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Computation of Supersonic Jet Noise Under Imperfectly Expanded Conditions

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Abstract

The turbulent mixing noise of supersonic jet under imperfectly expanded conditions is calculated for convergent and convergent-divergent (CD) axisymmetric nozzle geometries. The noise prediction incorporates CFD solution of Navier-Stokes equations. The effect of grid resolution on shock structure computation is demonstrated. Mixing noise spectra predicted from fine and coarse grid solutions exhibit little sensitivity to the grid resolution. A proper grid resolution, however, results in a significant improvement in shock capturing capability and helps predictions agree favorably with experimental data. Good agreement between predicted noise spectra and data shows that the CFD-incorporated noise prediction scheme, which was demonstrated for shock-free condition, works as well for shock-containing flow conditions.

Introduction

One of the key technical elements in NASA's High Speed Research Program (HSRP) is reducing the noise level to meet the federal noise regulation. The dominant noise source is associated with the supersonic jet discharged from the engine exhaust system. While the turbulence mixing is largely responsible for the generation of the jet noise, a broadband shock-associated noise is also generated when the nozzle operates at conditions other than its design condition. For both mixing and shock noise components, since the source of the noise is embedded in the jet plume, one can expect that jet noise can be predicted from the jet flow field solution. Mani et al.[1] developed a unified aerodynamic/acoustic prediction scheme by applying an extension of Reichardt's aerodynamic model to compute turbulent shear stresses which are utilized in estimating the noise source strength. While this method produces a fast and practical estimate of the jet noise, a modification by Khavaran et al.[2] has led to an improvement in aerodynamic solution. The most notable feature in Ref. 2 is that Reichardt's model in Ref. 1 is replaced with CFD solution of Reynolds-averaged Navier-Stokes equations. The major advantage of this work is that the essential, noise-related flow quantities such as turbulence intensity and shock strength can be better predicted.

The predictions in Ref. 2 were limited to a shock-free design condition and the effect of shock structure on the jet mixing noise was not addressed. The present work is aimed at investigating this issue. Under imperfectly expanded conditions the existence of the shock cell structure and its interaction with the convecting turbulence structure may not only generate a broadband shock-associated noise but also change the turbulence structure and thus the strength of the mixing noise source. Failure in capturing shock structures properly could lead to incorrect aeroacoustic predictions.

Nozzle geometries chosen for the comparison with experimental data include convergent and CD, axisymmetric nozzles. These nozzles have been tested by General Electric (GE) for NASA Lewis Research Center and both aerodynamic and acoustic test results were reported in Ref. 3. In order to better investigate the effect of shock structure, most imperfectly expanded test conditions were considered. The plan of the paper is as follows. First the effect of the grid size on the resolution of the shock structure is studied. Computed mean and turbulent quantities are then compared with test data at selected nozzle operating conditions. The predicted noise spectra are also compared with measured data followed by summary and conclusions.

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*Member, AIAA.

Method of Solution

The solution technique to compute the noise field is essentially based upon the methodology developed in Ref. 1 as modified in Ref. 2 and details are documented in Ref. 2. As mentioned earlier, a major modification was made such that Reichardt's aerodynamic model has been replaced with a CFD solution. This improvement, as shown in Ref. 2, not only eliminates some of the empiricism in original method of Ref. 1 but also provides a better estimate of source strength and sound/flow interaction. More critically, for the imperfectly expanded jet flow conditions, a CFD solution can properly predict the shock structure which is not taken into account in Reichardt's model.

In order to compute the flow field, the PARC code with a $k\text{-}\varepsilon$ turbulence model[4] was used. This code solves the complete Reynolds-averaged Navier-Stokes equations in conservative law form using the Beam and Warming approximate factorization algorithm and has been verified for a variety of aerodynamic problems.

As far as dealing with shock structure this code has a tendency of numerically attenuating downstream shocks. While the basic numerical schemes and turbulence modeling may be responsible for this attenuation problem, the effect of mesh size has not been addressed properly in the open literature. To investigate this issue and compare aerodynamic and acoustic results, GE's test data[3] were selected. Nozzle geometries include convergent and CD, axisymmetric nozzles. These two nozzles have the same equivalent diameter. The CD nozzle geometry is the same one studied in Ref. 2.

Results and Discussion

Effect of Grid Size on Shock Structure

The basic philosophy in studying the grid issue for this particular problem is that the grid size in a radial direction has little effect on resolving shock structures and thus only the number of grids in the axial direction is varied. Depicted on Fig. 1 are coarse (141 by 61) and fine (441 by 61) grids for the CD nozzle tested by GE. Note that both grids are highly clustered around the nozzle exit as well as the jet lipline. Figure 2 shows the centerline axial velocity profile for the CD nozzle operated at a nozzle pressure ratio (NPR) of 3.312. The design pressure ratio (DPR) for this nozzle is 3.121. Here U_j and D_{eq} correspond to the fully expanded jet velocity and the equivalent nozzle diameter respectively. Although the shock strengths are relatively weak due to slightly imperfectly expanded test condition, the fine grid solution exhibits a better capturing of the downstream shock structures. For the similar pressure ratio of 3.323, the convergent nozzle geometry shows much stronger shock data as shown on Fig. 3. Here 141 by 71 and 421 by 71 grids were used for coarse and fine grid solutions respectively. The predicted axial velocity profile along the centerline clearly shows that proper grid resolution is required for a better flow field solution including shock structures. Another evidence of the grid effect is shown by the Mach number contours in Fig. 4, where the downstream shock structures are better predicted in fine grid solution. In passing, even the fine grid prediction in Fig. 3 appears to attenuate downstream shock strengths. To investigate whether this is still related to the grid resolution a finer grid (561 by 71) solution was compared with the fine grid (421 by 71) solution in Fig. 5. The comparison clearly shows a grid improvement does not improve the solution and a more accurate numerical scheme with a better turbulence model appears to be required to improve the attenuation problem.

Aerodynamic Results From Fine Grid Solution

The fine grid solution is further compared with experimental data in Figs. 6 and 7. The nozzle geometries and pressure ratios are the same as those mentioned earlier. In Fig. 6, the mean velocity distribution along the radial direction at a fixed axial location shows that both convergent and CD nozzle solutions agree well with data.

As explained earlier the turbulence intensity obtained from CFD solution is directly related to the strength of the mixing noise sources. Depicted in Fig. 7 are the turbulent intensity profiles along the lipline and a fair agreement is shown with the data. The radial distribution of the turbulence intensity also compares well with data in Fig. 8, where both predictions show the maximum intensity around the nozzle liplines.

Acoustic Results

Based on the fine grid solutions of mean and turbulent quantities, one-third octave band sound pressure levels (SPL) for the convergent nozzle geometry are compared with measured data at 40 ft radius in Fig. 9. Here θ is measured with respect to the inlet axis. Only sound pressure levels in the rear quadrant region where the mixing noise is dominant are shown. Good agreement between prediction and data shows that the CFD-incorporated noise prediction scheme, which was demonstrated for shock-free condition in Ref. 2, also works as well for shock-containing flow conditions. Similar comparisons were made for the CD nozzle geometry as shown in Figs. 10 and 11. The predicted results correspond to the underexpanded (NPR = 3.312) and the overexpanded (NPR = 2.62) conditions respectively. Note that the design pressure ratio for the CD nozzle is 3.121. An interesting observation can be made by comparing the noise data between convergent and CD nozzles. Figure 12 shows measured noise data at several different observer angles for convergent and CD nozzle geometries operated at the same pressure ratio of 3.3. The equivalent diameter for two nozzles is the same here. It is obvious that the differences in spectra at angles 60° and 90° is due to the shock noise contribution. Note that, for the same pressure ratio and the nozzle equivalent diameter, the mixing noise as observed at angles 120° and 160° is almost identical. Considering the distinctive difference in the flow field between two nozzle geometries it appears that the mixing noise is almost independent of the shock strengths. This is also reflected on the prediction as shown in Fig. 13 and provides an indirect indication that the turbulence mixing noise is relatively insensitive to the variation of the shock structure.

Effect of Grid Size on Acoustic Prediction

Earlier, the effect of grid resolution on aerodynamic solution, especially the shock structure, was discussed. The question then naturally rises whether the noise is also affected by the grid resolution. In order to investigate this issue the test condition for the convergent nozzle geometry is considered. Depicted on Fig. 14 are the centerline axial velocity profile, lipline turbulent intensity, and the sound pressure level spectrum at 120° showing coarse and fine grid solutions. Despite the difference in mean flow quantities as represented by the centerline axial velocity profile in Fig. 14(a) the noise predictions exhibit little dependence on the grid resolution as shown in Fig. 14(c). This may be explained by the fact that the turbulence intensity distribution, which provides the estimate of the noise source strength, is about the same on the average between coarse and fine grid solutions as shown in Fig. 14(b). It should be noted, however, that proper capturing of the shock structures is still very important from the viewpoint of the sound propagation where the mean flow gradients determine the radiation patterns. This is more crucial in computation of the broadband shock-associated noise which is generated by the interaction between the shock-cell structure and turbulence.

Summary

In this study the turbulent mixing noise generated by imperfectly expanded supersonic jets is computed and compared with experimental data. The noise computation is based on CFD generated aerodynamic results using the PARC code and acoustic prediction methodology described in Ref. 2. The nozzle geometry selected for the comparison consists of convergent and CD, axisymmetric nozzles. The effect of better grid resolution upon capturing more accurate shock structures is investigated and demonstrated. Both aerodynamic and acoustic predictions agree well with measured data.

Comparison of measured noise spectra between convergent and CD nozzles of same equivalent diameter shows that, at the same nozzle pressure ratio, the mixing noise contribution is almost identical in spite of quite a difference in shock structures in the flow field. The prediction also reveals the same observation, which implies that the turbulent mixing noise is barely affected by the shock strengths. Similar arguments hold for the effect of grid resolution on the noise prediction. Although the fine grid flow solution agrees much better with aerodynamic data, the mixing noise spectra show little difference between fine and coarse grid noise predictions. This may not be true when it comes to incorporating the nonaxisymmetric nozzle geometry and sound/flow interaction where the mean flow gradients dominate the whole mechanism of sound radiation. Accurate prediction of flow field including shock structure is more important in properly estimating the shock associated noise.

References

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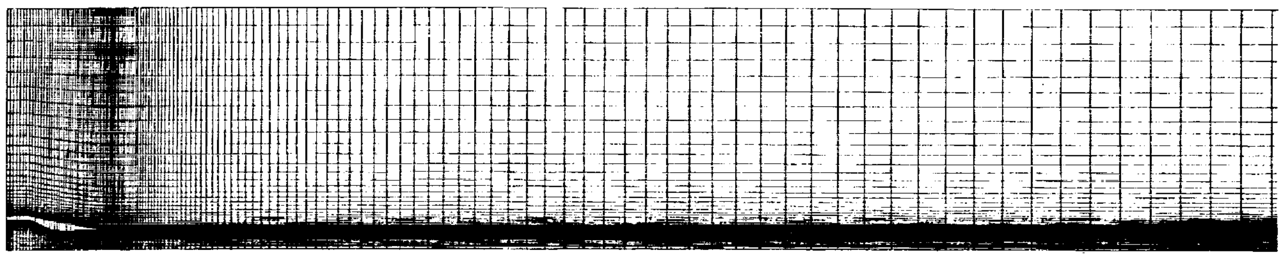
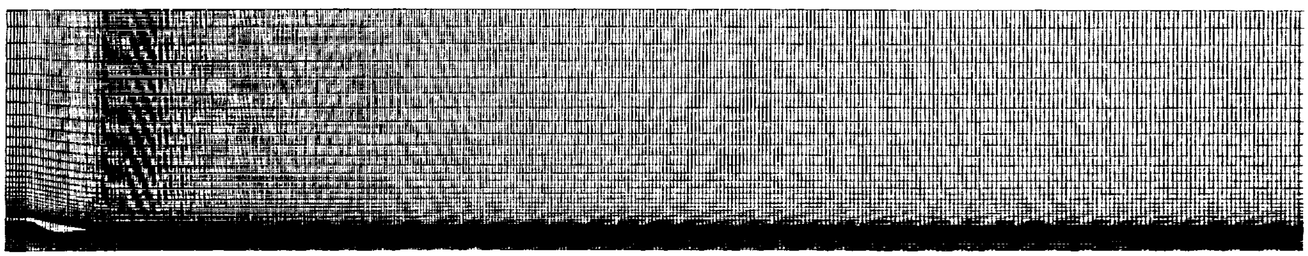
4. Chien, K.Y., "Prediction of Channel and Boundary Layer Flows with a Low Reynolds Number Turbulence Model," AIAA J., Vol. 20, 1982, pp. 33-38.



(a) Coarse grid (141x61).



(b) Fine grid (441x61).

Figure 1.—Grid for the CD nozzle geometry.

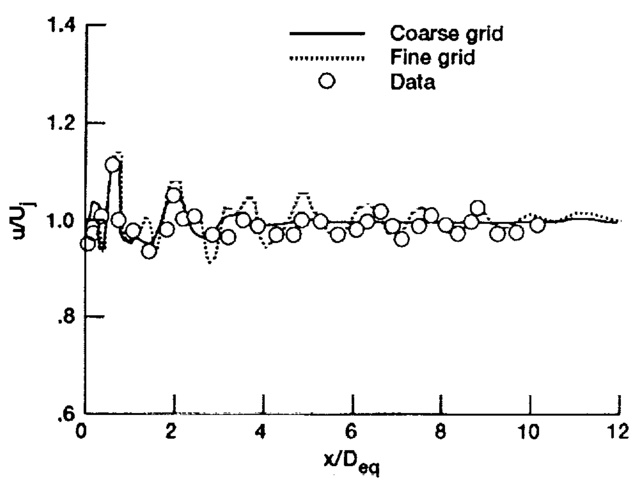


Figure 2.—Centerline axial velocity profile for the CD nozzle. NPR = 3.312, DPR = 3.121.

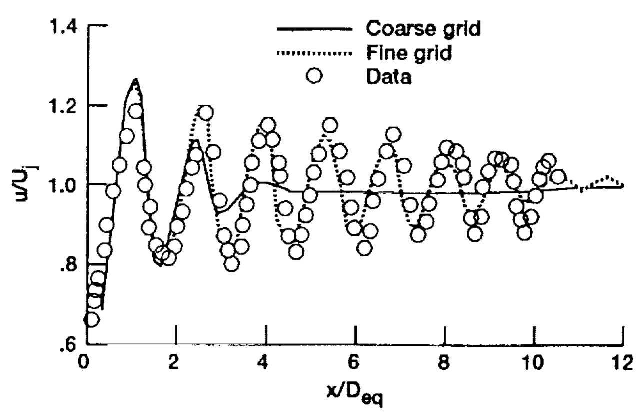
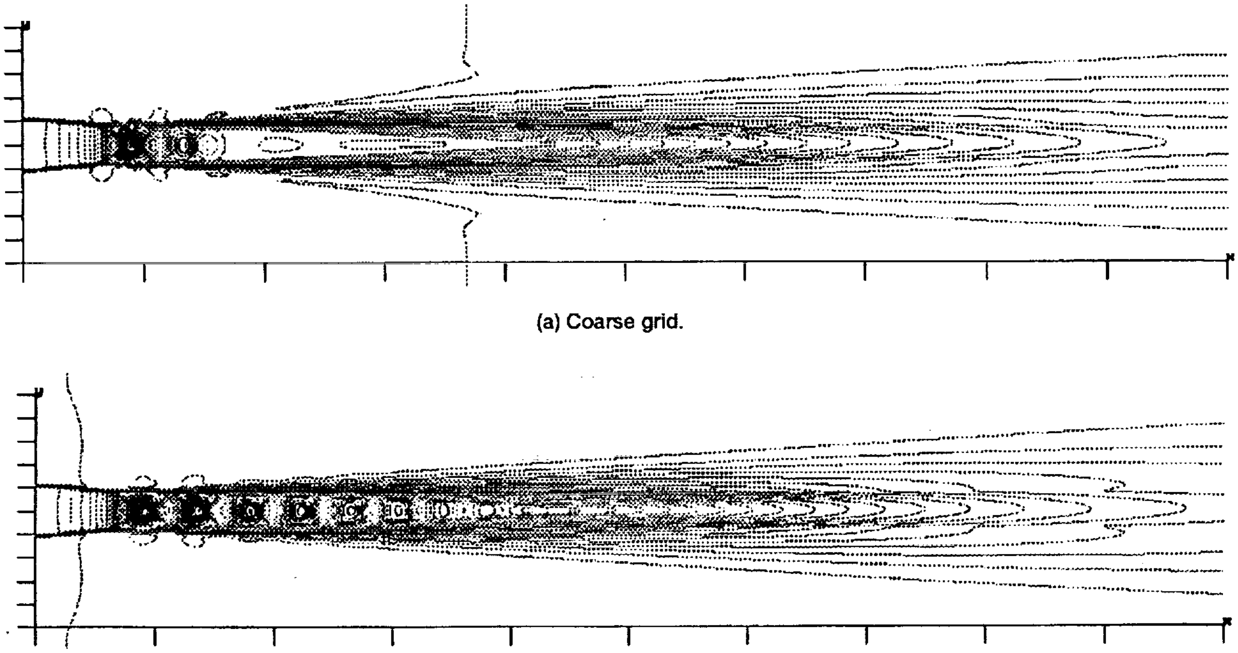


Figure 3.—Centerline axial velocity profile for the convergent nozzle. NPR = 3.323.



(a) Coarse grid.

(b) Fine grid.

Figure 4.—Mach number contour for the convergent nozzle. NPR = 3.323.

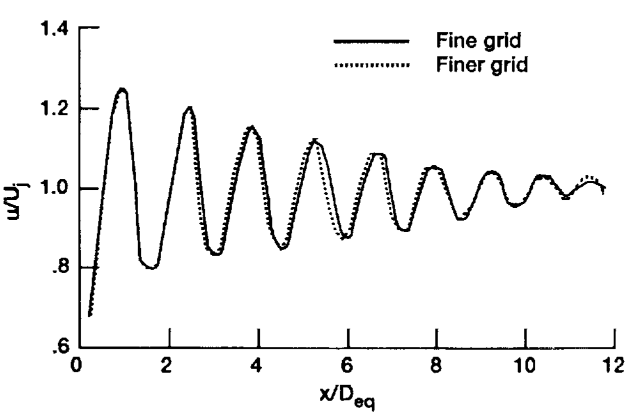


Figure 5.—Comparison of centerline axial velocity profile between fine grid (421x71) and finer grid (561x71) solutions. Nozzle geometry is convergent nozzle and NPR = 3.323.

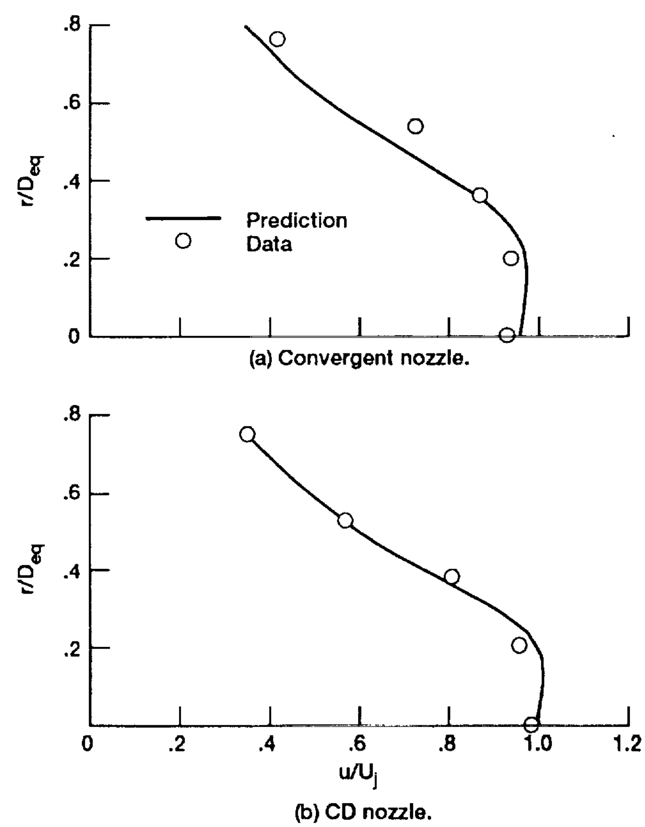


Figure 6.—Velocity profiles in a radial direction at x/D_{eq} = 8.5.

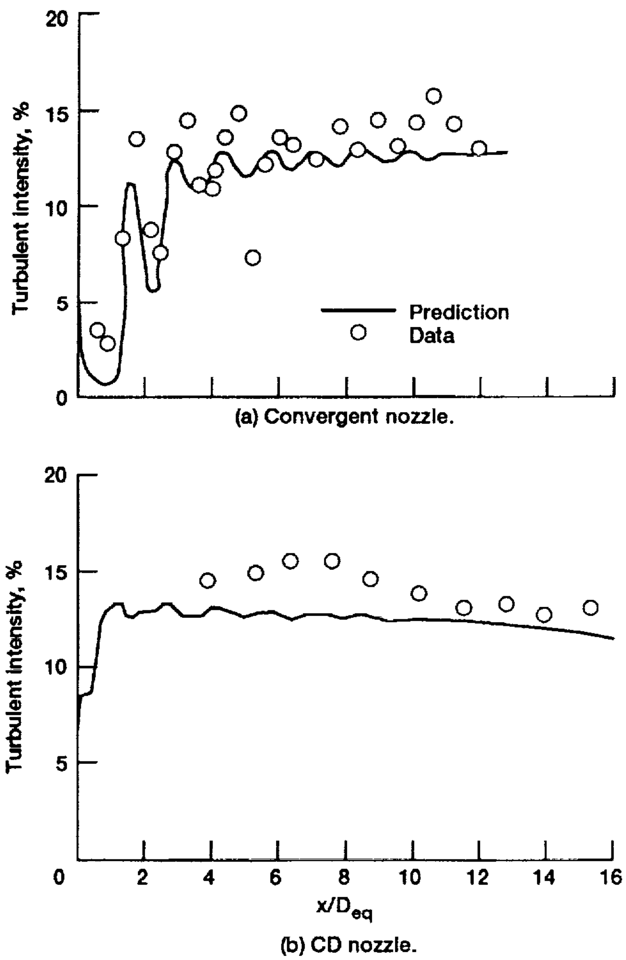


Figure 7.—Turbulent intensity profiles along the lipline.

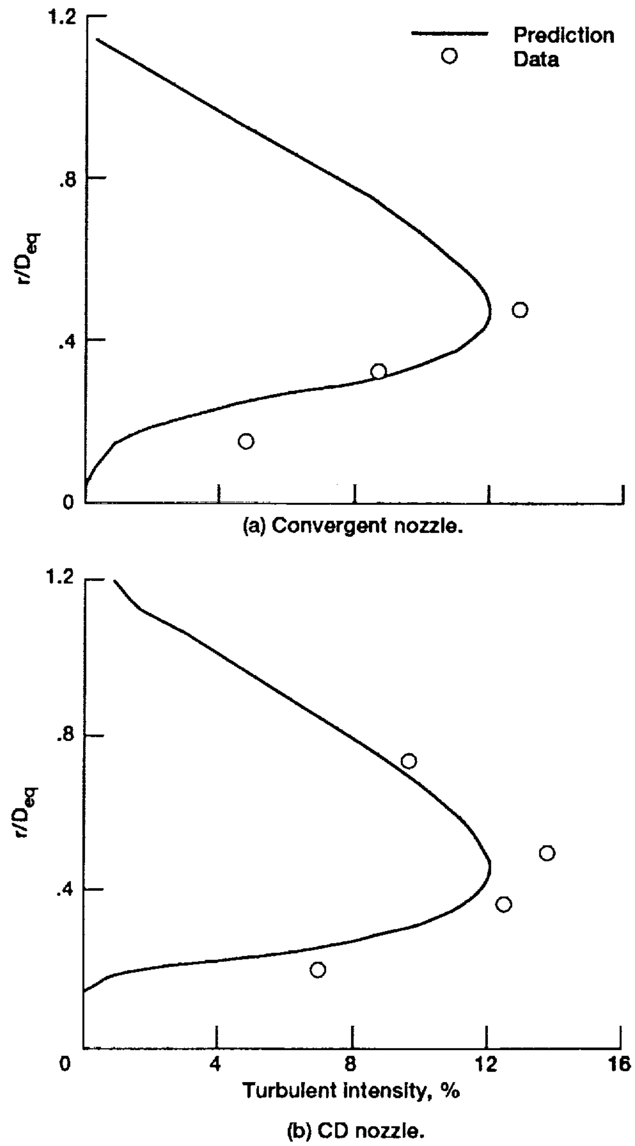
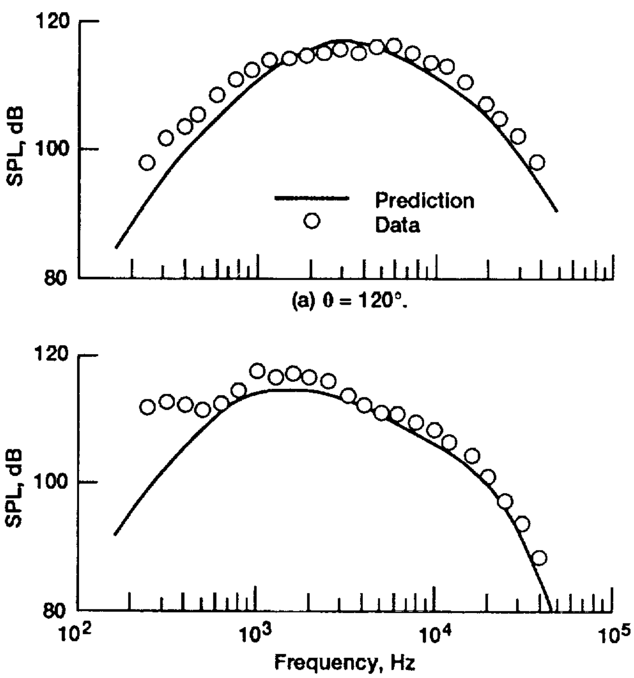


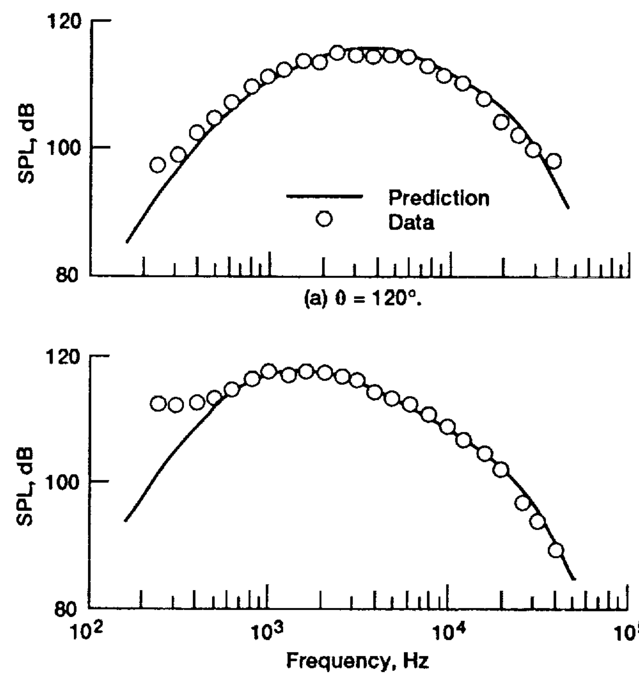
Figure 8.—Turbulent intensity profiles in a radial direction at $x/D_{eq} = 8.5$.



(a) θ = 120°.

(b) θ = 160°.

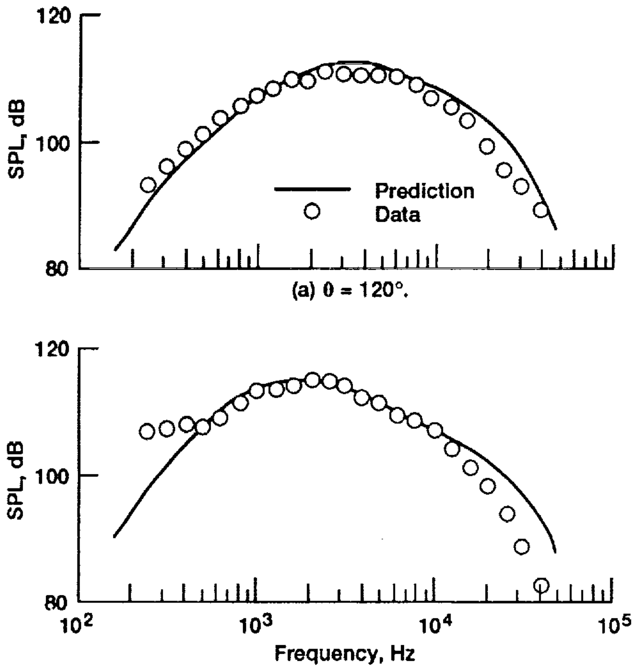
Figure 9.—Noise spectra for the convergent nozzle. NPR = 3.323.



(a) θ = 120°.

(b) θ = 160°.

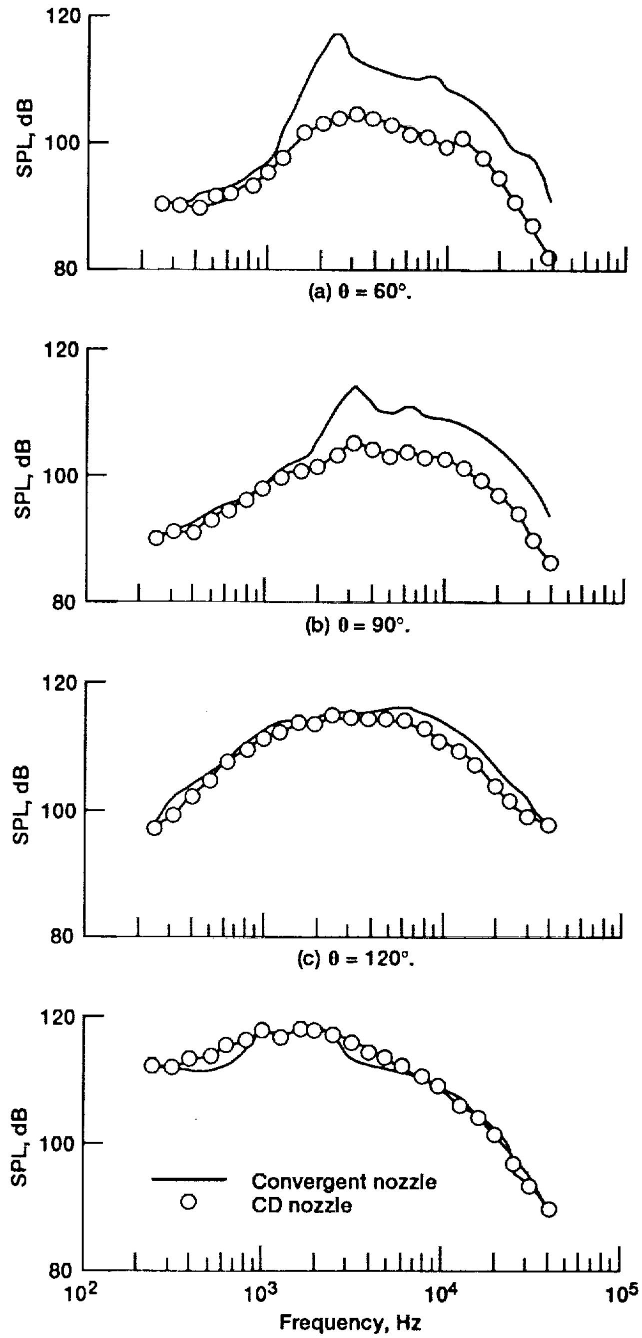
Figure 10.—Noise spectra for the CD nozzle at underexpanded condition. NPR = 3.312, DPR = 3.121.



(a) θ = 120°.

(b) θ = 160°.

Figure 11.—Noise spectra for the CD nozzle at overexpanded condition. NPR = 2.62, DPR = 3.121.



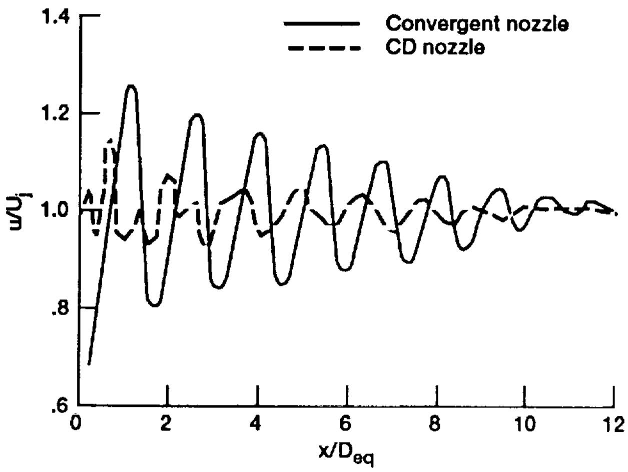
(a) θ = 60°.

(b) θ = 90°.

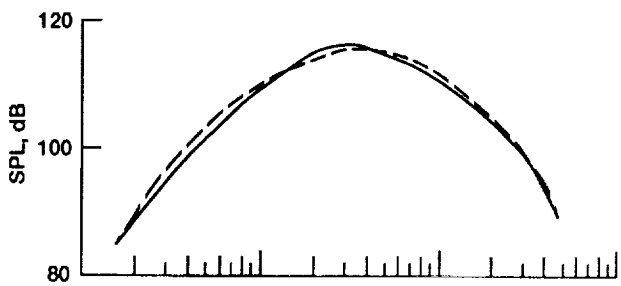
(c) θ = 120°.

(d) θ = 160°.

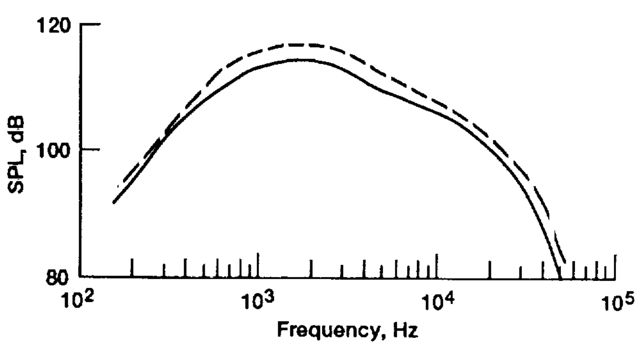
Figure 12.—Comparison of measured noise spectra between convergent nozzle and CD nozzle of same equivalent diameter at the same nozzle pressure ratio of 3.3.



(a) Velocity profile

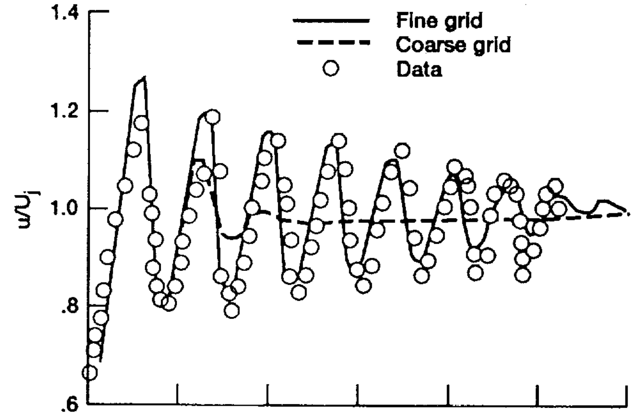


(b) Noise spectrum at θ = 120°.

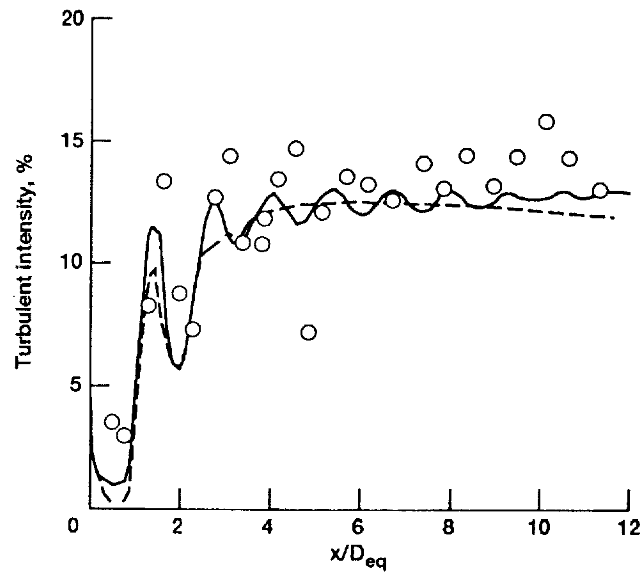


(c) Noise spectrum at θ = 160°.

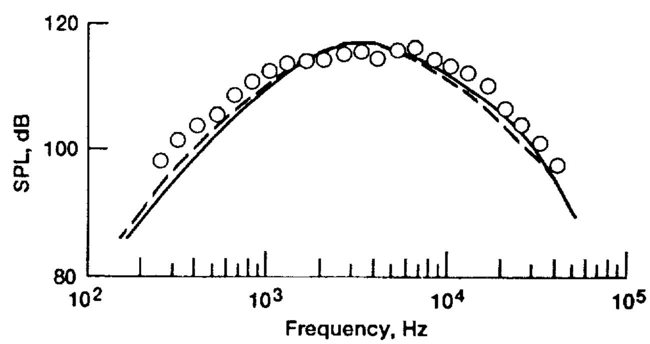
Figure 13.—Comparison of predicted centerline axial velocity profiles and noise spectra between convergent nozzle and CD nozzle of same equivalent diameter at the same nozzle pressure ratio of 3.3.



(a) Velocity profile



(b) Turbulent intensity profiles along the lipline.



(c) Noise spectrum at θ = 120°.

Figure 14.—Comparison of fine and coarse grid solutions with data for the convergent nozzle geometry. NPR = 3.323.

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13. ABSTRACT ***(Maximum 200 words)***

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