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INFLUENCE OF MULTITUBE MIXER NOZZLE GEOMETRY ON CTOL-OTW JET NOISE SHIELDING

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ABSTRACT

Acoustic shielding benefits for CTOL over-the-wing (OTW) applications were obtained experimentally with various multitube nozzles using a simple board to represent a wing. Eight nozzles consisting of three to thirteen 2.36-cm diameter tubes were tested. The nozzles included single and double rings of tubes. Shielding surface lengths of 15.0 to 54.4 cm were used with each nozzle. Far-field noise data were obtained at 90° from the jet axis and with a nominal jet exhaust velocity of 200 m/sec. The jet noise shielding benefits for the nozzles with double rows of tubes, in terms of sound pressure level spectra, are correlated successfully as a function of an earlier developed parameter for nozzles with a single ring of tubes that includes consideration of the number of tubes and the local peak velocity in the flow field at the trailing edge of the shielding surface.

INTRODUCTION

Jet noise shielding by a wing for conventional takeoff and landing (CTOL) aircraft is similar to that observed on the ground by the erection of a barrier between the noise source and an observer. The main differences between the two applications of barrier shielding are the nature and generation mechanisms of the respective noise sources (ref. 1) and the close proximity of the noise source to the shielding surface for aircraft compared with ground barrier applications. As discussed in references 1 and 2, the acoustic shielding benefits of

CTOL aircraft using engines installed over-the-wing (OTW) appear to be functions of shielding surface length (chordwise direction), nozzle type, nozzle size, jet velocity, jet relative velocity, and flap deflection. The effects of these variables on CTOL-OTW acoustic shielding benefits have been reported for single conical nozzles (ref. 1) and single-row multitube and multilobe mixer nozzles (ref. 2). In the latter study, it was shown that greater jet noise shielding was obtained using a mixer nozzle than was obtained with a single conical nozzle for the same total flow area. The acoustic data for the two types of nozzles were grossly correlated by assuming that the noise source alteration caused by the multijet mixing is related to the peak axial velocity at the trailing edge of the wing-flap system (ref. 2).

In the present report, the use of scale-model mixer nozzles with CTOL-OTW configurations is extended to include the effect on jet noise shielding of the individual tube spacing for a 6-tube mixer nozzle and of mixer nozzles consisting of multiple rings of tubes. Use of mixer nozzles with a large number of tubes or elements is considered desirable because the jet noise itself is reduced by such nozzles and then can be further attenuated by the shielding surface. The mixer nozzle configurations tested include 3, 6, 7, 12, and 13 tubes. An individual tube diameter of 2.36 cm was used for all configurations. Up to two rows of six tubes each with and without a tube on the nozzle centerline are included in the present study. Nominal total equivalent nozzle diameters ranged from 4.08 to 8.52 cm depending on the number of tubes. The surface shielding lengths were varied from 15.0 to 54.4 cm measured from the nozzle exhaust plane.

Acoustic results are presented in terms of spectral data taken at a directivity angle of 90° (directly below the shielding surface) and at a microphone distance of 3.05 m. From the acoustic data taken, the low frequency jet-surface interaction noise for the various nozzles are compared. Then the acoustic shielding benefits due to the surface representing a wing are discussed and compared with the correlation developed in reference 2. The data were obtained with a nominal jet velocity of 200 m/sec.

APPARATUS AND PROCEDURE

Facilities

Aerodynamic. - The local jet velocities in the flow field downstream of the nozzle exhaust plane for each nozzle were obtained, for the most part, from data taken in the program described in reference 3. Additional data, not available in this reference, were obtained using the test stand, associated equipment, and procedures described in reference 3.

Acoustic. - The effect of variations in the nozzle-to-shielding surface geometry on the acoustic attenuation of the jet noise were obtained using the cold-flow courtyard rig described in reference 1. The acoustic data herein are presented in terms of sound pressure level (SPL) spectra in decibels referenced to 2×10^{-5} N/m^2. No corrections are made to the acoustic data for ground reflections. Further details regarding acoustic measurement techniques and procedures are given in reference 1.

Configurations

A simple flat board (shielding surface) was used to shield the jet noise in the present study. (In refs. 1 and 2, it was shown that airfoils with zero flap deflection and simple boards yield the same amount of jet noise shielding.) The shielding surface was 0.95 cm thick and its span was 61 cm. The positioning of a typical nozzle to the shielding surface (board) is shown schematically in figure 1, together with pertinent dimensions. All nozzles were mounted so that two tubes were equidistant from the surface at a height of 4.45 cm and the jet flow was parallel to the surface. The surface projected 6.6 cm upstream of each nozzle exhaust plane. Shielding surface lengths of 15, 26.4, and 54.4 cm downstream of the nozzle exhaust plane were used as indicated in figure 1.

The coplanar multitube nozzles used in the present study consisted of 3, 6, 7, 12, and 13 individual tubes. Four different tube spacings were studied for the 6-tube nozzle in order to determine the effect of this variable on the low frequency jet-surface interaction noise and jet noise shielding. Sketches and pertinent dimensions of the nozzles are shown in figure 2. (The table in fig. 2 gives the tube spacings used with the four 6-tube nozzles tested.) All tubes used had an inside diameter of 2.36 cm and each tube was 10.15 cm long. The nominal equivalent diameter for the nozzles varied from 4.08 for the 3-tube mixer nozzle to 8.52 cm for the 13-tube mixer nozzle.

EMPIRICAL CORRELATION EQUATIONS FOR SHIELDING

According to reference 2, the shielding ΔSPL for mixer-type nozzles with a simple shielding surface (board) can be correlated in terms of the following equations (all symbols are defined in the Nomenclature):

$$\Delta SPL = 10 \log\left[1 + 0.6(Z'n')\right] \tag{1}$$

where

$$Z' = \frac{fL \times 10^{-6}}{U_j}\left[f_1(D_e')\right]\left[f_2(\theta)\right] \tag{2}$$

$$f_1(D_e') = \frac{a_o^2}{gD_x\sqrt{n'}}\left[1 + 4.5\times10^9\left(\frac{gD_x\sqrt{n'}}{a_o^2}\right)^2\right] \tag{3}$$

$$n' = 1 + \frac{n - 1}{1 + 0.1\left(\frac{U_j}{U} - 1\right)^{-3}} \tag{4}$$

$$f_2(\theta) = \frac{1}{1 + 0.033\left(\frac{\theta}{180 - \theta}\right)^4} \tag{5}$$

The source alteration parameter, n', utilizes the jet velocity, U_j, as a baseline velocity term in equation (4) and requires knowledge of the flow field to obtain the value of U. However, it was pointed out in reference 2 that a better baseline velocity term would be to use the local peak jet velocity when the core jet from one element begins to merge with adjacent core jets. Until such data are available the use of U_j as the baseline velocity for the n'-parameter is suggested for practical mixer nozzle designs.

FLOW FIELD CONSIDERATIONS

In the present work it is assumed that the noise source alteration caused by changes in jet mixing due to the particular mixer nozzle used is related to the peak axial velocity at the trailing edge of the shielding surface (ref. 2). The measured peak axial velocity for the mixer nozzles alone are plotted in figure 3 in terms of the peak local Mach number as a function of the axial distance downstream of the nozzle exhaust plane. Also indicated in the figure by the tick marks on the abscissa are the shielding surface lengths used. It is apparent that at surface shielding lengths of 15.0 and 26.4 cm, little difference in peak velocity between the nozzle configurations is noted. Those nozzles with a tube on the nozzle centerline (7- and 13-tube nozzles) have a slightly higher velocity (Mach number) than those without a centerline tube. For the 54.4 cm surface shielding length, a large difference in local velocity is noted for the nozzles without a tube on the nozzle centerline. The large velocity differences are caused by the change in spacing between the tubes making up a nozzle. With increases in tube spacing, the peak local velocity is significantly decreased (ref. 3) due to more mixing. For example, with a shielding surface length of 54.4 cm, the 6-tube mixer nozzle with tubes spaced 0.813 cm apart has a peak Mach number of about 0.36 at the surface trailing edge while with a 3.99 cm tube spacing the peak Mach number is only about 0.22.

It was shown in reference 2 that the shortest shielding surface, 15.0 cm, tends to provide shielding of jet noise where the individual jet core flows still can be identified. With the longer surfaces the shielding of the jet noise includes regions where the jets are beginning to merge or are actively coalescing into a single large diameter jet. Thus, with increasing shielding length downstream of the core flow region, the surface shields not only the core flow noise but also increasing amounts of the interaction jet noise sources associated with the jet mixing process. The effect of shielding these various flow regions on jet noise attenuation will be discussed later in terms of the peak axial velocity at the surface trailing edge.

JET NOISE WITH SURFACE SHIELDING

For a CTOL-OTW aircraft, the exhaust jet is located relatively close to the wing surface and is a distributed noise source. The noise obtained at the various frequencies of such an acoustic source is therefore generated at different distances from the surface and at different locations relative to the edge of the barrier (wing or flap trailing edge). An analytical model of the jet noise-source distribution, therefore, would have to include a complex integration to sum up the contributions of all the jet noise sources with their local surface shielding lengths.

The present approach employs empirical correlations of existing data to arrive at a prediction method for the shielding of jet noise by a wing-flap system. The analysis leading to the data correlation is given in terms of the SPL difference between nozzle-plus-shielding-surface and the nozzle-only, $SPL-SPL_N$ or ΔSPL.

A schematic plot of ΔSPL as a function of frequency for a CTOL-OTW configuration is shown in figure 4. Positive ΔSPL values indicate that jet-surface interaction noise sources are greater than the nozzle-alone jet noise, while negative ΔSPL values indicate a reduction in jet noise (shielding) by the wing-flap system. Four basic noise regions, denoted by A, B, C, and D are indicated in figure 4. Region A is characterized by noise amplification (increase) over that caused by nozzle-alone jet noise and is attributed to jet-surface interaction noise sources. Region B is a transition region into the shielding regime that is a function of the interplay between the regions of interaction noise sources and jet noise shielding. When the interaction jet-surface noise sources are strong (large positive ΔSPL values) the slope of this transition region is steep; whereas when they are weak, the slope of this transition region is shallow and blends rapidly into the jet noise shielding portion of the curve shown. Region C typifies a "barrier" shielding curve. The region C data are used herein to correlate jet noise shielding ΔSPL values. Region D frequently shows a reduced jet noise shielding capability at high frequencies inconsistent with barrier shielding analyses. The exact reasons for reduced jet noise shielding are not understood; however, it is believed that the reduced attenuation is primarily an aeroacoustic interaction anomaly (possibly a surface-edge effect) associated with a specific nozzle-wing configuration and reflects the presence of a high frequency noise floor. For jet noise shielding correlation purposes, only the data in region C are directly applicable. The data in regions B and D have been deleted in the shielding correlation plots in order to avoid confusing the data trends and correlation.

JET-SURFACE INTERACTION NOISE RESULTS

With a CTOL-OTW configuration the noise level at low frequencies is higher than that of the nozzle alone (ref. 1). This jet-surface interaction noise is believed to be caused by several noise sources including the fluctuating pressures caused by jet flow over the shielding surface and trailing edge interactions with the local jet flow. Jet-surface interaction noise is decreased by increasing the height of the nozzle above the shielding surface. Decreasing the shielding surface length with all other dimensions fixed causes a similar result.

In the following sections the effect on jet-surface interaction noise (region A, fig. 4) of tube spacing for a given multitube nozzle and the effect of the number of tubes for mixer nozzles are discussed.

Tube spacing effects. - The 6-tube nozzle configuration with four different tube spacings is used to illustrate the effect of this geometry variation on the jet-surface interaction noise. The SPL spectra for these 6-tube nozzles alone (without the shielding surface) serve as a baseline for the nozzle-surface configurations and are given in figure 5 as a function of frequency. In general, the nozzle spectra are independent of tube spacing except in the range of 200 to 800 hertz where the SPL increases somewhat as the tube spacing is decreased.

With the inclusion of the shielding surface, the added noise at low frequencies is clearly shown in figure 6. Also shown for comparison in figure 6 is the spectral band of the nozzle-alone data from figure 5. With the shortest shielding surface (15.0 cm), the increase in noise level with the shielding surface compared to the nozzle alone level (about 5 dB) is substantially independent of tube spacing. However, with the longer shielding surface lengths, the increase in noise level is dependent on tube spacing and is considerably greater than that for the shortest shielding surface. Increased SPL noise levels are incurred with decreased tube spacing. For the 6-tube mixer nozzle, the difference between the peak value of the interaction noise and the nozzle-only value at the same frequency appears to be grossly a function of $\left[1 + \left(\frac{U_j}{U} - 1\right)^{1/4} \frac{d}{D_x}\right]^{-1/2}$. The data are insufficient, however, to permit establishment of a comprehensive correlation parameter for the effect of tube spacing on jet-surface interaction noise. With increasing shielding surface length, the location of the peak SPL shifts to lower frequencies, apparently as a direct function of the surface length. Furthermore, the peak SPL appears to shift to lower frequencies with an increase in tube spacing, particularly for the longest shielding length of 54.4 cm.

Effect of tube number and tube rows. - The effect of the number of tubes as well as the number of tube rings on the jet-surface interaction noise is shown in figure 7. The effects are best illustrated by the data obtained with shielding surface lengths of 26.4 and 54.4 cm. With a shielding length of 54.4 cm (fig. 7(a)), the noise level, as expected, varies approximately with the equivalent diameter based on the total nozzle flow area. The spectra were not shifted in frequency by a change in the number of tubes for the various nozzles. The spectral data with a shielding surface length of 26.4 cm (fig. 7(b)) showed similar trends with respect to noise level as those for the longer shielding length. The spectra, however, did shift relative to each other, depending on the number of tubes in the nozzle. The shift in the spectra with tube number appears to be a function of equivalent diameter of the nozzle total flow area for the data shown in figure 7(b). For the shortest shielding surface, 15.0 cm, the data were insufficiently separated by nozzle type to permit establishing trends and parameters.

The lack of data at various model scales also prevented the development of scaling laws for the jet-surface interaction noise spectra associated with mixer nozzle CTOL-OTW configurations. In general, however, the data trends noted as well as the nominal peak frequencies of the interaction noise, 250 to 400 Hz, are similar to those obtained with conical nozzle configuration described in detail in reference 1.

JET NOISE SHIELDING RESULTS

Effect of tube spacing. - The effect of tube spacing on jet noise shielding by a surface (region C) was examined by use of the 6-tube mixer nozzles shown in figure 2(b). The data are shown in figure 8 in terms of $SPL-SPL_N$, or ΔSPL, as a function of frequency. The data are shown for the three shielding surface lengths used herein. In general, the effect of changing the tube spacing from 0.813 to 3.99 cm had no significant effect on the shielding benefits (ΔSPL). An exception is noted for the shortest shielding surface, 15 cm, for which the ΔSPL above about 500 hertz appears to be influenced by the tube spacing. In this frequency range, the ΔSPL decreases (less shielding of the jet noise) with increasing tube spacing, by as much as 3 dB for a tube spacing change from 0.813 to 2.72 cm. With a further increase in tube spacing to 3.99 cm, however, the ΔSPL increases again to within 1 dB of the values associated with the 0.813 tube spacing.

Effect of tube number. - The shielding benefits in terms of ΔSPL for the various nozzles types used herein are shown in figure 9 as a function of frequency and for shielding surface lengths of 15.0, 26.4, and 54.4 cm. It is apparent that the addition of a tube on the nozzle centerline does not significantly change the ΔSPL (figs. 9(b) and (c)). A comparison of the ΔSPL at a given frequency shows that generally the multirow nozzles (12- and 13-tube configurations) have somewhat greater ΔSPL values than the single-row nozzles (6- and 7-tube configurations).

COMPARISON OF MEASURED AND CALCULATED SHIELDING DATA

The measured ΔSPL data are compared with calculated values based on equations (1) to (4) for the mixer nozzles used herein in figures 10 and 11. The measured ΔSPL data shown are for region C (fig. 4) and are typical of the results obtained. In addition, comparisons of the measured and calculated ΔSPL values with an 8-tube mixer nozzle and with two lobed nozzles (7- and 8-lobes, respectively) are shown in figure 12. These data were previously reported in reference 2 and are included herein for completeness.

Generally good agreement between the calculated and measured ΔSPL values in region C were obtained for the single-row nozzles (6- and 7-tubes) as shown in figures 10 and 11(b). Varying the spacing between tubes for the 6-tube mixer nozzle (fig. 10) did not affect the correlation of the measured ΔSPL data with the calculated values. The measured ΔSPL values at high frequencies for the 3-tube nozzle (fig. 11(a)) were somewhat higher than predicted from equation (1).

The measured ΔSPL values with the 12- and 13-tube nozzles and short shielding lengths tended to be greater than the calculated values using equation (1), as shown in figures 11(c) and (d). The increase in

ΔSPL was largest with the shortest shielding surface length (15.0 cm) and amounted to about 3 dB. With the longer shielding surface lengths (26.4 and 54.36 cm) the measured ΔSPL values were generally within ±1 dB of the calculated curve. The general trend, however, for the multirow nozzles was to provide somewhat larger ΔSPL values with decreasing shielding surface length than those obtained with single-row mixer nozzles. Refinement of the present correlation equations to include this trend is beyond the scope of this report.

CONCLUDING REMARKS

From an acoustic point of view a mixer nozzle provides greater jet noise shielding benefits for CTOL-OTW applications than a single-tube (conical) nozzle. On the basis of the data obtained in the present program and the correlation equations used herein, a comparison of the representative jet noise shielding benefits to be gained by the use of multitube mixer nozzles compared with a single-tube nozzle are shown in figure 13. The calculated curves, based on the correlation equations included herein, shown in figure 13 are for a fixed total flow area for each nozzle (equivalent diameter of 5.8 cm). A shielding surface length of 26.4 cm and a jet Mach number of 0.64 was used in the calculations. It is apparent that the most significant shielding benefits for the configurations shown were obtained with the 6-tube mixer nozzle. At 20 kHz, the 6-tube mixer nozzle provided about 6 dB more jet noise shielding than the single-tube nozzle. Increasing the number of tubes to 12 (with a correspondingly smaller individual tube diameter since the flow area is held constant) provided up to about 2.5 dB more jet noise shielding at 20 kHz and about 1.0 dB at 500 Hz. It should be noted that multitube mixer nozzles with large numbers of tubes also provide some jet noise attenuation which together with their good shielding characteristics make their use desirable from acoustic considerations. However, other practical factors for these nozzles must be considered for aircraft applications such as lower flow coefficients, increased weight, and external aerodynamic characteristics.

Thus, the selection of a nozzle/wing combination will result from a trade-off of all these considerations.

NOMENCLATURE

a_o	ambient speed of sound
D_e	equivalent total nozzle diameter
D'_e	effective nozzle diameter, given by equation (3)
D_x	equivalent element or tube diameter
d	spacing between tubes (fig. 2(b))
f	1/3 octave band center frequency
f_1, f_2	functional notation
g	gravitational acceleration constant, 9.8 m/sec^2
L	shielding surface length downstream of nozzle exhaust plane
n	number of elements in mixer nozzle
n'	source alteration parameter
R	radius from nozzle centerline to tube centers
SPL	sound pressure level of nozzle-surface configuration, dB re 2×10^{-5} N/m^2
SPL_N	sound pressure level of nozzle only, dB re 2×10^{-5} N/m^2
ΔSPL	SPL - SPL_N, dB
U	peak local axial velocity at trailing edge of shielding surface
U_j	jet velocity at nozzle exhaust plane
Z'	jet noise shielding correlation parameter
θ	directivity angle measured from inlet

REFERENCES

1. von Glahn, U., Groesbeck, D., and Reshotko, M., "Geometry Considerations for Jet Noise Shielding with CTOL Engine-Over-the-Wing Concept," Am. Inst. Aero. Astro., New York, N. Y., Paper 74-568 (June 1974).

2. von Glahn, U., and Groesbeck, D., "Influence of Mixer Nozzle Velocity Decay Characteristics on CTOL-OTW Jet Noise Shielding," Am. Inst. Aero. Astro., New York, N. Y., Paper 75-97 (January 1975).

3. von Glahn, U., Groesbeck, D., and Huff, R., "Peak Axial-Velocity Decay with Single- and Multi-Element Nozzles," Am. Inst. Aero. Astro., New York, N. Y., Paper 72-48 (Jan. 1972).

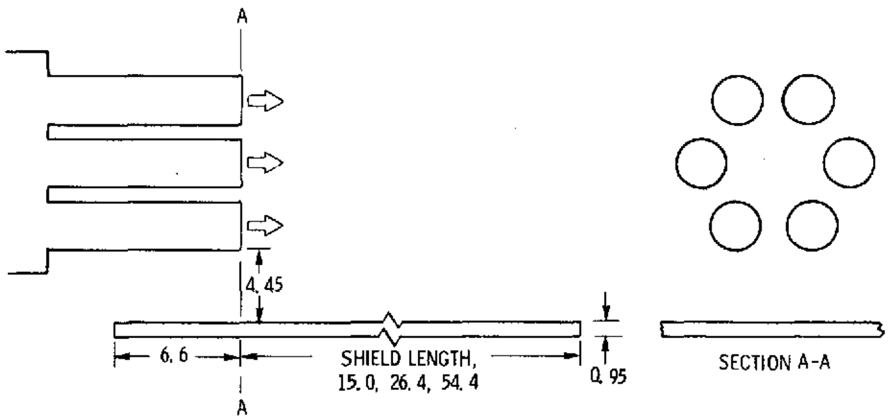

Figure 1. - Schematic sketch of typical nozzle-board model setup. All dimensions in centimeters.

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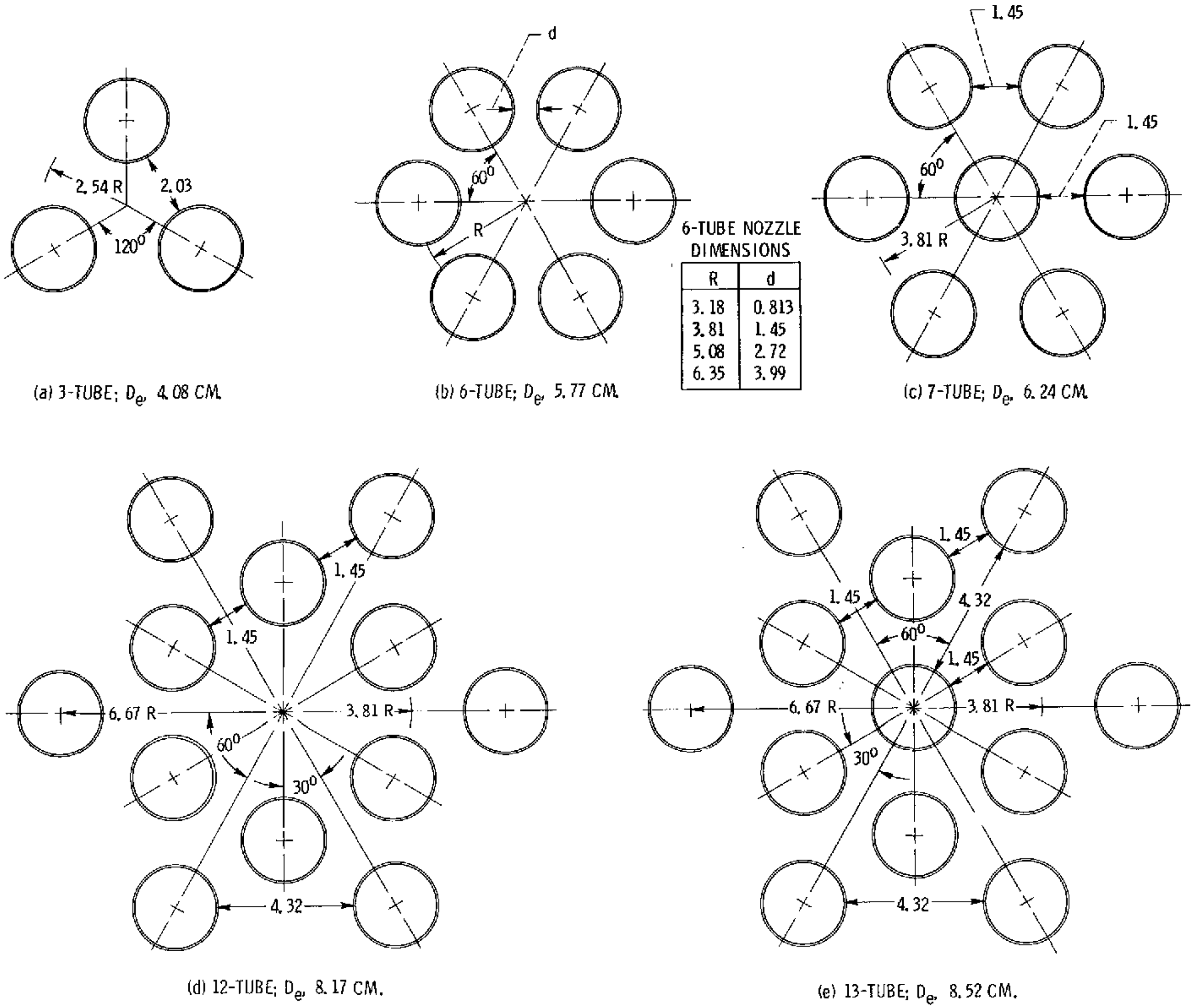

6-TUBE NOZZLE DIMENSIONS

R	d
3.18	0.813
3.81	1.45
5.08	2.72
6.35	3.99

Figure 2. - Multitube nozzle configurations tested. All dimensions in centimeters.

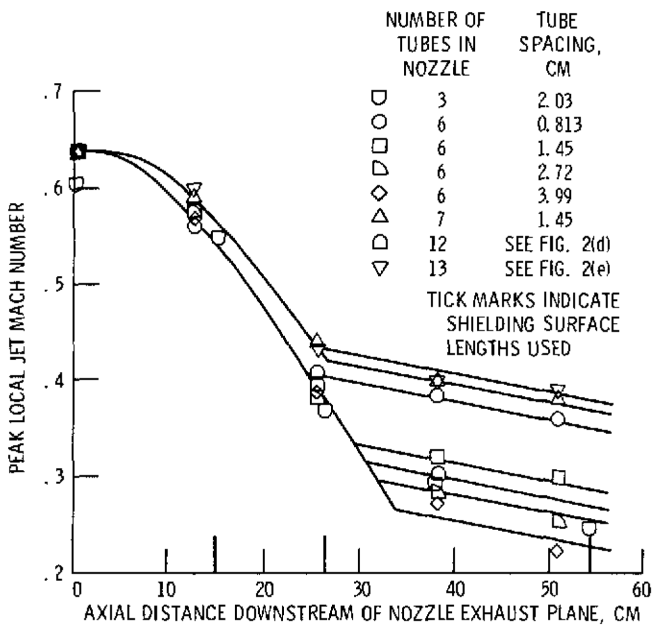

Figure 3. - Peak axial velocity decay characteristics for mixer nozzles alone.

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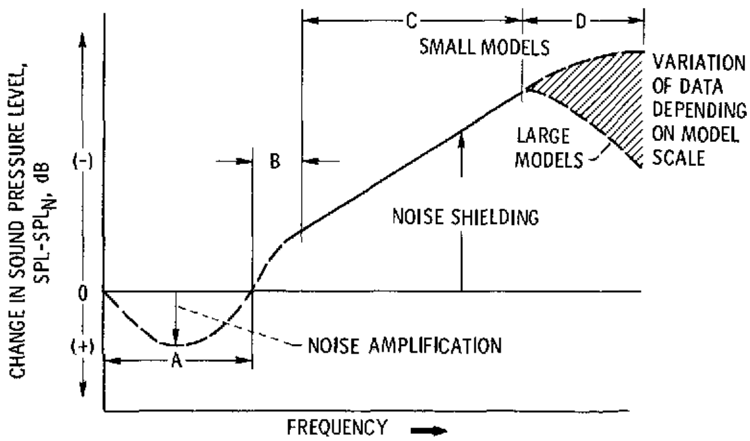

Figure 4. - Schematic representation of change in sound pressure level of jet noise due to a shielding surface.

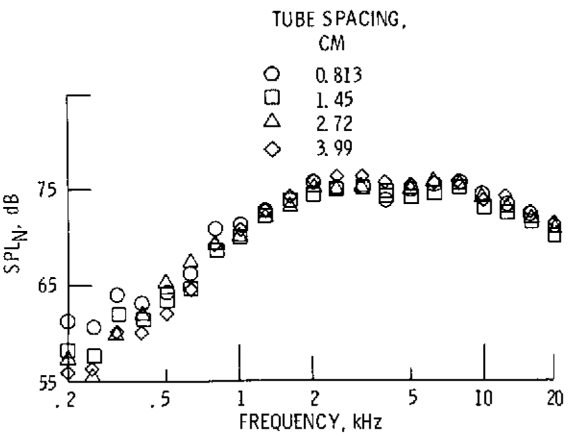

Figure 5. - Sound pressure level spectra for 6-tube mixer nozzles alone. Directivity angle, 90°; jet velocity, 200 m/sec.

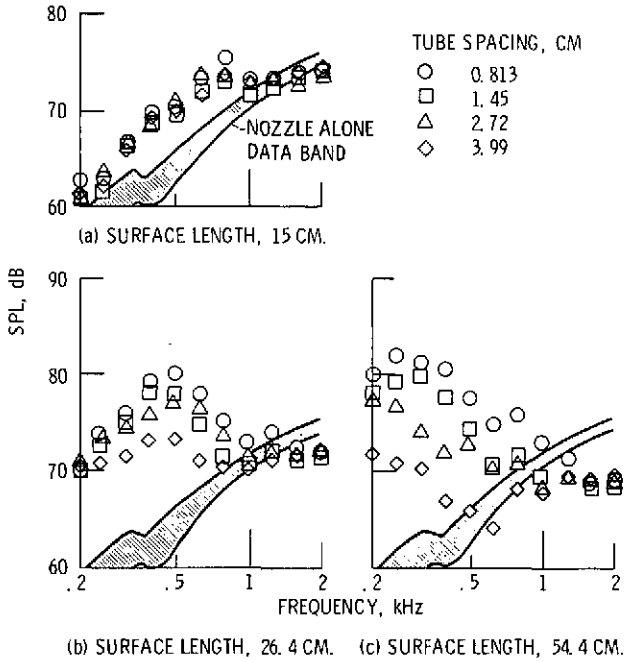

Figure 6. - Effect of tube spacing on jet-surface interaction noise with 6-tube mixer nozzle. Jet velocity, 200 m/sec.

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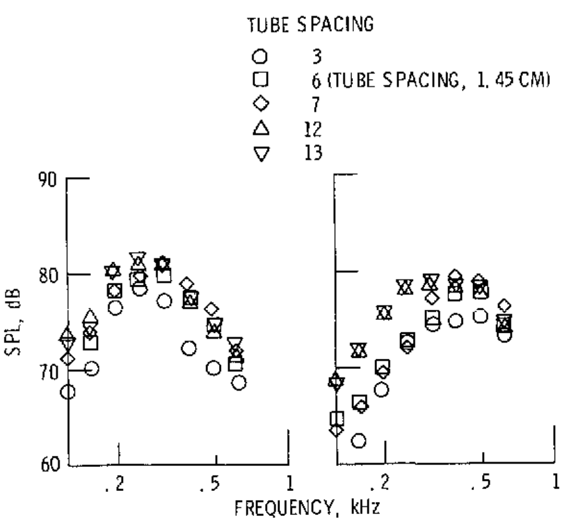


Figure 7. - Comparison of jet-surface interaction noise levels for 3- to 13-tube mixer nozzles. Jet velocity, 200 m/sec.

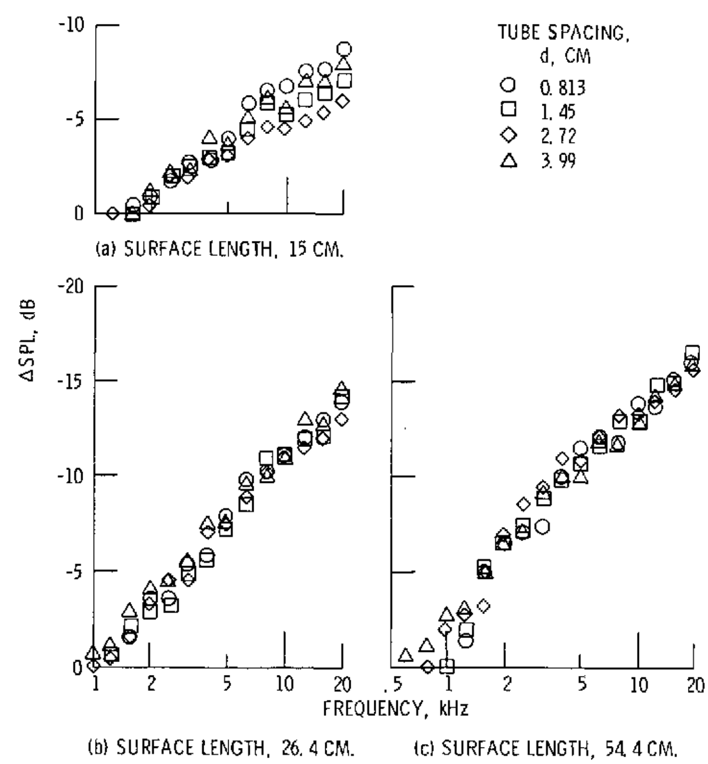


Figure 8. - Effect of tube spacing on jet noise shielding with 6-tube mixer nozzle.

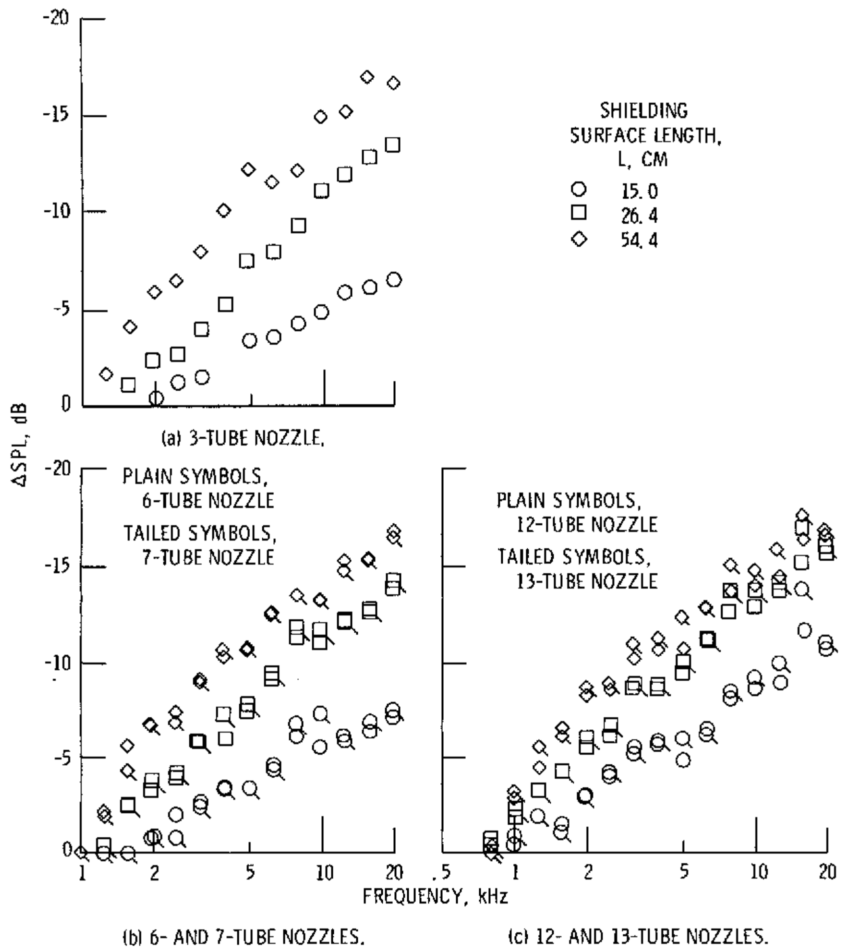


Figure 9. - Effect of shielding surface length on jet noise shielding with various mixer nozzles.

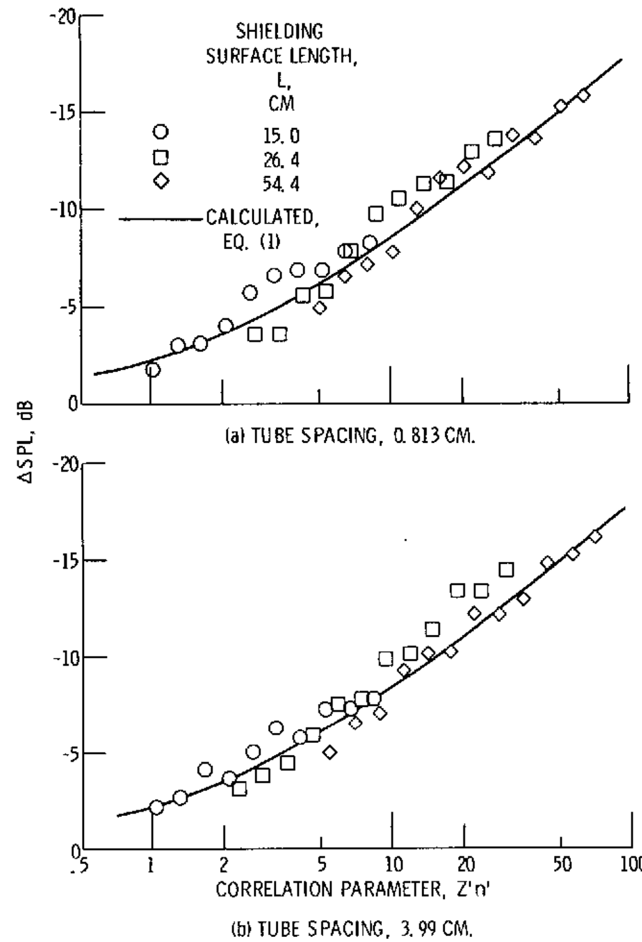
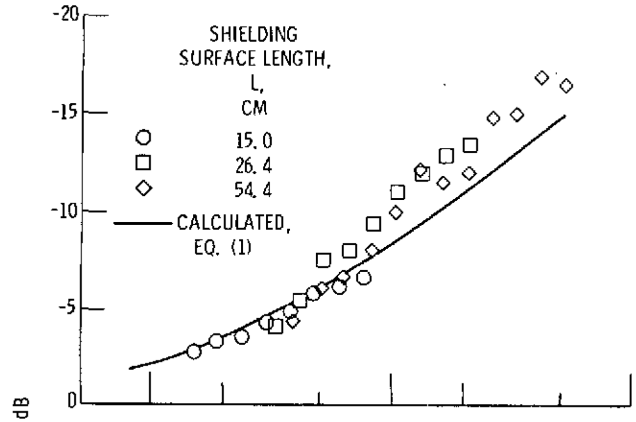
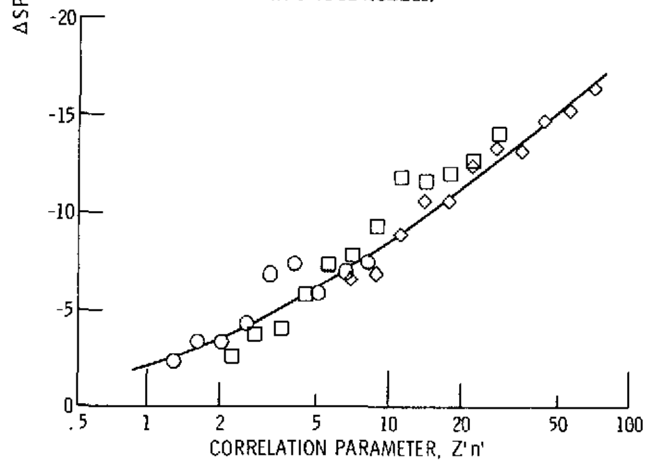


Figure 10. - Comparison of measured and calculated shielding ΔSPL for 6-tube nozzle with shielding surface. Region C.

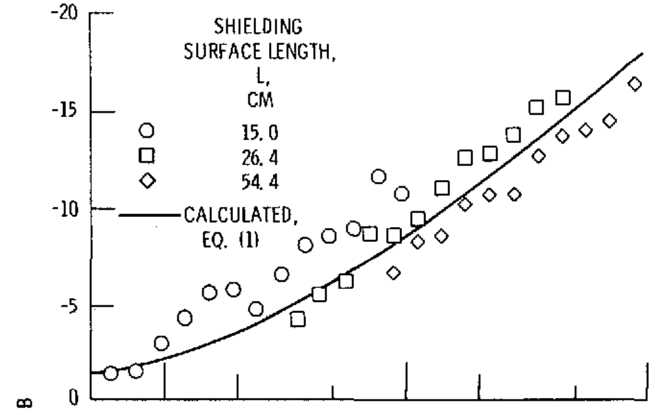


(a) 3-TUBE NOZZLE.

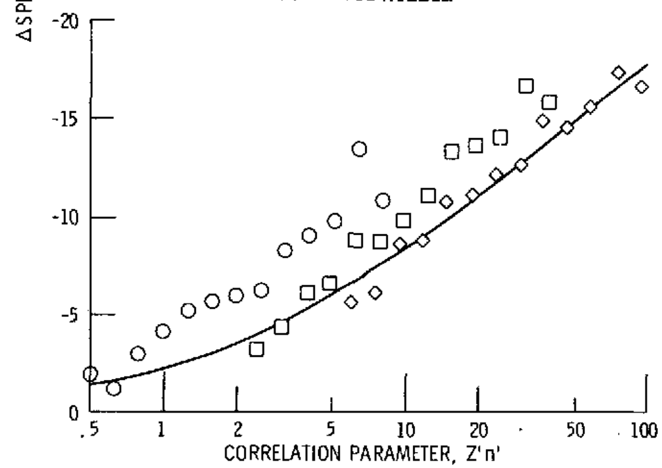


(b) 7-TUBE NOZZLE.

Figure 11. - Comparison of measured and calculated shielding ΔSPL for several mixer nozzles with shielding surface. Region C.

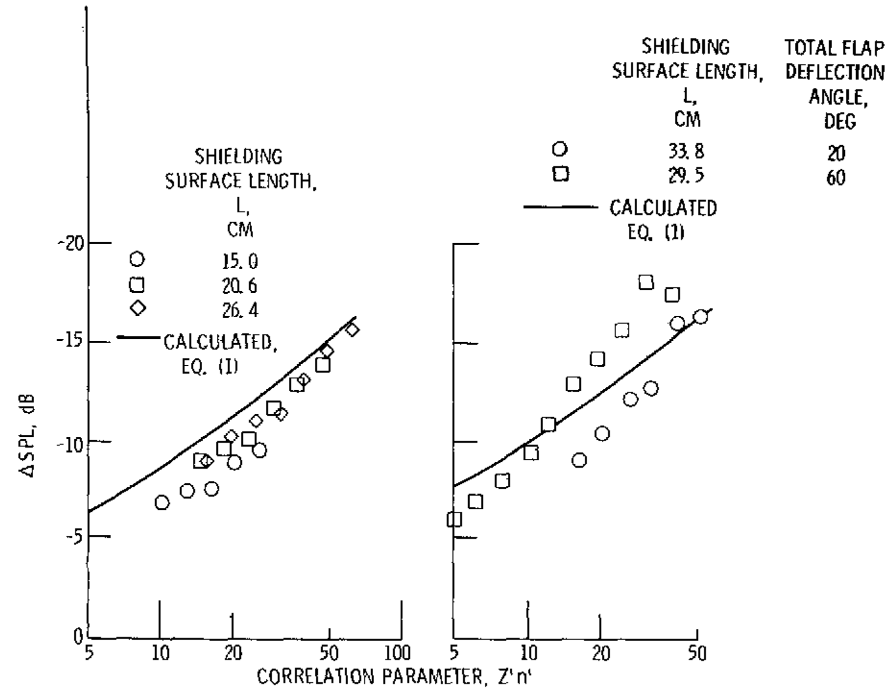


(c) 12-TUBE NOZZLE.



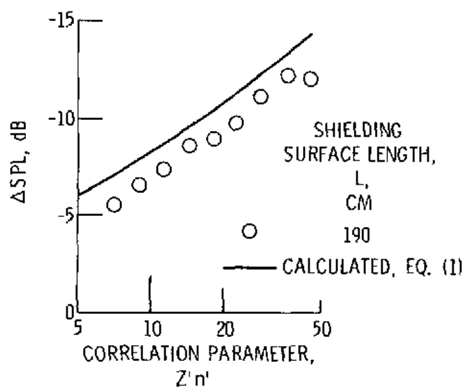
(d) 13-TUBE NOZZLE.

Figure 11. - Concluded.



(a) 8-TUBE NOZZLE; DIRECTIVITY ANGLE, θ, 90°.

(b) 8-LOBED NOZZLE WITH AIRFOIL; DIRECTIVITY ANGLE, θ, 100°.



(c) 7-LOBED NOZZLE WITH AIRFOIL; DIRECTIVITY ANGLE, θ, 90°.

Figure 12. - Comparison of measured jet noise shielding benefits with calculated values. Data taken from reference 2. Region C.

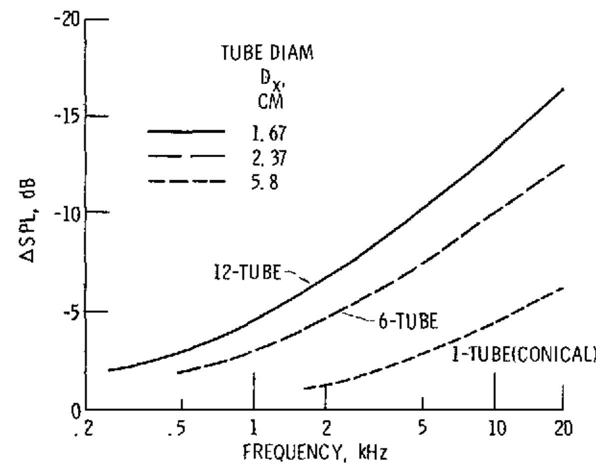


Figure 13. - Comparison of jet noise shielding benefits obtained with multitube nozzles and a single tube (conical) nozzle of equal flow area. U_j, 200 m/sec surface shielding length, 26.4 cm; directivity angle, 90°.