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Noise Characteristics of Two Parallel Jets with Unequal Flow

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Many jet noise suppression devices employ tubes, lobes, and similar devices to break up the flow. To understand the suppression mechanisms of these devices, a two-parallel-jet model experiment was conducted. The three-dimensional noise field was mapped for the case when one jet was at a velocity of 549 m/s and a total temperature of 538°C (jet 1) and the other was at 351 m/s and 93°C (jet 2). Mean flow profiles were also obtained at three axial stations. The experiments showed that noise from a high-velocity jet is reduced by placing a second jet of lower velocity parallel to it on the same side as the listener. The noise reduction is maximum on the lower velocity jet side of the plane containing the common diameter of the two jets. The noise reduction decreases as one moves azimuthally around the jets from this plane. No noise reduction is obtained at approximately 75 deg to this plane. Flow profiles showed insignificant mean flow interaction up to five nozzle diameters of the first jet. From a detailed examination of the noise results and earlier jet noise source location studies, it is concluded that for the present configuration with a spacing of about 1.5 diameters, acoustic shielding is the dominant mechanism responsible for the observed noise reduction as compared to mean flow interaction. Application of the two-parallel-jets results to bypass engine jet noise reduction is demonstrated through the example of a suppressor called the four-tube nonsymmetric nozzle.

Introduction

MANY jet noise suppression devices employ tubes, lobes, chutes, and similar devices to break up the flow. Due to complicated flowfields produced by these devices, it is usually not possible to isolate mechanisms responsible for noise reduction. Knowledge of the jet noise reduction mechanisms is essential for designing and optimizing suppressors. This creates a need to do experiments on configurations such as two-parallel-jet nozzles.

The two-parallel-flow jet (twin-jet) shown in Fig. 1 can be considered to be an element of a multitube nozzle. The configuration being very simple, the test results are relatively easier to interpret than data from configurations such as multitube nozzles.

Some of the two-parallel-jet studies reported in the literature can be found in Refs. 1-5. Kantola[1] tested the two-parallel-jet arrangement with both circular and rectangular cross sections. Both jets were attached to the same plenum chamber and as such both tubes had identical mean flow conditions. Kantola measured the noise from such devices in the far field at various locations and also determined the effect of varying the spacing between the two jets. The noise in the plane containing the centerlines of both jets was found to be lower compared to the value one would get if the sum of the sound energy by the individual jets were added together. Further, the noise reduction increased as the spacing between the two jets was increased from one to five nozzle diameters.

Borchers and Goethert[2] have reported tests using linear arrays of circular jets. The number of tubes in the array was varied between one and five. All of the tubes in the array had the same flow conditions. The effects of the number of nozzles in the array and the spacing ratio on noise were determined from freefield noise measurements. Effect on total acoustic power was determined by tests within a reverberant chamber. To determine the flow characteristics, mean flow and turbulence measurements were made. Instantaneous flowfield visualization was obtained by spark shadowgraph. The Borchers and Goethert study showed that for a spacing ratio of 1.5 there will be negligible mean flow interaction. For smaller spacing ratios, considerable interaction was found.

Bhat[3] did experiments on two parallel jets using jets of circular cross section. One important difference was that the tubes were connected to two different heated air plenum chambers. This made it possible to obtain different flows in the tubes. The experiments included both similar and dissimilar flow cases, equal and unequal tubes. The noise in the plane containing the two centerlines was lowest when the spacing was decreased from about 1.2 diam to about 1.0 diam. Thus the combined results of Refs. 1 and 3 seem to indicate that noise reduction is lowest for a spacing ratio of about one and larger noise reductions are obtained when the spacing between the tubes is either decreased or increased from about 1 diam. Bhat also found that when the tube toward the listener was shorter, additional lowering of noise occurred.

The three references discussed above are mutually consistent in several of the findings. They all find that the noise from a high-velocity jet is reduced when a second jet is introduced between the first jet and the observer. The noise reduction is very small for $\theta = 90$ deg (see Fig. 1). Also, noise reduction is not observed at the low-frequency end of the spectra. Further, for higher frequencies, it is found to be almost constant with frequency. Also, the lowest frequency at

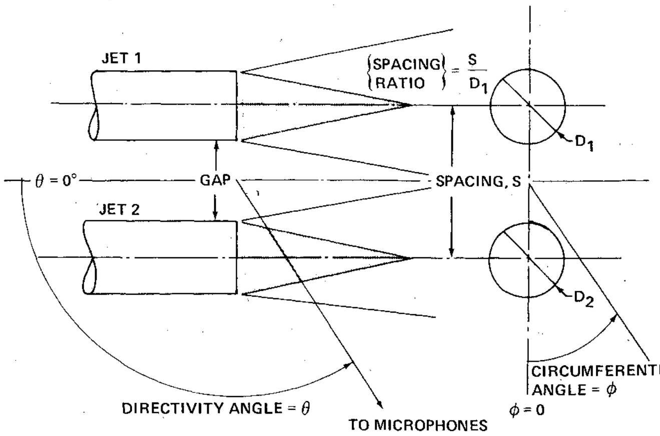

Fig. 1 Geometry of two parallel jets.

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which noise suppression starts is lower at higher values of the directivity angle θ.

The present experiments were done as an extension of the dissimilar flow study reported in Ref. 3. Noise measurements were made for twin jets with dissimilar flows in all significant directions. Mean flow profiles were obtained to assess the extent of flow interaction. In this paper, the experimental setup and results obtained are reported in detail. Using the information from the twin-jet test, a research model jet noise suppressor called the four-tube nonsymmetric nozzle was designed, built, and tested. In the section "An Application," a sample result from this suppressor test is presented.

Test Description

The twin-jet experiments were conducted in the Boeing Large Anechoic Test Chamber. This chamber has a working space of $20 \times 23 \times 9$ m and is lined with foam wedges. The two-parallel-jet model was connected to the preheated air supply as shown in Fig 2. Each jet was connected to a separate air supply and, as such, it was possible to set flow conditions in each jet independent of the other.

The two configurations were tested as shown in Table 1 using the microphone array in Fig. 3 for noise measurements. This array provided noise levels for directivity angles θ of 90-160 deg at a given model orientation. For each configuration an initial orientation of $\phi = 0$ deg was chosen. Noise measurements were made with the jets "on" one at a time and both together. Successive changes were made by rotating the model and maintaining the relative positions between the nozzles, but changing the circumferential ϕ. The noise measurements were made at the following values of ϕ: 0, 15, 30, 45, 60, 75, 90, 135, and 180 deg.

In all tests the gap between the nozzle lips was kept constant at $0.6D_1$ and the exits were coplanar. Although staggering and spacing also influence noise output, the scope of the test program did not allow tests to determine these effects. Some of these effects have been reported in the earlier paper by Bhat[3] for equal-sized jets with identical flow conditions.

The $0.6D_1$ gap between the nozzle lips gave a spacing ratio of 1.6 and 1.5 for configurations 1 and 2, respectively (Table 1). These spacing ratios were chosen so as to minimize the flow interaction for at least the first few diameters downstream of the nozzle exit. By minimizing the flow interaction, it was hoped that the effect of acoustic shielding and interaction could be clearly identified from the noise measurements.

Mean total pressure and temperature traverses were made along the common diameter across the two flows at $0.3D_1$ downstream of the nozzle exit and at the $2.6D_1$ and $5D_1$ stations. (Because of probe temperature limitations, the jet 1 gas conditions were reduced to 503 m/s and 454°C for this test. This lowering of jet 1 conditions was deemed acceptable because it did not have any significant effect on the flow interaction which was of interest.) The profiles were measured for each jet operating alone and for two jets operating together.

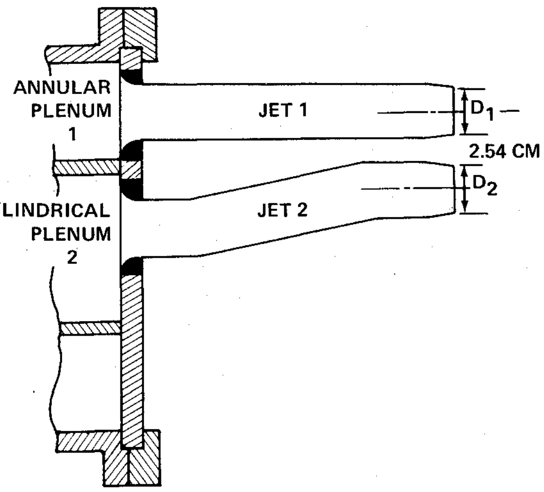

Fig. 2 Two-parallel-jet model attached to facility plenum chambers.

Results

The noise data were reduced to one-third octave band sound pressure levels (SPL), perceived noise level (PNL), and overall SPL (OASPL) at each microphone position. Further, a weighted PNL called PNLW2 was also calculated using the expression:

$$\text{PNLW2} = 10 \log_{10} \sum_{\theta = 90 \text{ deg}}^{\theta = 160 \text{ deg}} 10^{\left(\frac{\text{PNL}(\theta) - 10 \log_{10} \sin^2 \theta}{10}\right)}$$

PNLW2, which is calculated for static tests, is very roughly analogous to the effective perceived noise level (EPNL) used in measuring aircraft flyover noise. It provides a means of weighting the PNLs to account for noise time duration as a function of emission angle when the airplane flies overhead. PNLW2 can therefore be looked upon as an artifice to assess relative subjective noise changes on an overall basis.

In this study, the one-third octave band SPLs were scaled to equivalent full-scale values before calculating PNLs. For this purpose a scale factor of 17.6 and extrapolation distance of 457 m were used. Although these choices were arbitrary, it was felt that the resulting PNL and PNLW2 would give a better feel for the noise changes produced by the two-jet configuration for typical full-scale situations. In the following paragraphs the test results will be presented in the order of increasing detail. It should be noted that only PNL and PNLW2 are scaled to full-scale as described above. The one-third octave band SPLs and overall SPLs are presented as measured on a 4.57 m sideline.

PNLW2

The twin-jet noise levels are compared against single-flow noise levels in Fig. 4. The single-flow noise levels are axisymmetric and, therefore, constant with ϕ. Jet 1 noise levels are dominant over that of jet 2 as seen in Fig. 4. When both jets are turned on, maximum noise reductions of about 7.5 dB are obtained for both $D_2 = 3.51$ and 4.32 cm cases at $\phi = 0$ deg. The noise reduction gradually reduces to zero for ϕ equal to about 75 deg. In the $\phi = 0$-75 deg region, the noise levels for twin jets do not appear to depend very much on the jet 2 diameter (D_2). Between $\phi = 75$ and 180 deg, the twin jet is louder than jet 1 alone and has a maximum at $\phi = 90$ deg.

OASPL and PNL

Comparisons of OASPLs at four directivity angles, $\theta = 90$, 120, 140, and 160 deg are presented in Fig. 5. The twin jet

Table 1 Configurations

Configuration	Spacing ratio, S/D_1	Diameter, cm Jet 1	Diameter, cm Jet 2	Exit velocity, m/s Jet 1	Exit velocity, m/s Jet 2	Temperature, °C Jet 1	Temperature, °C Jet 2
1	1.6	4.32	4.32	549	351	538	93
2	1.5	4.32	3.51	549	351	538	93

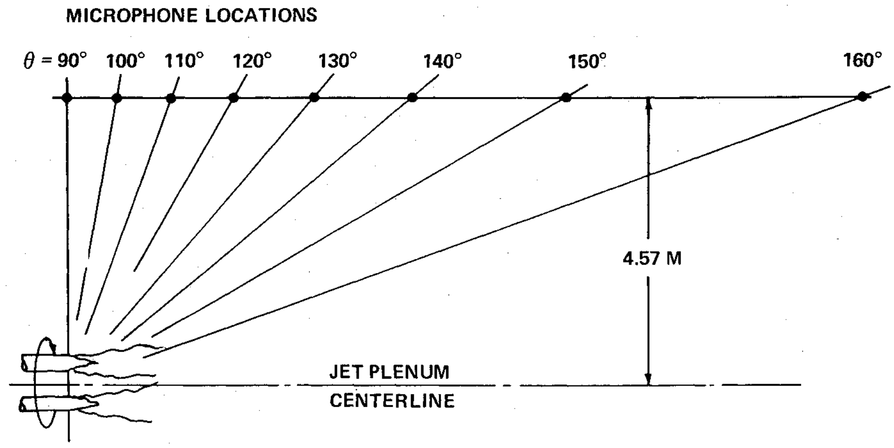

Fig. 3 Microphone array.

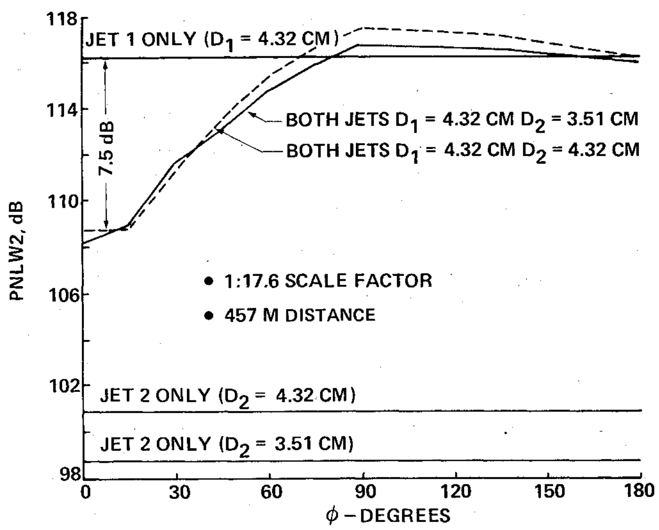

Fig. 4 Overall noise reduction as a function of circumferential angle.

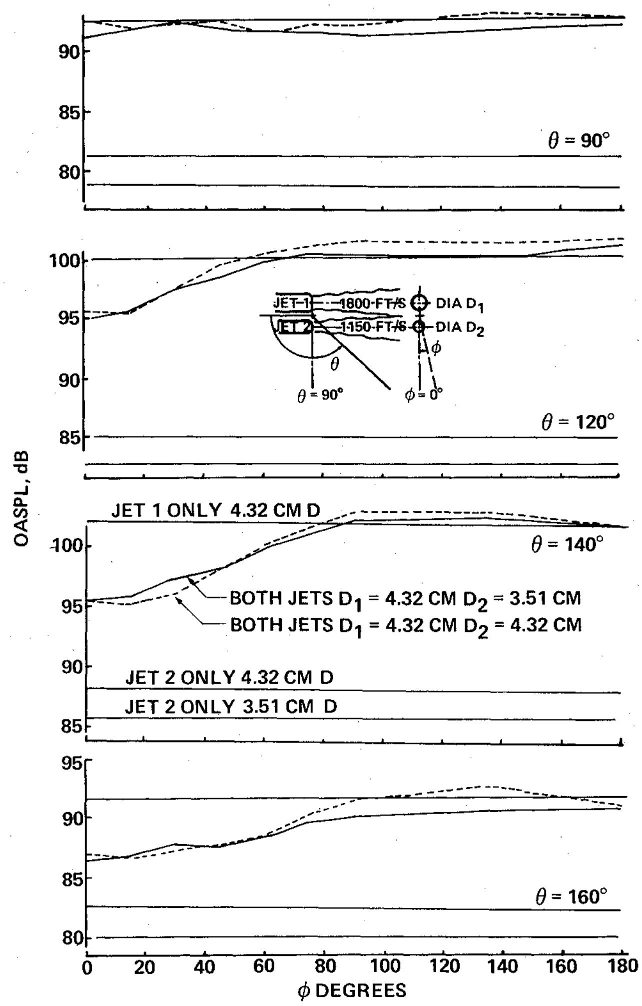

Fig. 5 OASPL as function of circumferential angle θ.

does not show any noise reduction at $\theta=90$ deg but shows noise reductions at higher θ angles. The largest noise reductions are obtained at $\theta=140$ deg. At $\theta=140$ deg, the trends with ϕ are similar to those obtained on a PNLW2 basis in Fig. 4. Again, for ϕ between 0 and 75 deg the noise reductions obtained are not very sensitive to D_2.

Similar comparisons were made using PNLs. The trends observed were the same as those for OASPL. As an example, the $\theta=140$ deg case is presented in Fig. 6. The maximum reduction of about 10 PNdB is obtained at $\phi=0$.

Directivity at $\phi=0$ deg

The distributions of OASPL and PNL as a function of θ are shown in Figs. 7 and 8, respectively. Noise reductions can be seen to be minimum near $\theta=90$ deg and maximum around $\theta=140$ deg. Also, noise reduction extends over the entire aft arc.

Spectral Comparisons at $\phi=0$ deg

The model scale spectra at the 4.57 m sideline are compared in Fig. 9 for directivity angles $\theta=90$, 120, 140, and 160 deg. At $\theta=90$ deg, no noise reduction is obtained up to about 10,000 Hz and at higher frequencies a small noise increase is seen. At $\theta=120$ deg, there are small differences between jet 1 only and twin-jet levels up to about 1250 Hz. For all frequencies greater than 1250 Hz, noise reduction is obtained. This trend is found again at $\theta=140$ deg except that noise reduction starts at a lower frequency (630 Hz) and the noise reductions are larger. At $\theta=160$ deg noise reductions start at a still lower frequency (400 Hz), although the reductions are of smaller magnitude.

Earlier it was stated that jet 2 only noise levels could be considered to be the noise floor. However, at the high-frequency end of the spectra the noise levels for the twin-jet cases are lower than jet 2 levels at both $\theta=120$ and 140 deg. However, jet 2 still has the lowest values for overall quantities such as OASPL, PNL, PNLW2, etc.

Flow Profiles

Flow profiles were obtained with jet 1 only, jet 2 only, and both flows on. The single-flow cases were compared with the both-flow "on" cases at each traversing station to determine flow interaction. These comparisons are shown in Figs. 10 and 11 for the $2.6D_1$ and $5D_1$ stations. At the nozzle exit, only

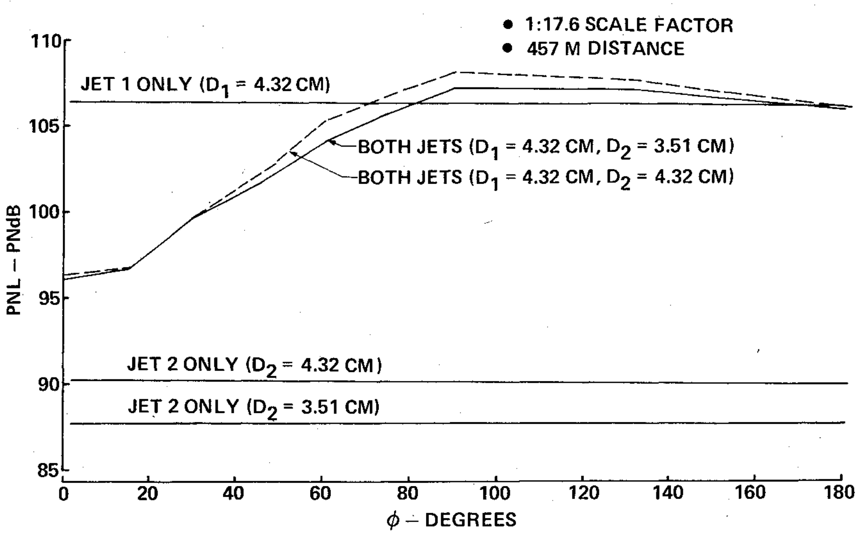

Fig. 6 PNL as function of ϕ at $\theta = 140$ deg.

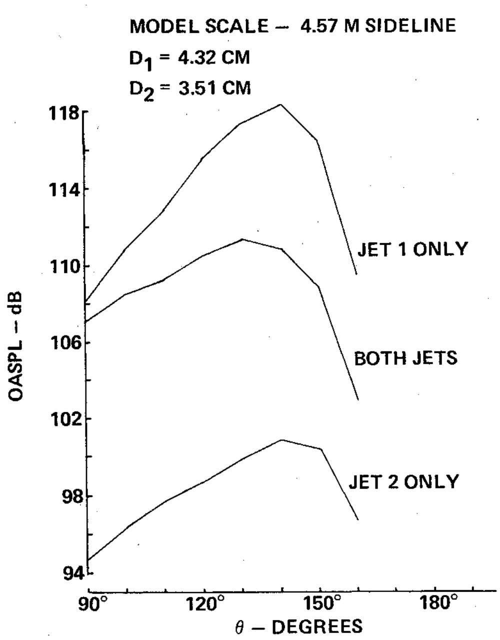

Fig. 7 OASPL as function of directivity angle θ for circumferential angle $\phi = 0$ deg.

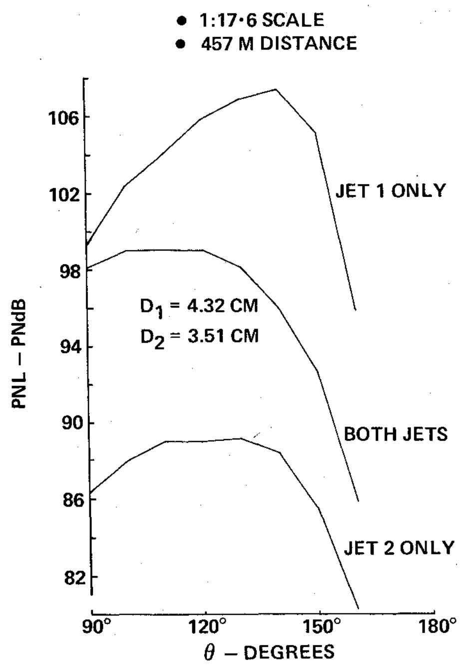

Fig. 8 PNL as function of directivity angle θ for circumferential angle $\phi = 0$ deg.

the both-flow "on" case is presented (Fig. 12). The two flows are independent of each other at this location since the tubes are placed $0.6D_l$ apart. In Figs. 10 and 11 it can be seen that the total pressure profile obtained with each jet "on" separately is very similar to that obtained for the twin jet. Thus, there is no significant mean flow interaction between the two jets up to the $5D_l$ station.

Discussion of the Twin-Jet Results

The results presented in the previous section have shown that:

1) On a PNLW2 basis, maximum noise reduction is obtained when the lower velocity jet is placed between the higher velocity jet and the observer ($\phi = 0$ deg). This noise reduction is not sensitive to the diameter of the lower velocity jet over the diameter range ($D_2 = 0.8$ - $1.0D_l$) tested.

2) Although maximum noise reduction is obtained at $\phi = 0$ deg, noise reduction extends to $\phi = 70$-75 deg.

3) On an OASPL or PNL basis, maximum noise reductions are observed for the directivity angle $\theta = 140$ deg which reduces to zero at $\theta = 90$ deg. The trend with the circumferential angle ϕ is similar to that for PNLW2 at any θ location.

4) The low-frequency end of the spectrum is not affected. The minimum frequency above which noise reduction is obtained varies with the directivity angle θ.

5) No significant mean flow interaction occurs between the two jets up to $5D_l$ downstream of the noise exits. This agrees with the findings of Ref. 2.

Based on these results and earlier jet noise studies, an attempt will now be made to explain the mechanisms responsible for the observed noise reductions.

Analytical predictions[6] for jet noise source locations are shown in Fig. 13 for jet 1. It is seen that the higher frequency noise is generated nearer to the nozzle exit. The peak noise (at $\theta = 140$ deg) for this nozzle was obtained at 4000 Hz (Fig. 9). In Fig. 13, it is seen that 4000 Hz is generated at approximately six nozzle diameters downstream of the exit. Also, no noise reductions were observed in Fig. 9 below 630 Hz which on Fig. 13 means that the only noise generated between the nozzle exit and $12D_l$ locations was attenuated for the $\theta = 140$ deg location.

Also, most noise reduction is obtained for noise generated up to $6D_l$. However, flow measurement showed no significant mean flow interaction up to $5D_l$. Thus, it is apparent that mixing between the two jets is not the dominant

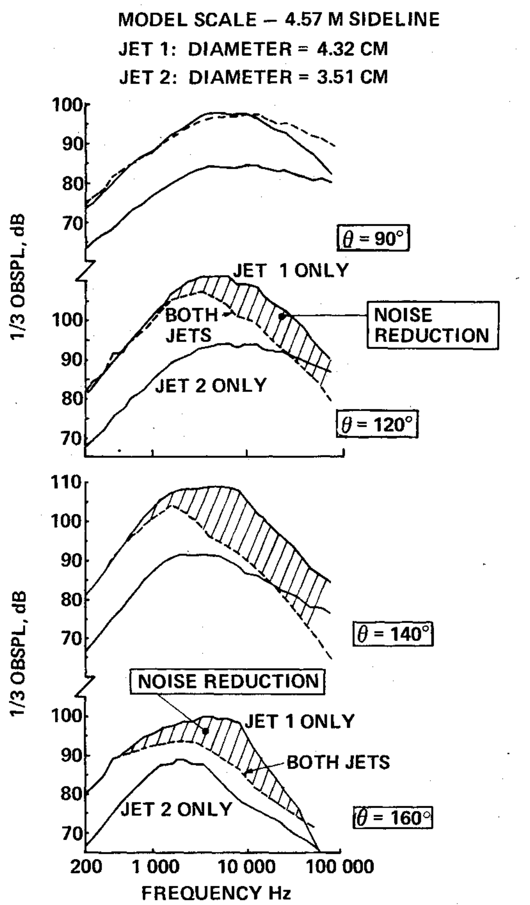

Fig. 9 Spectra at $\phi = 0$ deg for various directivity (θ) angles.

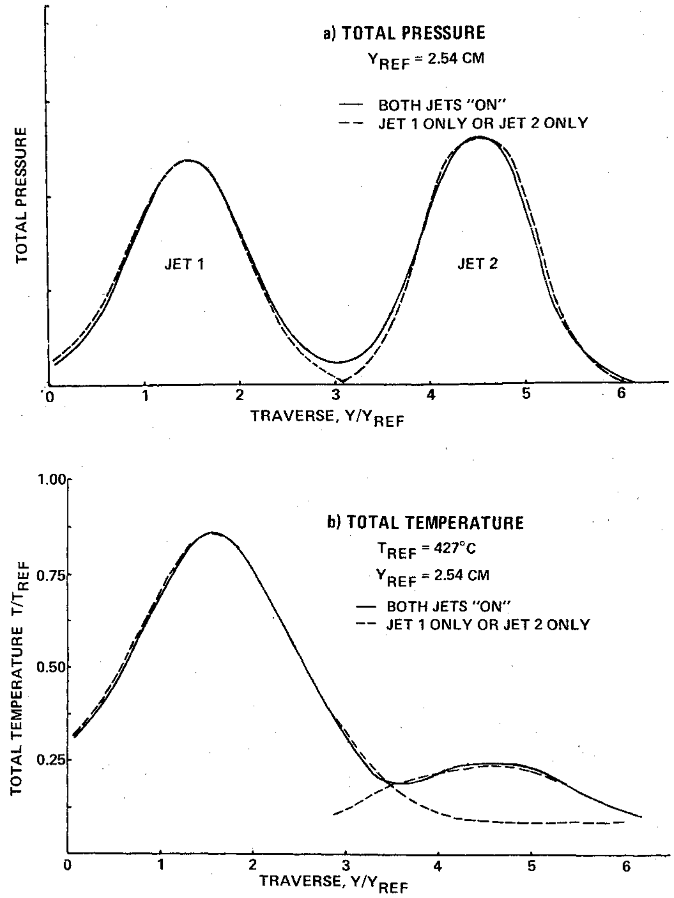

Fig. 11 Flow profiles at $X/D_1 = 5$.

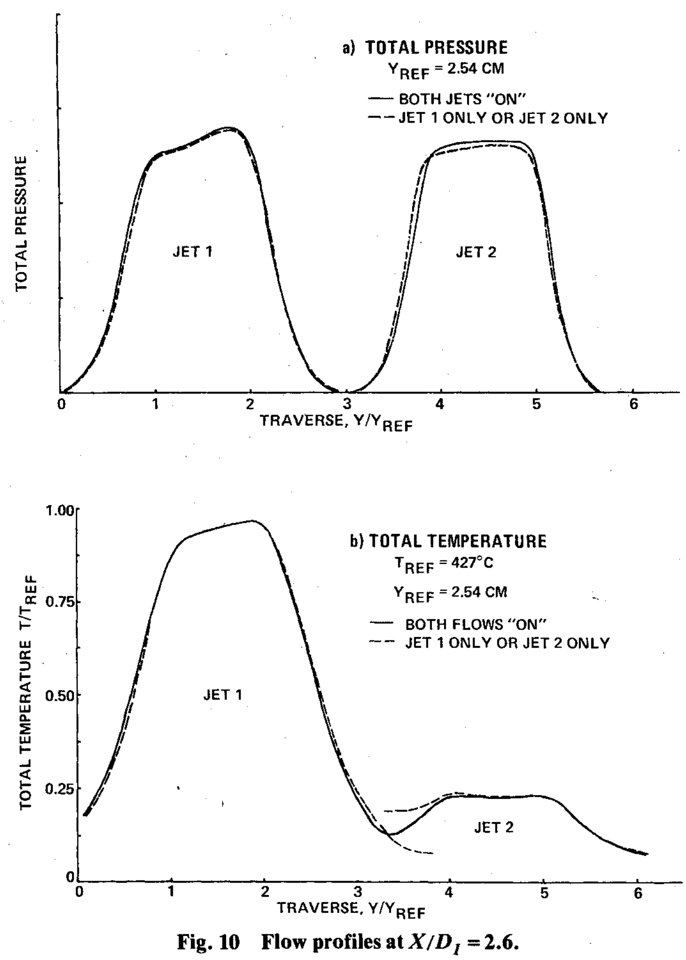

Fig. 10 Flow profiles at $X/D_1 = 2.6$.

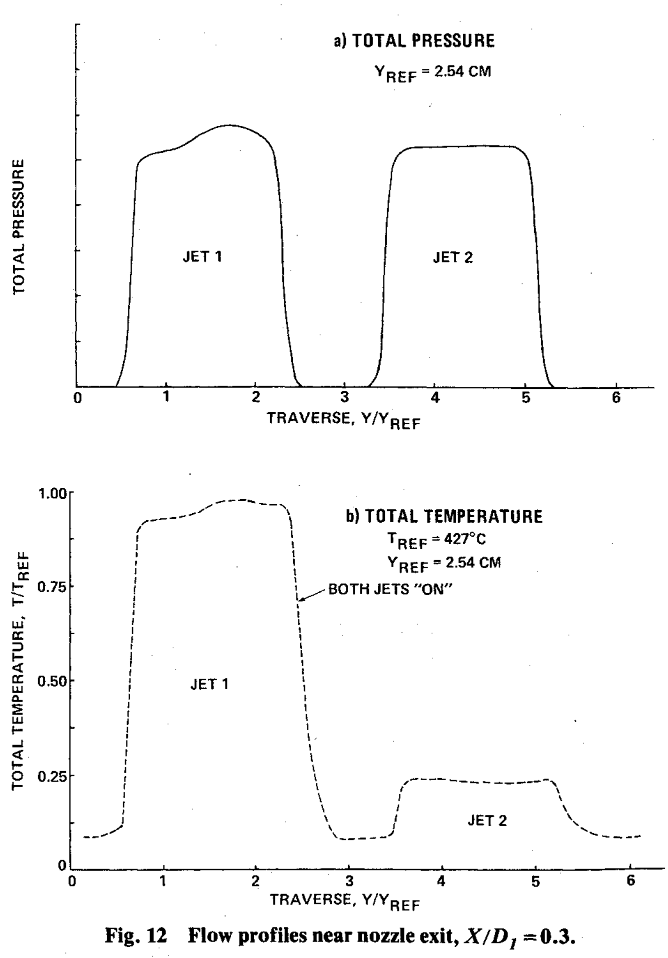

Fig. 12 Flow profiles near nozzle exit, $X/D_1 = 0.3$.

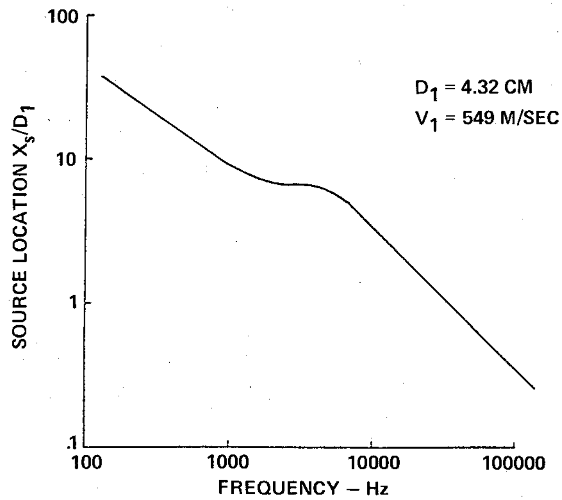

Fig. 13 Analytical prediction of noise source location (from Ref. 6 for jet 1).

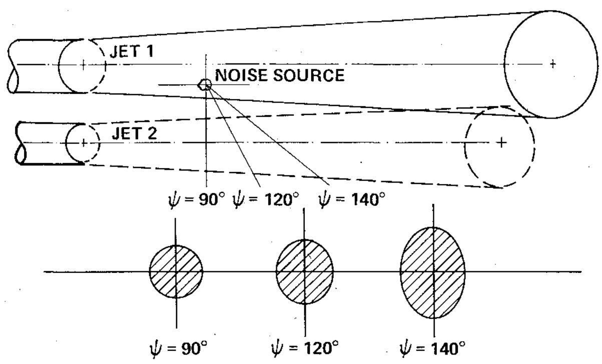

Fig. 14 Noise transmission path schematic.

mechanism for the observed noise reductions. Therefore, acoustic shielding (which could include reflection, refraction, absorption, and scattering) appears to be the dominant mechanism. The noise results will not be examined to determine if the observed results are consistent with those that one would expect with shielding.

The flow geometry is examined in Fig. 14. In the earlier discussion, it was shown that only noise generated up to $6D_I$ experiences significant reduction. Also, in Fig. 9, it has been shown that noise reduction is negligible for $\theta = 90$ deg and increases for larger values of θ. Thus, it can be seen that noise generated at various portions of jet 1 between $X=0$ and $6D_I$ become attenuated while passing through jet 2 at angles $\theta > 90$ deg.

Acoustic shielding studies in the literature have shown similar results. For example, in Ref. 7, it is shown that a two-dimensional jet does not provide shielding for angles $\theta \approx 90$ deg but provides shielding as θ is increased. Thus the results of the present twin-jet experiments are similar to those obtained from shielding studies. Another factor may be the area of cross section of the second jet which is providing the noise attenuation. In the lower portion of Fig. 14, the approximate cross sections of jet 2 which provide shielding as a function are shown at different directivity angles. It can be seen that for $\psi = 90$ deg, jet 2 presents the smallest cross section for shielding and that this cross section increases with increasing ψ. This is consistent with increasing attenuations as a function of θ. Note that for the far-field location, $\psi \approx \theta$.

Referring to Fig. 5, it is seen that the range of circumferential angles over which OASPL reduction is observed increases with increasing directivity angle θ. This again is consistent with the fact that the cross section of jet 2 which provides shielding increases with θ.

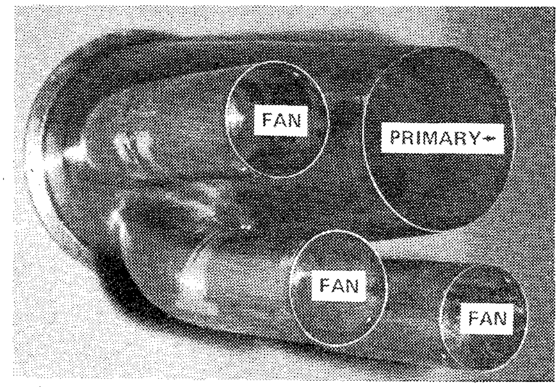

Fig. 15 Four-tube nonsymmetric nozzle research jet noise suppressor model.

The discussion in the previous paragraphs thus leads to the conclusion that the observed noise reductions are due mainly to acoustic shielding rather than mean flow mixing for the present twin-jet configuration with a spacing of about $1.5D_I$. If the spacing were reduced, mean flow interactions could, of course, become important. Also, since no dynamic flow measurements were made, it is not possible to say whether or not there is interaction between the two jets which could affect the turbulence, source strength, radiation efficiency, and large-scale eddy structure.

An Application

The knowledge acquired from the twin-jet test can be used in several different ways. One such use is in the design of turbofan engine jet noise suppressors. A model research suppressor called the four-tube nonsymmetric nozzle[8] was built and tested to examine the applicability to turbofan engines. This will be briefly described in the following paragraphs.

The four-tube nozzle is shown in Fig. 15. The center tube carries high-velocity hot flow similar to primary flow of typical turbofan engines. The center tube is surrounded by three smaller tubes which carry lower velocity, lower temperature flows typical of the fan flow. The smaller tubes are arranged over a smaller angular region around the center tube. The reasons for this are:

1) In airplane applications noise reduction is required only over a limited angular range toward the ground.

2) If symmetric arrangement is used, less shielding flow would be available in the direction of the listener, and the jets on the opposite side of the high-velocity noisy jet may reflect back toward the listener.

OASPLs as a function of directivity angle on the quietest side ($\phi = 0$) of the four-tube nonsymmetric nozzle are presented in Fig. 16. In this figure noise levels obtained by having primary flow only, secondary flow only, and both flows "on" together are shown. Also, the logarithmic sum of primary flow only and secondary flow only levels are shown by the solid line for reference. The solid line represents the level one would expect if there were no interactions of any kind between the primary and secondary Jets. It is seen in Fig. 16 that the four-tube nozzle is quieter than the primary jet alone and also quieter than the reference solid-line level for aft angles of 130-160 deg. At 90-130 deg the four-tube level is higher than for primary jet alone but about equal to the reference solid line level. Further, the four-tube nozzle has a lower peak OASPL than either the primary jet only or the reference solid line.

It can thus be seen that the results of the twin-jet configuration can be used to design jet noise suppressors to give noise reductions in preferred directions. Of course, for specific applications, extensive development work will be necessary before any optimum suppressor design is obtained.

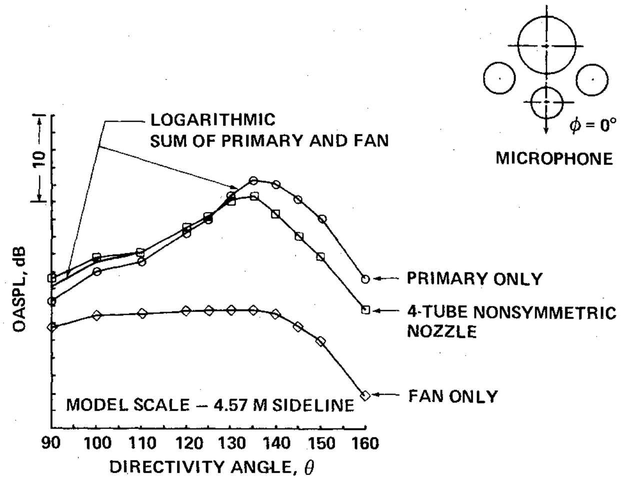

Fig. 16 Typical result from four-tube nonsymmetric nozzle research jet noise suppressor model.

A more direct application of the twin-jet results for over- and under-the-wing engine placement has been discussed in Refs. 4 and 5. Reference 4 also presented experiments with a twin-engine F-111A aircraft flying next to an instrumented tower. An interesting result from this experiment was that twin-jet noise reduction is obtained even under flight conditions. It should be noted that all other twin-jet studies, including the present study, have been done under static conditions.

Conclusions

The following conclusions can be drawn from the results and discussions presented in this paper:

1) Noise from a high-velocity noisy jet is reduced when a second quieter jet of lower velocity is placed parallel to the first on the same side as the listener.

2) Maximum OASPL reduction of about 7.5 dB is obtained at a directivity angle $\theta = 140$ deg directly below the low-velocity jet ($\phi = 0$). Noise reduction gradually reduces to zero for a value of ϕ about 75 deg.

3) For the configuration tested, the noise reduction is not very sensitive to the change of the diameter of the second jet from $D_2 = 0.80$ to $1.0D_1$.

4) There is no significant mean flow interaction up to $5D_1$ downstream of the nozzle exits. Since no dynamic flow measurements were made it is not possible to comment on dynamic flow interactions.

5) The noise reductions observed appear to be due mainly to acoustic shielding rather than mean flow interaction. The spacing ratio in these tests was about 1.4. If the spacing is reduced flow interactions can become important.

6) The usefulness of the twin-jet results has been demonstrated through the test of a jet noise suppressor called the four-tube nonsymmetric nozzle. This device has demonstrated that it may be possible to design nonsymmetric jet noise suppressors which give noise reductions in preferred directions. For any specific application, of course, extensive developmental work would be necessary before an optimum suppressor design is obtained.

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