EFFECTS OF NOZZLE DESIGN ON THE NOISE FROM SUPERSONIC JETS

John M. Seiner, Thomas D. Norum, and Lucio Maestrello
NASA Langley Research Center

SUMMARY

The aeroacoustic supersonic performance of various internal nozzle geometries is evaluated for shock noise content over a wide range of nozzle pressure ratios. The noise emission of a Mach 1.5 and 2.0 convergent-divergent (C-D) nozzle is measured and compared to convergent nozzles. Comparisons are also made for a Mach 1.5 conical C-D nozzle and a porous plug nozzle. The Mach 1.5 conical C-D nozzle shows a small reduction in shock noise relative to the shock free case of the Mach 1.5 C-D nozzle. The Mach 1.5 C-D nozzle is found to have a wide operating nozzle pressure ratio range around its design point where shock noise remains unimportant compared to the jet mixing noise component. However it is found that the Mach 2 C-D nozzle shows no significant acoustic benefit relative to the convergent nozzle. Results from the porous plug nozzle indicate that shock noise may be completely eliminated, and the jet mixing noise reduced.

INTRODUCTION

One of the key aeroacoustic problems regarding the design of a supersonic cruise aircraft is increased acoustic emission produced by the presence of shocks in the jet exhaust plumes. This excess shock associated noise can completely dominate the jet mixing noise components in the forward quadrant of an aircraft engine that is operated with a supercritical nozzle pressure ratio. The recent theoretical work of Howe and Ffowcs-Williams[1] suggests that shock noise is an important component of the noise associated with the Concorde aircraft. The reduction of this shock noise component is important both from the standpoint of community noise and acoustic fatigue of the aircraft structure as documented by Hay and Rose[2].

A simple illustration of the physics (see Harper-Bourne and Fisher[3]) associated with the generation of shock noise is shown in figure 1. This figure depicts a standard converging nozzle operating with a supercritical nozzle pressure ratio, so that at the exit of the nozzle the static pressure is higher than that of the surrounding ambient medium. Upon leaving the nozzle exit the flow expands through the regular series of shocks in an attempt to lower the jet's static pressure to that of the surrounding medium. As the turbulent eddies convect through the shock cell system in the outer radial regions of the jet plume, intense omnidirectional broadband noise is produced with a peak frequency associated with the eddy convection velocity and shock cell spacing. The turbulence itself produces an unsteady location for the shock waves in the shear layer which, at certain nozzle pressure ratios, can cause the shock cell system to go into a resonant mode from acoustic feedback to the nozzle lip. This condition, which was first described by Powell[4], is known as screech and has only been clearly documented for unheated model supersonic jets.

The empirical model of Harper-Bourne and Fisher adequately treats the broadband shock noise component produced by convergent nozzles up to a nozzle pressure ratio where a Mach disc begins to form. This occurs at a value of $\beta = (M_J^2 - 1)^{\frac{1}{2}} \sim 1.1$, where M_J is the fully expanded Mach number. The model of Harper-Bourne and Fisher was primarily developed from measurements with unheated convergent nozzles, but recently Tanna[5] has established the validity of this model for heated model supersonic convergent nozzles. The essential limitation of the Harper-Bourne and Fisher model is that it is only valid for predicting the shock content associated with convergent nozzles. It is, of course, important that a new model be developed that treats nozzle configurations which achieve a reduction or complete elimination of shock noise.

Seiner and Norum[6] have investigated the off-design performance of laboratory type convergent-divergent nozzles, and have shown that a good noise reduction benefit exists over a wide operating pressure ratio range around the nozzle's design point. While this noise reduction benefit is encouraging, of broader issue is the shock noise reduction potential that is likely to be available with the use of industrial type convergent-divergent nozzles.

This paper reports on two studies conducted at the Langley Research Center on the reduction of shock cell noise by means of convergent-divergent (C-D) nozzles and a porous plug suppressor. In the first study the noise characteristics of both convergent and convergent-divergent nozzles were documented over a wide operating nozzle pressure ratio range. The nozzle pressure ratio range was selected to span the design points of a Mach 1.5 and Mach 2 C-D nozzle. In this way the off-design performance of these various nozzle geometries could be evaluated to provide new basic understanding of the shock noise production process, and provide a data base for the development of more accurate prediction schemes.

In the second study a porous plug was introduced into the center of the jet flow from a convergent nozzle. Maestrello[7,8] has shown that the porous plug nozzle suppressor does indicate a cancellation of the shock noise component with an additional reduction in the jet mixing noise. This paper reports on the acoustic performance of a much shorter porous plug nozzle suppressor than was used in references 7 and 8. The results show that good noise reduction is still achieved.

PROPERTIES OF OFF-DESIGN CONVERGENT-DIVERGENT NOZZLES

Acoustic Facility

The acoustic facility used at the NASA Langley Research Center consists of an anechoic room with interior working dimensions of 6.71 m x 8.43 m x 7.23 m. Nozzles are supported vertically in this chamber. The far-field acoustic measurements involve the use of 18 quarter inch free-field condenser microphones (B&K 4135) located uniformly at 7.5° intervals on a fixed radius of 3.66 m between 30° and 157.5° with respect to the upstream jet axis. The acoustic data were recorded on FM tape (DC-80 kHz). An illustration of the experimental arrangement is shown in figure 2.

For this acoustic program six nozzles were constructed whose internal contours are shown in figure 3. Of these, two are Mach 1 nozzles, one a conical convergent and the other a contoured convergent nozzle, the exit flow from the latter being parallel to the jet axis. The conical convergent nozzle represents the typical internal geometry for current commercial aircraft engine nozzles, and therefore its characteristic acoustic emission represents the reference case upon which comparisons are made. Three nozzles are convergent-divergent, and these include a Mach 1.5 C-D and Mach 2.0 C-D nozzle designed by the method of characteristics for parallel flow at the nozzle exit. These exit Mach numbers were selected on the basis that the Mach 1.5 nozzle is typical for the nozzle pressure ratio being considered for American supersonic cruise aircraft, while the Mach 2 represents a current upperbound for military type aircraft. The last C-D nozzle is a Mach 1.5 conical C-D nozzle, designed to approximate the contour of the nozzle in the F-15 airplane. The initial flow from this nozzle is divergent. The final nozzle is a contoured convergent nozzle that adapts the porous plug.

The exit diameter for each nozzle, except for the porous plug application, was chosen so that at specific points certain nozzles would exhibit the same ideal thrust. The Mach 2 nozzle was selected as the reference and constructed with an exit diameter of 5 cm. So that the Mach 1 nozzles would deliver the same thrust at the Mach 2 pressure ratio, thay were each constructed with a 3.95 cm exit diameter. The Mach 1.5 nozzles were constructed with a 4.28 cm exit diameter so that they and the Mach 1 nozzles would have the same thrust at the Mach 1.5 pressure ratio. For the above nozzles the 3.66 m microphone radius represents distances where $R/D \geq 72$.

Several pressure ratios were investigated which represent both design and off-design conditions for all nozzles. The pressure ratios under study in terms of β = 0., .2, .4, .6, .7, .8, .94, 1., 1.1, 1.34, 1.5, 1.72, 2., 2.1, and 2.15, where the values of 1.1 and 1.72 reflect the design pressure ratios of the C-D nozzles.

Experimental Results

Flow Field of a Mach 2 C-D Nozzle - A typical example of the shock structure encountered with the operation of a convergent-divergent nozzle at an off-design pressure ratio is shown in the schlieren photograph of figure 4. This photograph represents the case for the Mach 2 C-D nozzle operating in the underexpanded mode at a pressure ratio of 11.31 (β = 2). The centerline variation of Mach number for this case is shown in the lower portion of figure 4. At least 10 shock cells are evident, and these extend to a region between 25 and 30 jet diameters downstream of the jet exit. This figure shows that the supersonic core length is approximately 33 jet diameters and that the shock cell system is extinguished several diameters upstream of the sonic point. For this pressure ratio the fully expanded Mach number is 2.24, and the average trend of the Mach number variation approaches this in the first 15 jet diameters.

As was discussed in the Introduction, unheated supersonic model jets produce high amplitude discrete frequency noise generation known as screech. This component does not appear prevalent in hot engine jet exhaust plumes, and the suppression of this component is common practice with research on model unheated jets. The general problems associated with the suppression of the screech mode in model jets are discussed by Seiner and Norum[6], and there it is shown that the stabilization of the oscillating shock structure by a tab leads to serious difficulties in interpreting acoustic data for shock noise content. Therefore the comparisons in this section are for model nozzles without screech suppression, although results from the use of a tab are presented in figures 5a and 5b.

Directivity and Power Spectra of Shock Associated Noise - The directivity of overall acoustic levels clearly indicates the degree of shock noise contamination to be observed when running a convergent nozzle relative to a C-D nozzle at its design point. Figures 5a and 5b show acoustic level as a function of angle relative to the jet flow inlet at a pressure ratio of 3.60 (β - 1.1). Results are shown for the conical convergent and conical C-D nozzles, and the Mach 1.5 C-D nozzle. Figure 5a includes the effect of the screech mode, while figure 5b displays a comparison with the screech mode suppressed by a tab. All three nozzles were designed to have the same thrust at this pressure ratio. By comparing the directivities of figures 5a and 5b it is evident that the Mach 1 conical nozzle contains strong screech tones at the Mach 1.5 design pressure ratio. With the screech mode suppressed there is little difference in the noise levels of the conical convergent and conical C-D nozzle. One can also observe that each conical nozzle still exhibits strong shock noise when compared with the shock free noise levels obtained with the Mach 1.5 C-D nozzle.

The data of figure 5 indicates that shock noise dominates the jet forward arc ($0 \leq \psi \leq 90°$). The narrowband power spectral density curves of figures 6a and 6b show the nature of this shock noise content at $\psi = 45°$ for the Mach 1 conical and Mach 1.5 conical C-D nozzles respectively. In each case the shock free contoured Mach 1.5 nozzle is shown for comparison. It is evident from these data that the broadband shock noise of both conical nozzles are relatively the same. Except for the presence of screech tones in the Mach 1 conical nozzle, the conical C-D nozzle appears to offer an insignificant acoustic benefit at these conditions relative to the conical convergent nozzle.

Shock Noise Benefit of C-D Nozzles - In order to evaluate the extent of the pressure ratio range where a C-D nozzle, designed for shock free flow, offers a noise reduction relative to a convergent nozzle the overall sound pressure level variation with β is shown in figure 7 at $\psi = 45°$. This figure indicates that there is a large range of nozzle pressure ratios around the design point of the Mach 1.5 C-D nozzle ($\beta = 1.1$) where considerably less noise is radiated compared to that produced by the strong shock cell structure of the Mach 1 conical nozzle. One can also observe with the Mach 1 conical nozzle that beyond $\beta = 1.1$ the variation of acoustic level with the parameter β levels off and even decreases. This change in shape corresponds to the change observed in the secondary wavelength of the shock cell system resulting from the formation of a Mach disc as was reported in reference 6. Evidently as the Mach disc forms the strength of the shock cell system starting with the second shock cell, weakens in the jet's shear layer. Figure 7 also shows the variation of sound pressure with β for the Mach 1.5 conical C-D nozzle, and as expected, the acoustic benefit is much smaller than for the Mach 1.5 C-D nozzle.

In consideration of the complexity associated with integration of an engine nozzle with the optimum operating conditions of an aircraft's engine and airframe, it is difficult to prescribe what one may consider to be the best method for evaluating a jet noise benefit. Since we are attempting to compare the relative acoustic performance of convergent and C-D nozzles, a logical choice in model scale appears to be the ideal thrust. Also, the total integrated sound power of the flow appears to provide the most complete view of the dominance of the shock noise component over jet mixing noise. Hence, the total integrated sound power level is presented against ideal thrust in figure 8 for the three contoured nozzles tested.

In this figure the three darkened symbols correspond to the design points of the three nozzles. For both C-D nozzles the minimum noise point for each depression around the design point occurs in the overexpanded region, not at the design point. For the Mach 1.5 C-D nozzle, there is a 6 dB maximum difference compared to a contoured convergent nozzle with identical thrust. There is also a wide operating range where the Mach 1.5 C-D nozzle produces less noise. The case of the Mach 2 C-D nozzle is very disappointing since figure 8 shows that in comparison to a convergent nozzle it produces more noise at the same thrust almost across the entire pressure ratio range. As noted before, this primarily occurs since shock noise is relatively weak with a Mach 1 convergent nozzle at high nozzle pressure ratios, and the formation of a Mach disc produces a substantial region of subsonic flow which reduces the jet mixing noise. Figure 8 indicates that a Mach 1.5 C-D nozzle could represent an optimum selection for a design Mach number. This, of course, requires further investigation.

The results of this study are only strictly relevant to the case of unheated model jets where the dominance of the shock noise component over jet mixing noise can be clearly distinguished. With increasing jet exit velocity due to heat addition, the jet mixing noise increases but the shock noise remains relatively constant (see Tanna[5]). Thus, the results shown in this section, and particularly in figures 7 and 8, most likely indicate the maximum noise benefit available through use of a convergent-divergent nozzle.

POROUS PLUG NOZZLE SUPPRESSOR

The use of a porous plug nozzle as a means of reducing jet noise has been detailed in references 7 and 8. This section reports results for a porous plug centerbody with a shorter length than in the previous reports. Included are shadowgraph pictures and the associated acoustic far-field spectra for the plug nozzle in comparison to a standard convergent nozzle.

Description of the Nozzle - The porous plug nozzle suppressor is shown in figure 9. This configuration has a plug/nozzle diameter ratio 0.833, with a flow exit area of 20.27 cm^2. The porous centerbody extends 24 cm from the nozzle exit, and it has a surface porosity of about 2 percent (ratio of open area to total area) which was accomplished by drilling a pattern of 0.07 cm radial holes around its periphery. The interior cavity of the plug is sealed on one end inside the nozzle and is vented to the jet stream all along its length.

A standard convergent nozzle with an exit diameter of 5.08 cm and with the same open flow exit area as the porous plug nozzle was tested to obtain comparable data as a basis for evaluating the aeroacoustic performance of the porous plug nozzle. The test was conducted over a range of pressure ratios between 1.136 - 3.72 and at ambient temperature.

Experimental Results - The shadowgraph pictures of figure 9 illustrate some of the operational features of the porous plug nozzle at a pressure ratio of 3.72. These pictures are for a longer plug, reported in references 7 and 8 and are shown here for the purpose of illustrating the concept of the flow behavior over a porous surface.

The flow of the standard convergent nozzle (figure 9, top) is underexpanded, a condition favorable for the formation of shocks in the jet. Portions of shock cells are evident, and others were observed downstream of the region shown in the photograph. The shocks are weaker further downstream and eventually disappear as the flow becomes subsonic. The interaction of these shocks with convected turbulence is the source of broadband shock noise emanating from the jet.

The flow development of a nonporous plug nozzle (a plug nozzle without venting holes) is shown in the middle photograph of figure 9. The shock pattern appears to be much weaker than in the standard nozzle, probably due to the elimination of shock focusing at the centerline. The flow from the porous plug nozzle (figure 9, bottom) looks free of shocks, indicating that the venting holes permit an adjustment of pressure gradient in the flow and hence preventing the formation of shocks.

Far-field acoustic power spectra of the porous plug and standard convergent nozzles are compared in figure 10. The data were obtained at 3.81 m from the jet exit and are presented for angles of 50°, 90°, and 160° from the inlet.

The spectra of the standard jet at angles of 50° and 90° exhibit both screech tones and broadband shock noise. A smaller tone appears at 160°, although this spectra appears to be dominated by jet mixing noise. The data from the porous plug nozzle indicate no peaks due to shock associated noise. This result is consistent with the shadowgraph of figure 9 which suggests that the shock waves are eliminated in the porous plug nozzle flow.

Note also that the porous plug nozzle spectra indicate noise reductions at essentially all frequencies at each of the angles. In particular, significant reductions are obtained at 160°, where the mixing noise dominates. This suggests that in addition to shock noise reduction, the porous plug nozzle also yields a reduction in the jet mixing noise.

Although not shown here, significant mixing noise reduction occurs even when the Mach number is subsonic, particularly at small angles from the jet axis. The differences in the noise levels between using a short porous plug and a longer one were reported in references 7 and 8. There it was shown that a longer plug produces less jet mixing noise at low frequency at angles near the jet axis. This difference reflects the trade-off between using a short versus longer plug centerbody.

CONCLUSIONS

This paper has examined the potential noise benefit offered by a convergent-divergent nozzle relative to a conical convergent nozzle over a wide range of operating pressure ratios. In the case of the shock free contoured Mach 1.5 C-D nozzle a 6 dB reduction of total integrated sound power was achieved over a Mach 1 contoured convergent nozzle operated at the same thrust. A smaller reduction of total acoustic power was found in the comparative case of the Mach 1.5 conical C-D nozzle. For the case of a Mach 2 nozzle, its benefit over a convergent nozzle is less promising unless it would be imperative to reduce the sound pressure levels slightly in the jet's forward arc as has been reported in reference 6. The data with C-D nozzles clearly indicate that current concepts regarding the design of the Mach 1.5 conical C-D nozzle is inadequate for elimination of shock noize. It is perhaps possible to emulate the shock noise reduction performance of the laboratory type C-D nozzle by considering other internal nozzle shapes that cancel internal shock waves more completely.

The results on the porous plug nozzle suppressor show that both the screech and broadband shock associated noise are eliminated with an additional decrease in the jet mixing component. The noise reduction of the plug nozzle suppressor is parametrically dependent on the plug's surface porosity and length.

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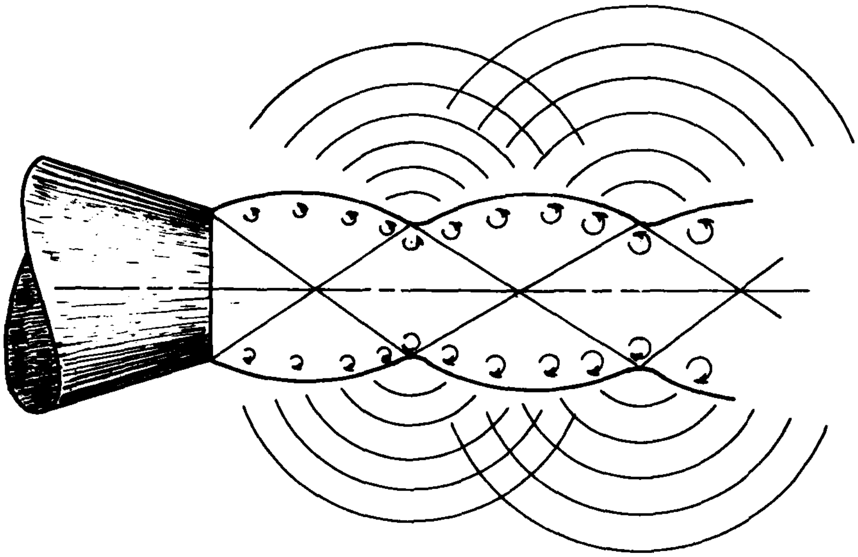

Figure 1.- Illustration of shock associated noise.

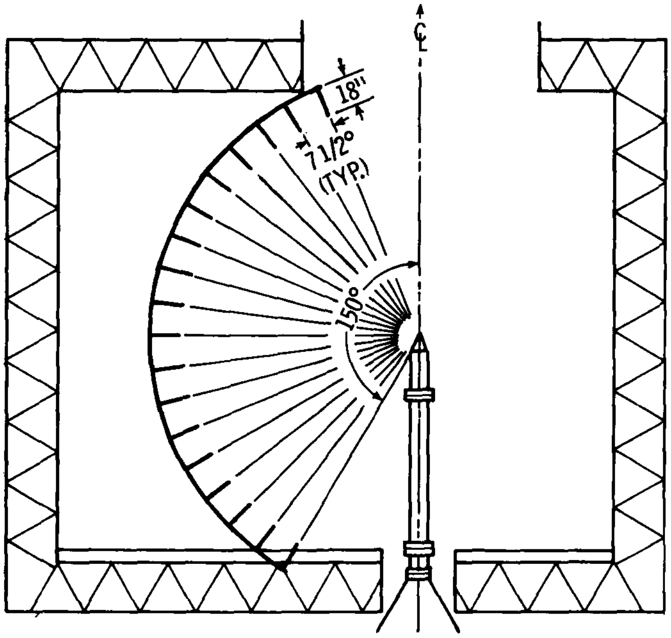

Figure 2.- Anechoic test facility.

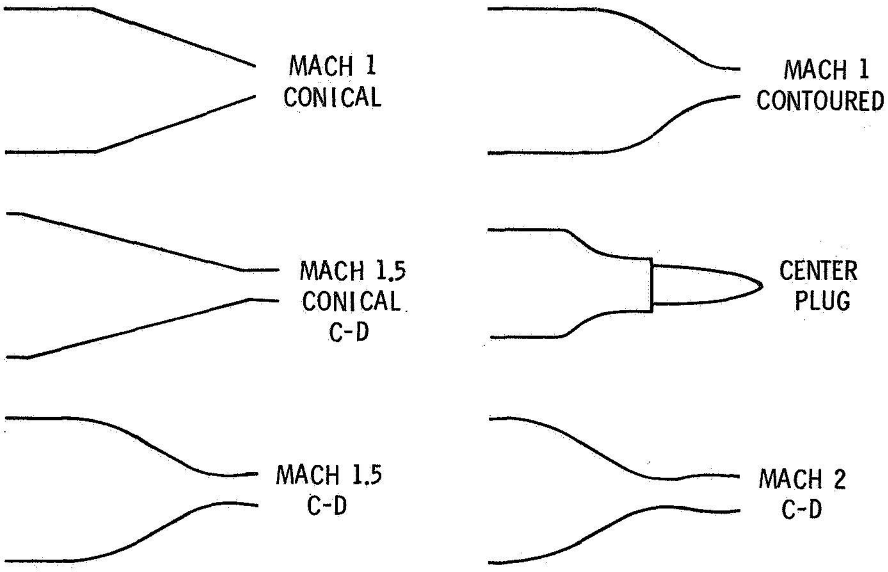

Figure 3.- Nozzle contours for shock noise study.

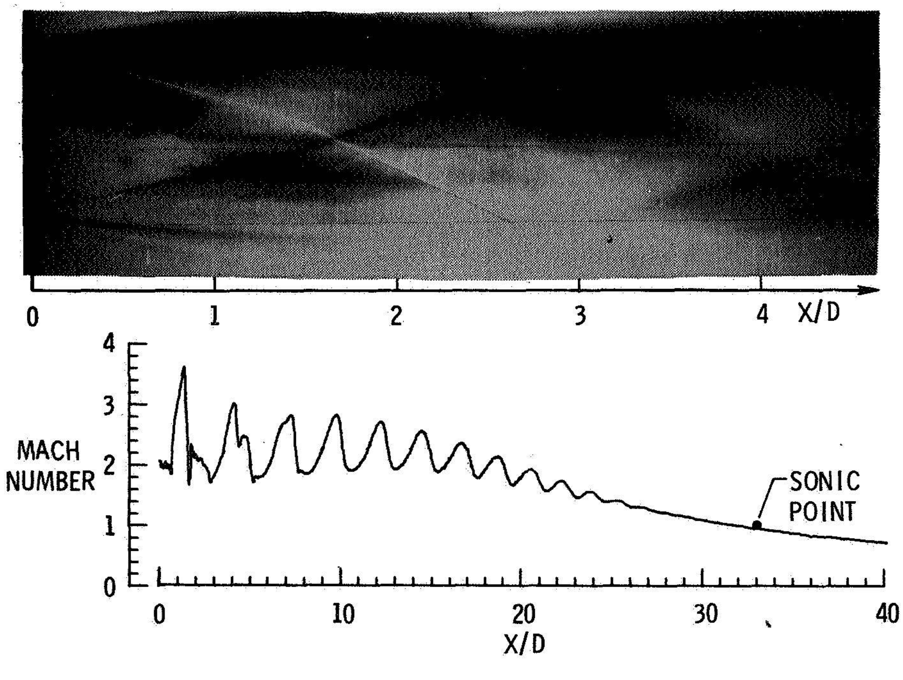

Figure 4.- Mach 2 C-D nozzle at $\beta = 2$.

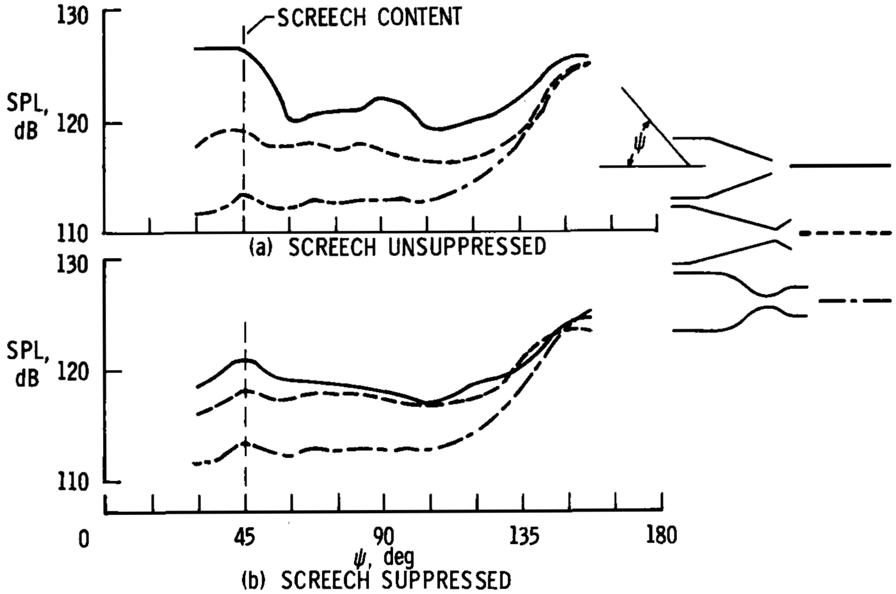

Figure 5.- Shock noise directivity at $\beta = 1.1$.

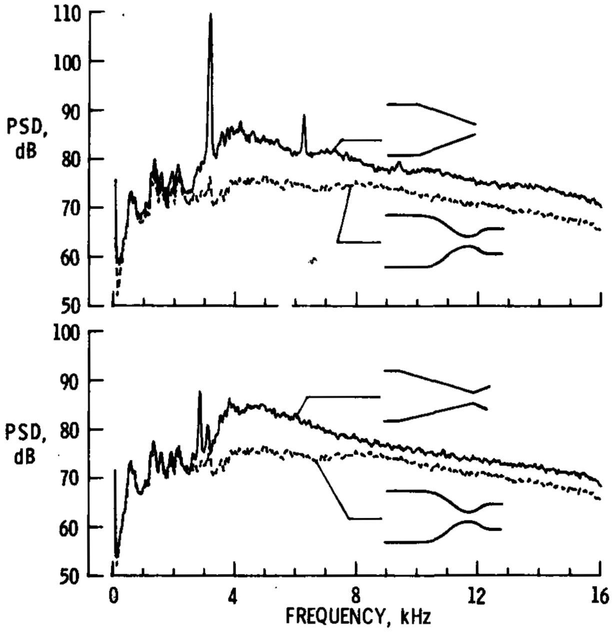

Figure 6.- Power spectral density at $\beta = 1.1$, 45° from inlet.

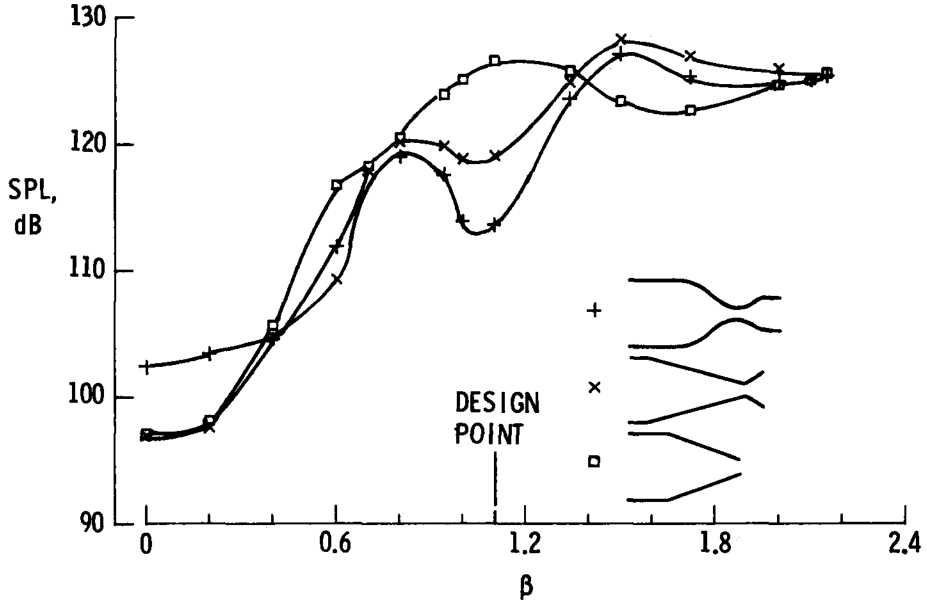

Figure 7.- Shock noise benefit of Mach 1.5 nozzles.

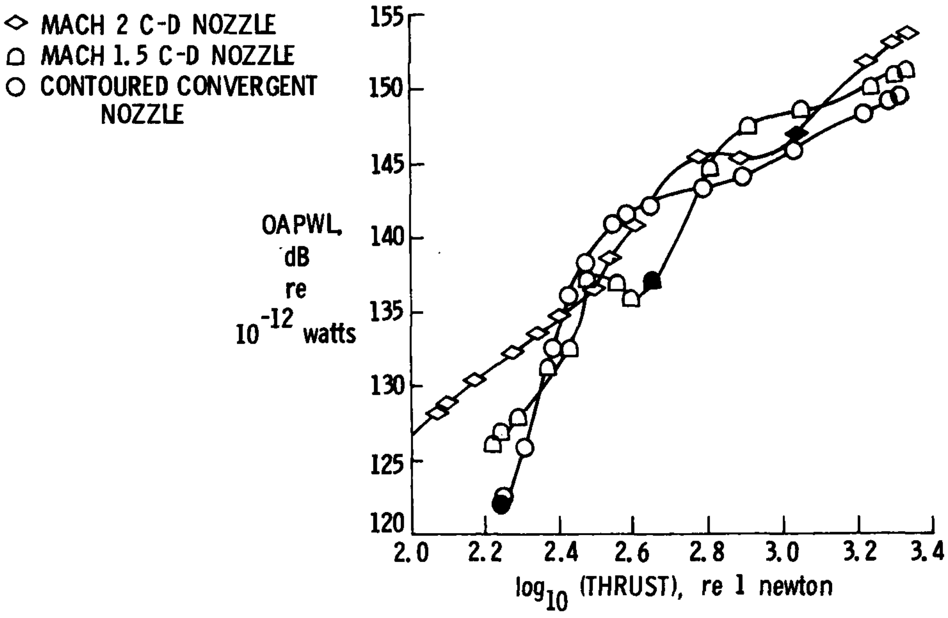

Figure 8.- Maximum overall noise benefit of C-D nozzles.

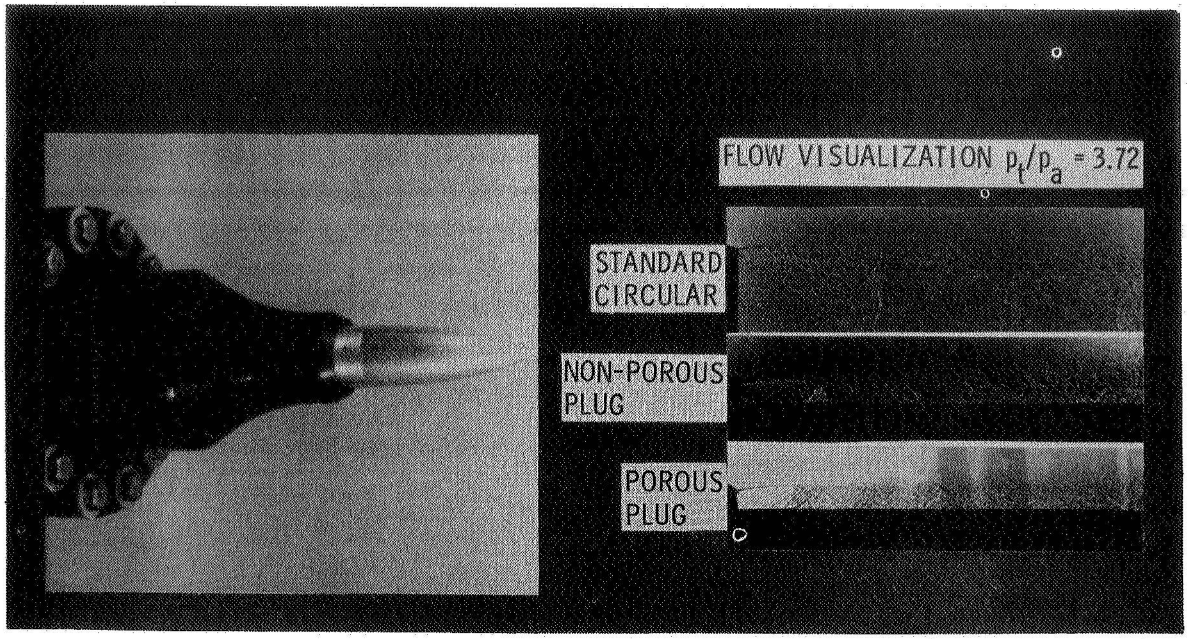

Figure 9.- Porous plug nozzle suppressor.

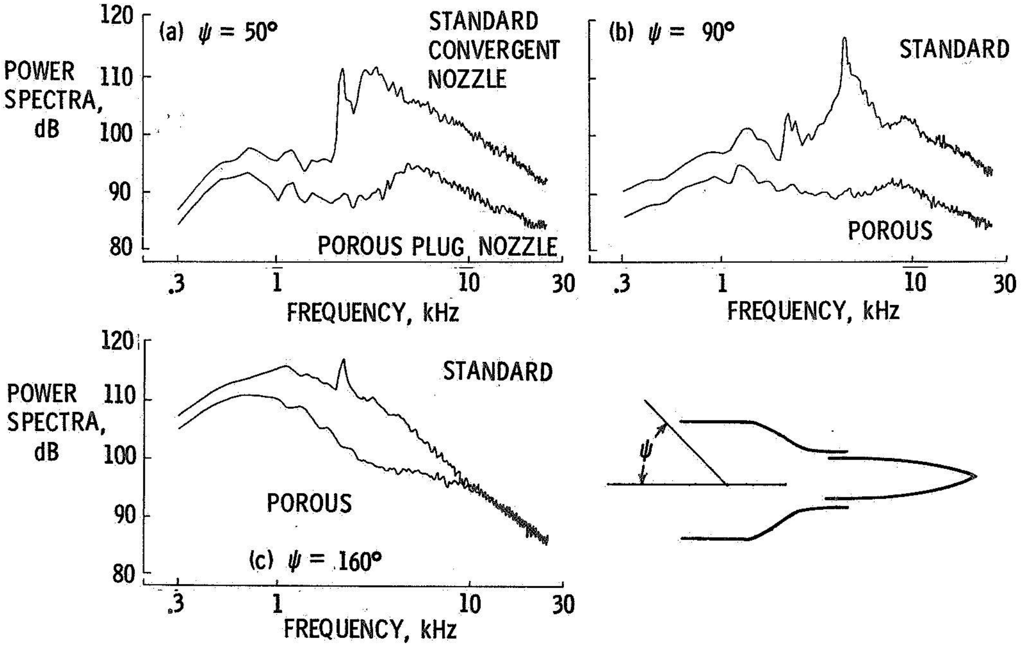

Figure 10.- Noise benefits of porous plug nozzle.