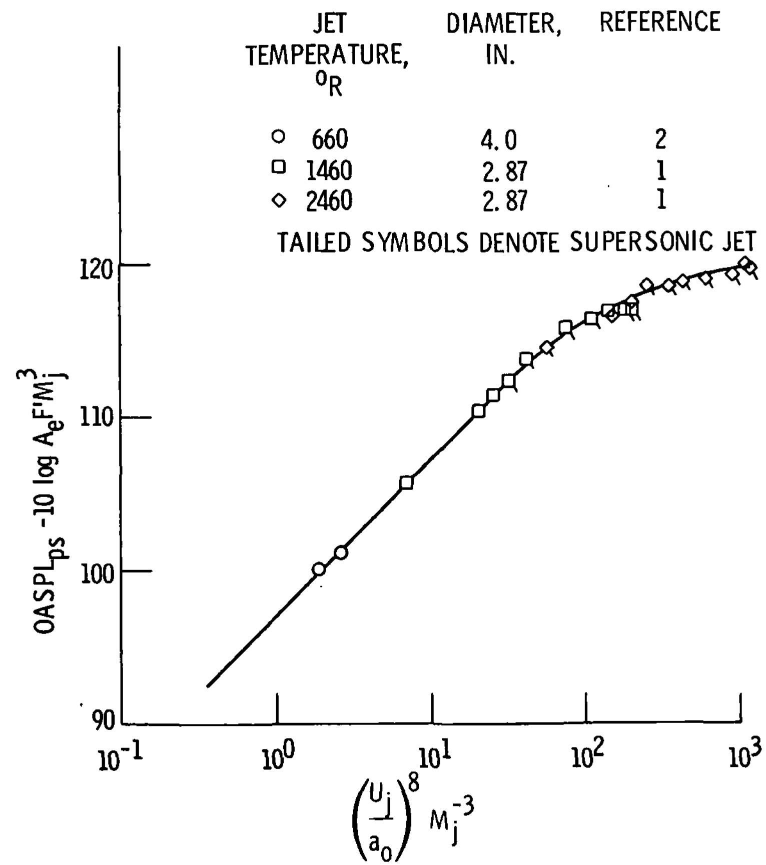

Figure 10. - Correlation of peak-sideline OASPL including shock noise.