Experimental Investigation of Noise Reduction from Two Parallel-Flow Jets

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Multitube nozzles have been developed to suppress turbojet engines in a number of cases. The concept of two parallel-flow jets forms a basic element of the multitube nozzle. Hence, the acoustic characteristics of two parallel-flow jets have been investigated as a fundamental study aimed at understanding jet noise suppression mechanisms which then could lead to improved jet noise suppressors. Model-scale tests were conducted in an anechoic environment. Acoustic measurements were made in the plane containing the axis of the two jets using a far-field microphone array. The effect of tube geometry (lateral tube spacing, longitudinal tube staggering, and tube size) was studied with the same flow through both tubes. The effect of flow parameters was investigated using twin coplanar jets. Detailed acoustic test results were evaluated in terms of engineering as well as subjective units. The following general conclusions were drawn from the study: 1) two coplanar parallel-flow jets with dissimilar unmixed flow can be quieter than an equivalent fully mixed single-flow jet; 2) two parallel-flow jets with the same flow can be up to 3 dB quieter than the equivalent single-flow jet; 3) two parallel-flow jets become quieter when lateral spacing is reduced, the nozzle near the observer is staggered upstream, or a smaller nozzle is placed near the observer; and 4) for two parallel-flow jets with dissimilar flows, the noise at 90 to 110 deg from the inlet axis depends mainly on the peak jet velocity, and noise at 120 to 160 deg depends very strongly on only that part of velocity profile which the observer can "see" directly.

I. Introduction

THE present two parallel-flow jet study was conceived and planned as a fundamental research study that will contribute to the development of jet noise reduction technology. Hence, studying suppression mechanisms/potential was emphasized in the study. A better understanding of the fundamental jet noise suppression mechanisms is essential for designing a practical jet noise suppressor. Because of the complexity of the problem, studies to isolate various basic suppressor mechanisms are needed. Once the basic mechanisms and their suppression potentials are understood, the most promising mechanisms can be combined optimally into new suppressor nozzle concepts.

In recent years, a large number of jet noise suppressor nozzle configurations have been tested by various investigators. In search of a practical suppressor, a variety of multitube, multilobe, and multispoke nozzles, with and without ejector shrouds, have been studied. One of the promising nozzle configurations which has emerged out of these studies is a multitube nozzle.[1] Two parallel-flow jets form the basic element of a multitube nozzle. Thus, the basic jet noise suppression mechanisms of a multitube nozzle can be investigated through two parallel-flow jet studies.

Most of the development work on this nozzle configuration is aimed at reducing jet noise of a high-speed turbojet engine. Figure 1 shows a typical flowfield. The jet exhaust is divided into several smaller jets. Each of these elemental jets, although mixing with its surroundings, also interacts acoustically and aerodynamically with other elemental jets. The various suppression mechanisms of a multitube nozzle can be subdivided broadly into two fundamental categories: 1) source modification and reduction through jet interaction; and 2) propagation path modification and noise redirection by shielding due to the outer tube row.

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These types of suppression mechanisms can be isolated and studied with the two parallel-flow jets. This is because the flow field for two parallel jets (Fig. 2) is very similar to that of a multitube nozzle. In addition, the two parallel-flow geometries also can be used very effectively to study the effect of noise propagation through jet shear layers.

The technical objective of the present study is to improve understanding of the jet noise suppression mechanisms of a multitube nozzle. In order to meet this technical objective, a series of tests with each test emphasizing the particular suppression mechanism is required.

In the subsequent sections of this paper, facility and nozzle hardware used in the two parallel-flow jet investigation are described. The acoustic test results are discussed in terms of physical and subjective units. The results show the effects of various geometric parameters and flow conditions on noise. The observed noise trends are related to changes in the mean velocity profile. The study has provided some insight into the noise suppression mechanisms of a multitube nozzle. Application of these fundamental results for designing acoustically improved nozzles also are discussed.

II. Test Description

Facility

The parallel-flow jet experiments were conducted in an environmental test facility known as the large test chamber

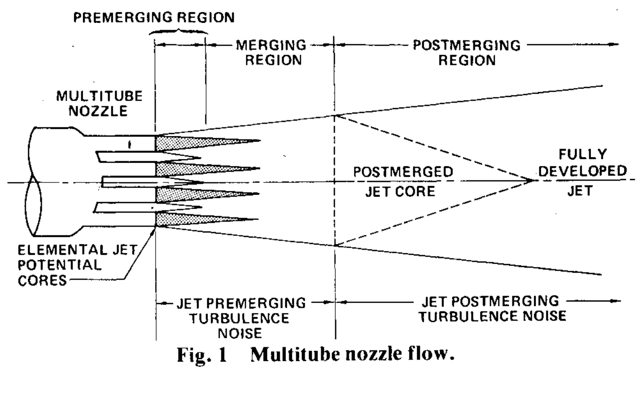

Fig. 1 Multitube nozzle flow.

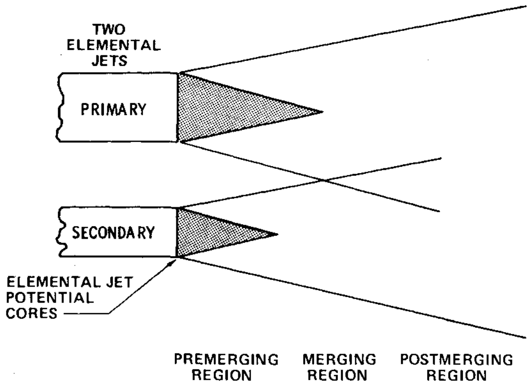

Fig. 2 Two parallel-flow jets.

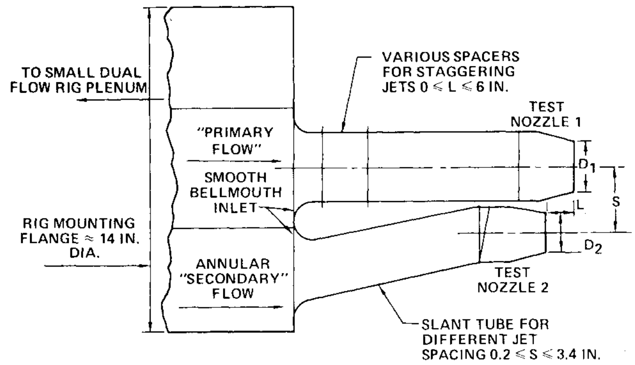

Fig. 3 Two parallel-flow jets mounting.

(LTC), which is located in the Boeing Plant II complex in Seattle, Wash. This facility is described in detail in Ref. 2. The LTC is an advanced large anechoic chamber with internal clear dimensions of 65 × 75 × 30 ft and is self-ventilated. The chamber is treated acoustically on all interior surfaces with sound-absorbing wedges. The model jets are operated from a nearby control room. The jet plume is located as far away from the LTC walls as possible and is aimed toward an exhaust stack that also performs as an ejector. The nearest wedge-covered surface (floor and ceiling) parallel to the jet plume is 15 ft. The resulting geometry minimizes the enclosure wall interference effects.

The jet rig (Fig. 3) used has the capability of providing primary- and secondary-flow hot air, up to about 1200° F, using propane burners. The temperatures and pressures of the nozzle charging station were monitored and recorded during each test run. This information, along with the mass flow measurements, was used to assure that the actual jet flow conditions during a test run were close to the target conditions. Because of "on-line" data processing requirements, each test run (flow condition) was 5-6 min long.

Table 1 Range of Parameters

1) Nozzle geometry parameters (same flow through both nozzles)
   Spacing: Longitudinal staggering L/D = 0 to 3.4
   Lateral separation S/D = 1.12 to 2.0
   Size: Nozzle diameter ratio D_1/D_2 = 0.7 to 1.4
2) Flow parameters (twin nozzle with $L/D = 0$, $S/D = 1.12$)
   Velocity ratio V_1/V_2 = 1.0 to 1.6
   Temperature ratio T_{T1}/T_{T2} = 2.5 to 1.0

Nozzle Hardware and Test Conditions

The arrangement of mounting two parallel-flow jets on the rig is shown in Fig. 3. Each tube had a smooth bellmouth entrance. The ratio of tube cross-sectional area to the nozzle area was always greater than 1.3. The minimum area ratio criterion of 1.3 was based on past experience in designing multitube nozzles. For an area ratio greater than 1.3, elemental tube nozzle discharge and thrust coefficients do not deviate significantly from that of a well-designed simple round convergent (RC) nozzle. The actual mass flow measurements verified that the discharge coefficients for the elemental tube nozzles, used in the present experiments, usually were between 0.96 and 0.99. The area ratio requirement established the minimum limit for the lateral spacing of two jets. For two equal-diameter jets, this minimum lateral spacing in terms of the nondimensional parameter S/D is 1.12. The 1.7 in.-diam nozzles were used in the majority of the experiments. The range of parameters investigated is shown in Table 1.

The longitudinal staggering L/D of jets was changed using different spacers between nozzle 1 and the rig mounting. Thus, the longitudinal staggering only could be changed in steps. The lateral separation S/D was changed by rotating the slant tube upstream of test nozzle 2. Thus, S/D could be changed continuously. Nozzles 1 and 2 were connected to the usual "primary" and "secondary" lines of the rig.

The effects of jet size and tube spacing were investigated using the same flow conditions for both jets. The effects of change in the jet flow conditions were investigated for an identical coplanar twin-nozzle configuration.

Some of the exact flow conditions of interest in the present test are listed in Table 2. The test conditions can be subdivided

Table 2 Flow conditions of interest

Condition number	Jet flow 1: Temperature T_{T1}, ° F	Jet flow 1: Jet velocity V_1, ft/s	Jet flow 2: Temperature T_{T2}, ° F	Jet flow 2: Jet velocity V_2, ft/s	Comments
10	655	1570	655	1570	Ideal complete
20	589	1460	589	1460	mixing of two
30	510	1300	510	1300	independent
40	449	1150	449	1150	flow conditions
50	387	950	387	950	
60	316	700	316	700	
70[a]	1110	1960	215	1200	Two independent
80[a]	1016	1800	197	1150	flow conditions
90[a]	914	1600	178	1080	
100[a]	840	1400	154	960	
110[a]	762	1160	133	800	
120[a]	671	830	109	640	
170[a]	1016	1600	197	1300	Ideal partial
180[a]	805	1600	370	1300	mixing of flow
190[a]	589	1600	589	1300	condition 80

[a] These flow conditions also were transposed between flow 1 and flow 2.

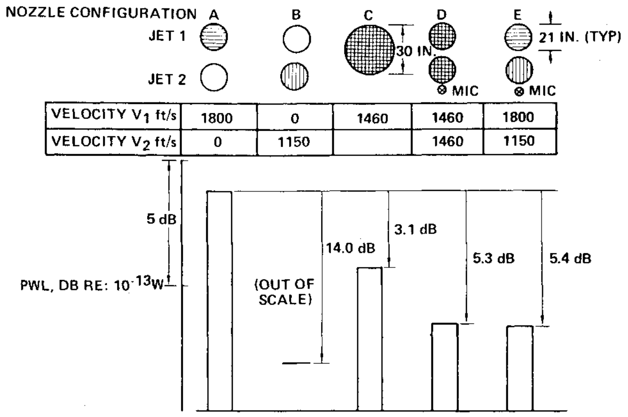

Fig. 4 Acoustic power reduction of two parallel-flow jets.

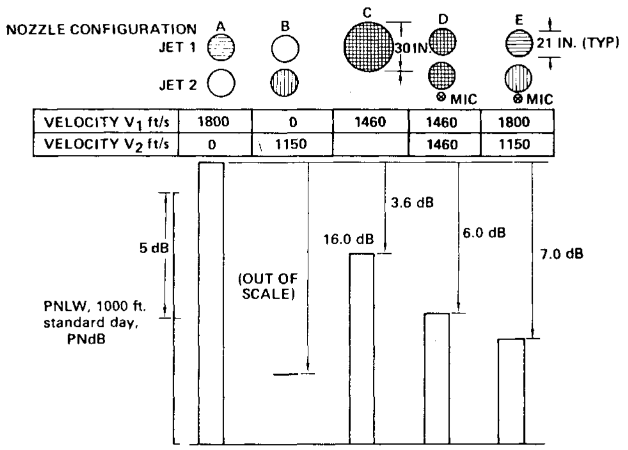

Fig. 5 Subjective noise reduction of two parallel-flow jets.

into three groups:

Group 1) Conditions 70-120 are considered basic independent flow conditions. Velocity ratio and temperature ratio are different for different conditions.

Group 2) Conditions 10-60 are derived from conditions 70-120, respectively. The derived flow conditions were obtained by ideally mixing flow 1 and flow 2 by conserving mass and momentum.

Group 3) Conditions 170-190 are derived from condition 80. For these conditions, different degrees of temperature mixing which correspond to different temperature ratios are assumed while a constant velocity ratio of 0.81 is kept. Once again the mass and momentum are conserved; i.e., conditions 170-190 will produce the same thrust as conditions 80 and 20. Hence these conditions will be referred to as "conditions with equivalent thrust."

Acoustic Measurements

Acoustic measurements were made using 2-ft sideline (near-field) and 25-ft polar (far-field) microphone arrays. Both microphone arrays were located in the plane of jet axis. All acoustic data were processed using the Boeing Noise Technology Laboratories on-line data reduction system. The data were scaled to a 30-in. diam jet and extrapolated to a 1000-ft distance for calculating perceived noise level (PNL) and duration-weighted PNL (PNLW), where PNLW is defined as follows:

$$\text{PNLW} = 10\log_{10} \sum_{\theta=100°}^{150°} \left[\left\{ \frac{\text{PNL}(\theta) - 10\log_{10}\sin^2\theta}{10} \; \frac{}{10} \right\} \right]$$

PNLW is a unit that provides a measure of duration-integrated noise exposure for the static test data in a manner very similar to the EPNL for flight test data.

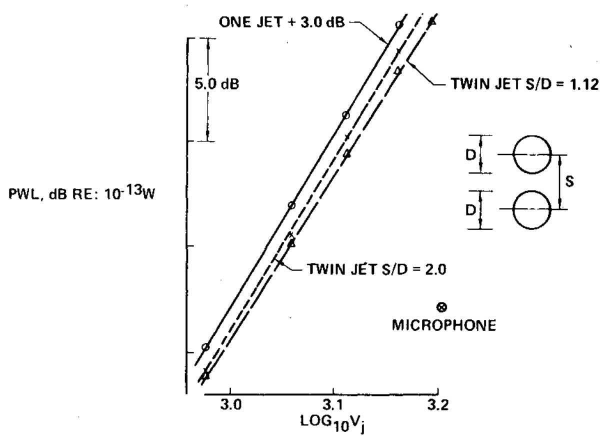

Fig. 6 Effect of S/D on twin parallel-flow jet noise.

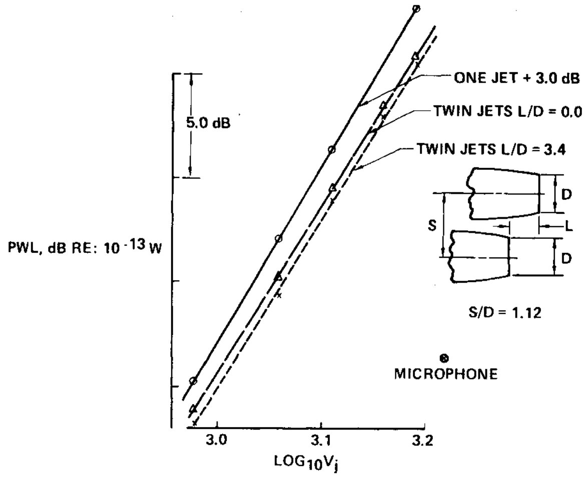

Fig. 7 Effect of L/D on twin parallel-flow jet noise.

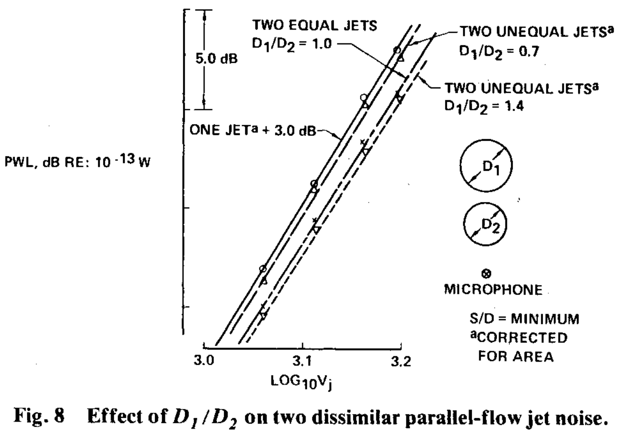

Fig. 8 Effect of D_1/D_2 on two dissimilar parallel-flow jet noise.

Acoustic power (PWL) radiated in the plane of the microphone array also was calculated. This was achieved by assuming that the same noise level as measured by the microphone array was present in all azimuthal directions. Thus PWL numbers as shown in the present paper are indicative of the acoustic power as "seen" by the observer on the ground.†

†In reality, noise radiated by two parallel-flow jets will not be symmetric in all azimuthal directions. Hence the PWL numbers shown in this paper do not represent the total acoustic power radiated in all directions by the two jets.

III. Results

Overview

The test results are presented in terms of physical (SPL and PWL) as well as subjective (PNL and PNLW) units. For evaluating results in terms of subjective units, the model data are scaled to typical full-scale (30-in.-diam nozzle, 1000-ft alt) conditions. The scaled results in terms of PWL and PNLW for typical conditions are shown in Figs. 4 and 5, respectively.

The results for the following nozzle configurations are presented in Figs. 4 and 5: configuration A) high-velocity single flow; configuration B) low-velocity single-flow; configuration C) single flow with equivalent ideally mixed velocity and area (high- and low-velocity flows mixed); configuration D) two parallel-flow jets with ideally mixed velocity through both jets and total flow area equal to configuration C; and configuration E) two parallel-flow jets with higher-velocity flow conditions through one nozzle, lower-velocity flow conditions through the other nozzle, and the noise measurement on the same side as the lower-velocity flow nozzle.

Configuration A is used as a reference level for measuring noise suppression potential. Configuration B, due to low velocity, shows the lowest noise levels. Configuration C is 3.1 PWL dB and 3.6 PNLW dB quieter than the referenced configuration A. Configurations D and E represent the same two parallel-flow geometries but with different flow conditions. Configuration D has flow conditions similar to configuration C with the exception that the flow in configuration D is divided equally into two circular jets. If the noise produced by the jet, which is away from the observer, is shielded completely by the nearer jet, then the two parallel-flow jet configuration D should be 3 dB quieter than the single-flow jet (configuration C). The results show that configuration D is also 2.2 PWL dB quieter than con-

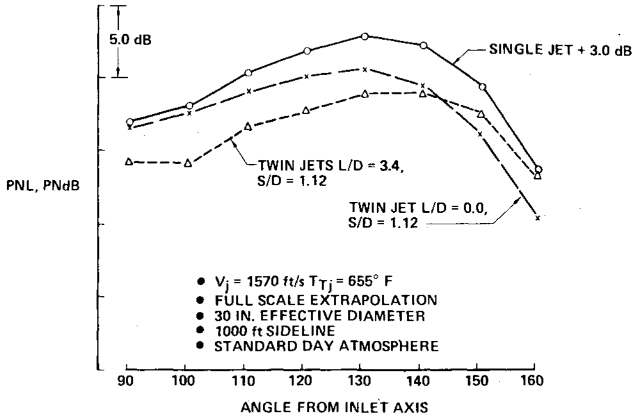

Fig. 11 **Effect of tube spacing on perceived noise level directivity.**

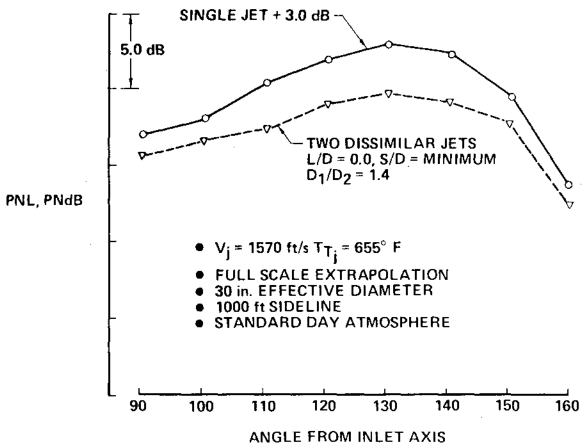

Fig. 12 **Effect of tube size on perceived noise level directivity.**

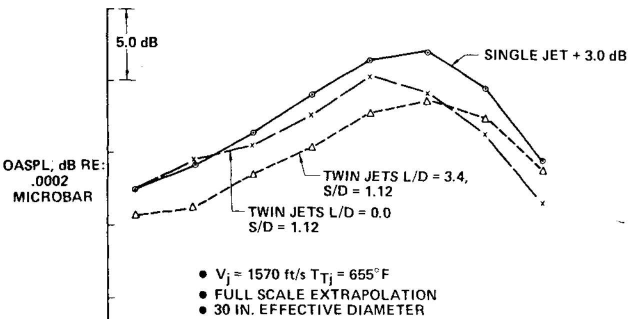

Fig. 9 **Effect of tube spacing on overall sound pressure directivity.**

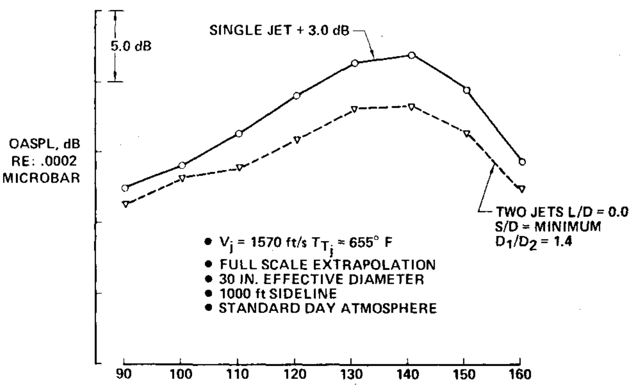

Fig. 10 **Effect of tube size on overall sound pressure directivity.**

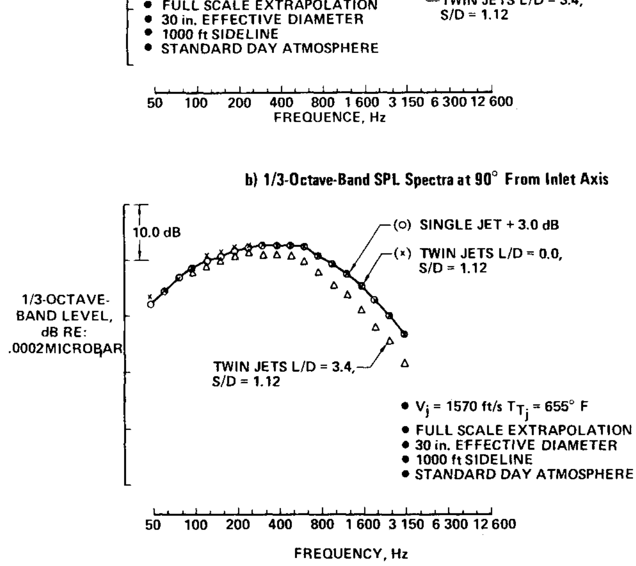

Fig. 13 **Effect of tube spacing on ⅓-octave-band SPL.**

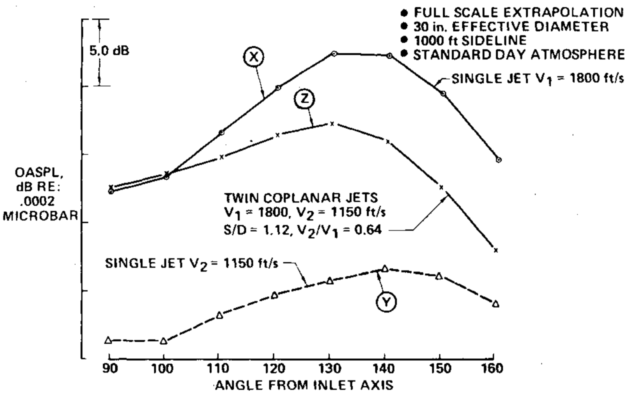

Fig. 14 OASPL for twin nozzles with dissimilar flow ($V_{peak} = 1800$ ft/s).

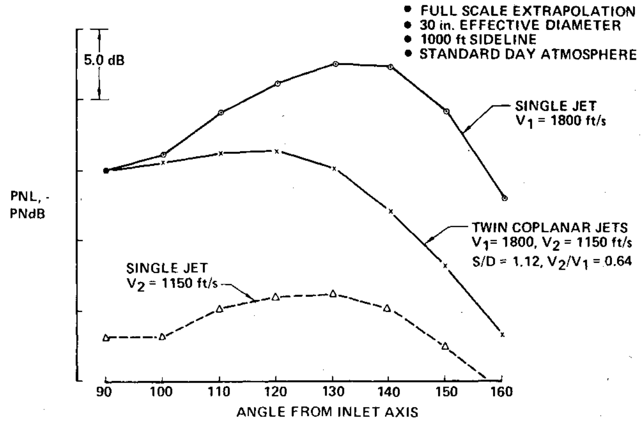

Fig. 16 PNL for twin nozzles with dissimilar flow ($V_{peak} = 1800$ ft/s).

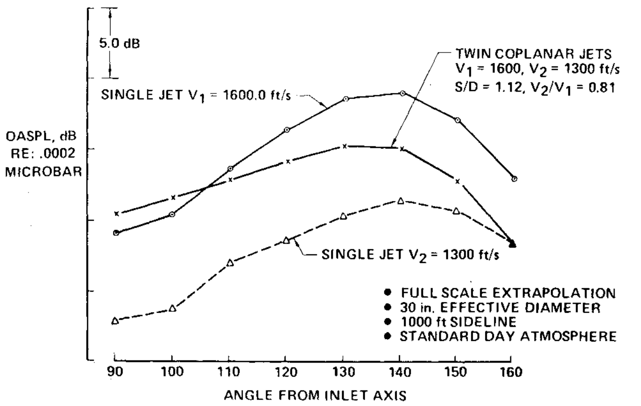

Fig. 15 OASPL for twin nozzles with dissimilar flow ($V_{peak} = 1600$ ft/s).

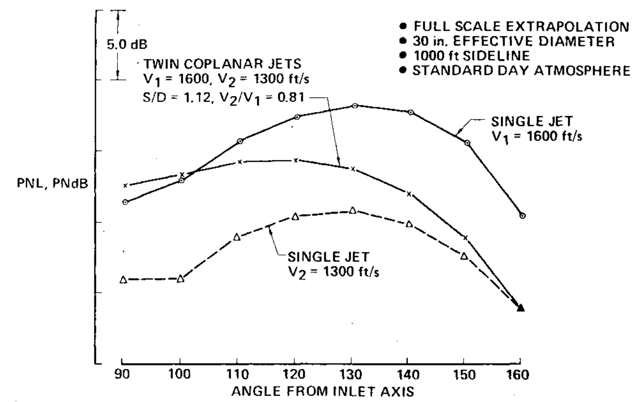

Fig. 17 PNL for twin nozzles with dissimilar flow ($V_{peak} = 1600$ ft/s).

figuration C. Configuration D is also 2.4 PNLW dB quieter than configuration C. Therefore, a twin-jet flow is quieter than the equivalent single-jet flow by about 2 dB and quieter by 5 to 6 dB than the higher-velocity primary-flow jet.

Configuration E represents two parallel-flow jets with dissimilar flows. The flow conditions are selected to provide equal thrust with configurations C, D, and E with the same total mass flow rate. The higher-velocity flow conditions are maintained through the nozzle away from the observer, and the lower-velocity flow conditions are maintained through the nozzle nearer to the observer. Configuration E is 3 to 4 PWL dB and 7 PNLW dB quieter than the reference high-velocity single-flow jet in the preferred direction.‡

The extrapolated noise data (Figs. 4 and 5) indicate that a dissimilar flow through two parallel-flow jets can be quieter in a preferred direction than an equivalent "mixed" single-flow jet. This important new information can be used for understanding how a multitube nozzle works and for designing improved multitube nozzles. In particular, elemental tube geometry and gas flow conditions through individual tubes will influence the noise characteristics of a multitube nozzle. The results pertinent to these two effects will be presented in the following two sections.

Nozzle Geometry Effects

As mentioned earlier, the effects of jet spacing and size were studied with the same flow through both nozzles. The effects of jet spacing and jet diameter on PWL are shown in Figs. 6-8. The effect of lateral separation S/D on PWL is shown in Fig. 6. At all velocities of the present experiment, the data show that the PWL for two jets is quieter than the area-corrected PWL for a single jet. The two jets with $S/D = 1.12$ show a lower PWL than the two jets with $S/D = 2.0$. The effect of longitudinal jet staggering for a constant lateral spacing, $S/D = 1.12$, is shown in Fig. 7. The PWL is lower when L/D is increased. The effect of tube size (different nozzle diameter ratios) is illustrated in Fig. 8. For the range of nozzle diameters investigated, the lowest value of PWL (for a given velocity) is observed when the smaller of the two jets is placed on the observer side.

The noise changes produced by the two jets showed dependence on all three geometric parameters: lateral spacing, streamwise staggering, and nozzle size. For a given gas condition, the PWL for the two parallel-flow jets was 1 to 3 dB lower than the equivalent single-flow jet. The 3-dB reduction in PWL seems to imply that the observer does not hear the farther jet with the proper geometric parameters. The noise reduction capability of the two parallel-flow jets will change with angle and frequency.

Given the observed changes in PWL, data that show dependence on angle and frequency now are presented. Data are presented for a jet velocity of 1570 ft/s and are typical of trends at other velocities. Overall sound pressure level (OASPL) and perceived noise level (PNL) directives are shown in Figs. 9-12. Both the OASPL and PNL directives show similar dependence on angle. The noise radiated by twin coplanar jets ($L/D = 0$, $S/D = 1.12$) at 90 deg to the jet axis is almost the same as that radiated by an equivalent single-flow jet. The twin coplanar jets radiate less noise to the jet axis (Figs. 8 and 10). In contrast to the twin coplanar jets, the twin staggered jets ($L/D = 3.4$, $S/D = 1.12$) are quieter than the single jet at angles between 90 and 150 deg from the inlet axis and approach the single-jet noise level at 160 deg. The directivities for the staggered jets show lower noise levels than the equivalent-diameter single-flow jet at all angles (Figs. 10 and 11).

‡The preferred direction is the quiet side: usually the same side as the low-velocity jet.

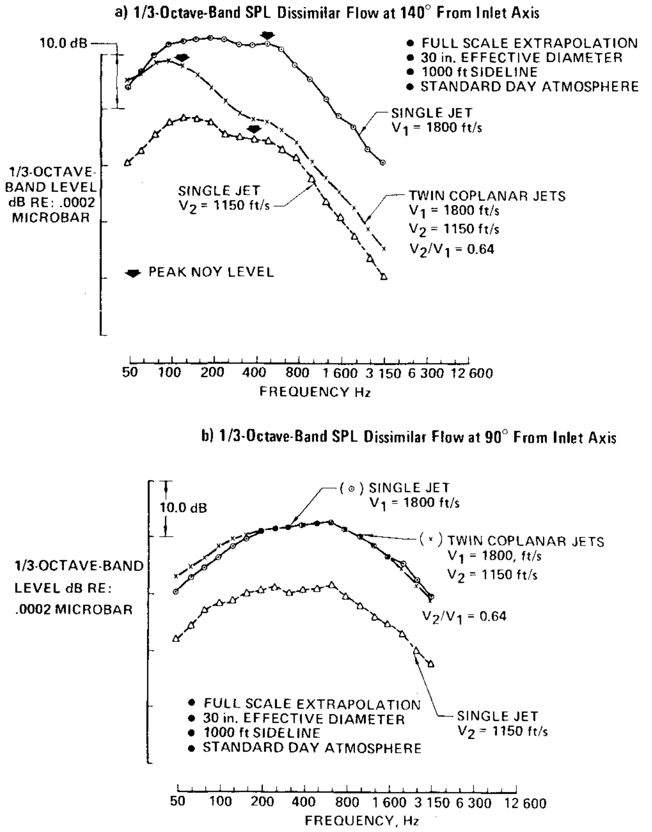

Fig. 18 ⅓-octave-band SPL for twin jets with dissimilar flow (V_{peak} = 1800 ft/s).

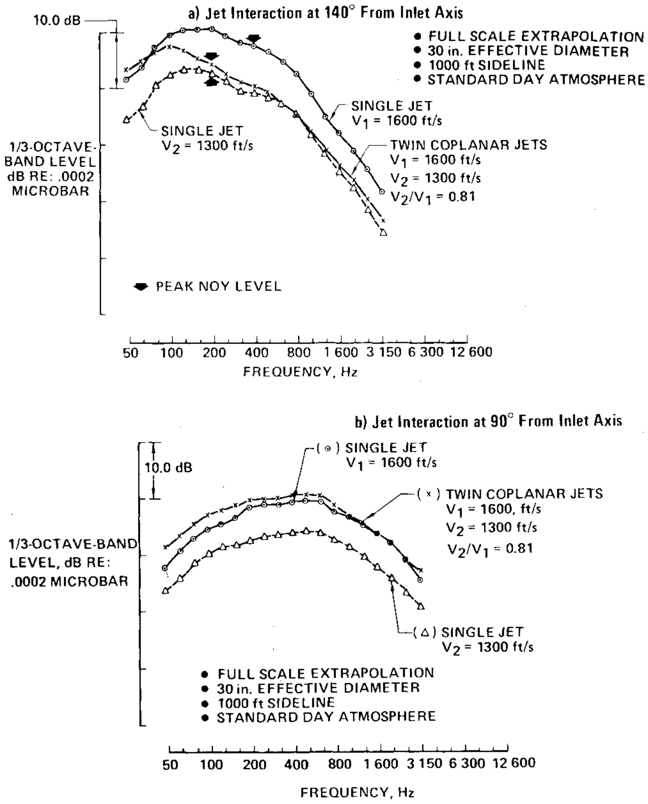

Fig. 19 ⅓-octave band SPL for twin jets with dissimilar flow, (V_{peak} = 1600 ft/s).

Peak ΔOASPL and ΔPNL reductions of 3 to 4 dB were observed for the two parallel-flow jets when compared with an equivalent single-flow jet. Although changes with angles for different nozzle configurations were observed, the noise reduction at 140 deg was about the same for all two parallel-flow nozzle configurations (Figs. 9-12).

One-third-octave-band SPL frequency spectra for twin jets are compared with the noise spectra for an equivalent-thrust single-flow jet in Fig. 13. At 90 deg, the one-third-octave-band SPL spectra for the coplanar twin jets and the single-flow jet are almost the same. The staggered twin-jet configuration shows 2 to 5 dB lower SPL at high frequencies than the single jet at 140 deg. Both of the twin-jet configurations show comparable SPL, which is 2 to 5 dB lower than the single jet. The dependence of the noise of two parallel-flow jets on various geometric parameters can be summarized as 1) lower noise for smaller lateral spacing, 2) lower noise at 90 deg with streamwise flow staggering, and 3) lower noise with the smaller jet near the observer.

Gas Condition Effects

The effects of dissimilar gas flow conditions were studied using two identical coplanar nozzles. In the previous section, two parallel-flow jet data were compared with an equivalent-diameter single-flow jet. Acoustic data for the twin nozzles with dissimilar flows (Figs. 14-19) are presented differently; the twin-nozzle data are compared with noise radiated by each of the two individual jets run one at a time with the respective flow conditions. Figure 16 can be used as an example to illustrate the point. Curves X and Y show directiveness for single jets 1 and 2 (Fig. 3) at velocities of $V_I = 1800$ ft/s and $V_2 = 1500$ ft/s, respectively. Again, the velocities used are selected as representative. (Similar effects were observed at other conditions.) Curve Z is the noise directivity on the quiet side of the twin nozzles when both jets are run. The logic in presenting comparisons in this form is that the high-velocity jet by itself is the aeroacoustic noise source that needs quieting, whereas the low jet by itself radiates a certain level of noise which sets the noise floor. Hence, the high-velocity jet cannot be quieted (as can be seen from data presented below) to noise levels lower than the noise radiated by the low-velocity jet. Therefore, the data comparisons show the noise source level, the noise floor, and the reduced noise level with the two jets interacting. The difference in the noise level between curves X and Z is a measure of the noise reduction by twin nozzles due to jet interaction and shielding. The detailed comparisons now are presented for two cases with similar flows ($V_2/V_I = 0.64$, 0.81). These cases produce equivalent total thrust.

The OASPL (Figs. 14 and 15) and PNL directives (Figs. 16 and 19) for the two cases show very similar trends. At 90 and 100 deg, the noise radiated by twin coplanar jets is at about the same level as an individual high-velocity jet. At these angles, the individual low-velocity jet noise level is significantly lower than the twin jet. At 110 to 160 deg, the twin jet is quieter than the individual high-velocity jet. The amount of noise reduction appears to depend on angle and on the noise floor level set by the low-velocity jet. For example, in Fig. 16 the maximum noise reduction of 11 PNdB is observed at 150 deg from the inlet axis. The effect of the noise floor can be seen from data presented in Figs. 15 and 17, where the noise levels for the twin jet and low-velocity single jet are equal at a 160 deg angle.

One-third-octave-band SPL spectra are shown in Figs. 18 and 19. At 140 deg and higher frequencies, the twin coplanar jet noise levels are significantly lower than the high-velocity single jet. The spectrum for the lower velocity ratio condition (Fig. 19a) is nearly equal to the noise floor due to the low-velocity jet over most of the high-frequency range. At 140 deg, the jet interaction does not seem to affect the low-frequency noise levels. At 90 deg, the one-third-octave-band spectrum levels for the twin coplanar jet and the higher-velocity single jet are about the same in the high-frequency range. The two interacting jets seem to radiate 1 to 3 dB more low-frequency noise than the single high-velocity jet.

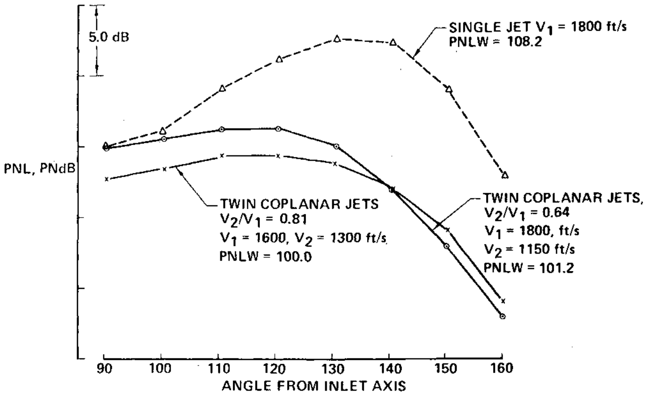

Fig. 20 PNL directivity for twin nozzle with different flow conditions (equivalent thrust).

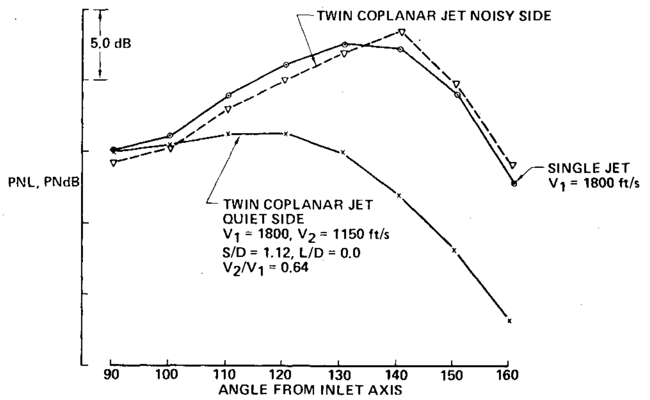

Fig. 21 Comparison of PNL directivity on noisy and quiet side for twin nozzle with dissimilar flow (V_{peak} = 1800 ft/s).

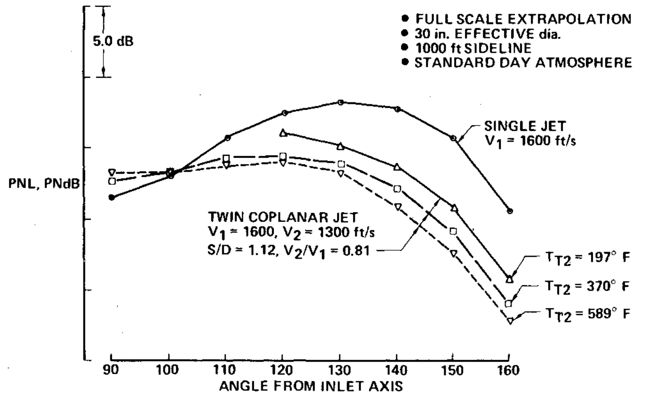

Fig. 22 PNL directivities for different low-velocity jet flow temperatures.

The PNL directivities for the two cases through the twin coplanar nozzles now are compared directly (Fig. 20). For 90 to 130 deg, the PNL for the lower velocity ratio flow condition is 1 to 2 PNdB higher than the higher velocity ratio condition. The trend is reversed at the 150- and 160-deg angles. Increasing flow velocity through the nozzle near the observer will increase the noise level at angles close to the jet axis.

So far, all comparisons have been made on the "quiet side." The PNL directivity on the noisy side (observer on high-velocity side of twin jets) was observed to be very similar to a high-velocity single jet (Fig. 21). The tests also showed that the temperature of the low-velocity stream affects the noise radiated by twin coplanar jets. For example, the data presented in Fig. 22 show that the twin-jet is reduced when the

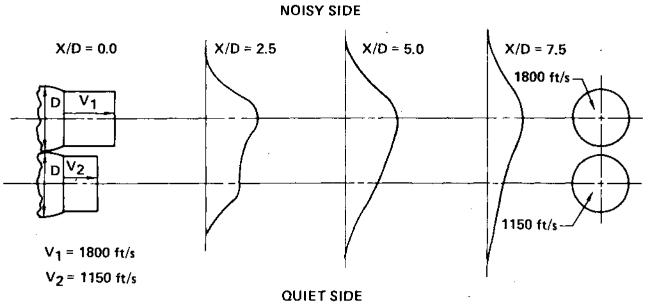

Fig. 23 Velocity profile for twin coplanar jets with dissimilar flow.

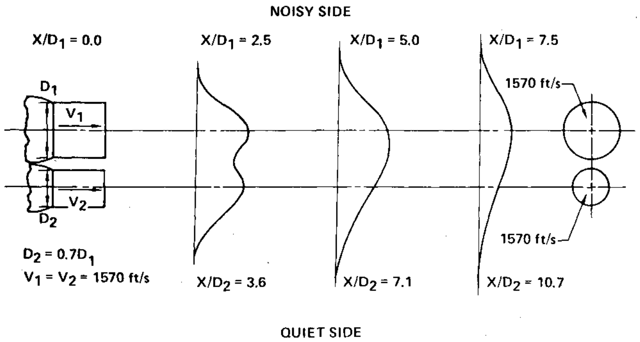

Fig. 24 Velocity profile for two different-size jets with same flow.

temperature of the low-velocity jet is increased. The change in noise level radiated by the low-velocity jet (noise floor) and the change in noise refraction due to the change in jet temperature are likely causes of the observed trend.

The twin coplanar jets with dissimilar flows thus have shown significantly different noise levels at peak noise angles on the two opposite sides in the plane containing the two-jet axis. However, noise levels at 90 deg, but on two opposite sides, appear to be comparable. These noise characteristics are, in certain respects, quite different from that of a simple round jet. These differences can be related to differences in the jet mean flowfields. Typical mean velocity profiles in the plane of the two-jet axis for twin coplanar jets are shown in Fig. 23.§ Velocity profiles are shown at four different streamwise locations. They exhibit a nonsymmetric shape with steeper gradients on the noisy side than on the quiet side. It appears that the noise signature at angles between 120 and 160 deg from the inlet, and particularly at high frequencies, depends mostly on that part of the velocity profile (and its gradient) which the observer can "see" directly; i.e., one side of the velocity profile and the noise generated by it appear to contribute negligibly on the other side at these angles (120 to 160 deg). As mentioned earlier, the noise reduction on the quiet side is due to both reduction in the source (because of lower shear) and redirection of noise due to propagation effects. The latter effect may be predominant at angles greater than 120 deg.

It is interesting to examine whether or not the preceding discussion can be extended to the results presented for the nozzle geometry effects. Nozzles with the same flow but two different diameters will be examined for this purpose. Figure 24 shows schematically velocity profiles for this configuration. For a given location downstream from the nozzle

§Velocity profiles shown in Figs. 23 and 24 have been hypothesized. There is a high degree of confidence in these hypothesized profiles because they have been derived from actual velocity profiles measured for similar two parallel-flow nozzles with similar flow conditions. The exact shape of the velocity profile and its development downstream from the nozzle exit will depend on various geometric parameters, e.g., nozzle separation, and on various flow parameters, e.g., V_1/V_2 and T_{T1}/T_{T2}.

exit, the velocity (V_2) of the smaller jet will decay faster than that of the larger jet (V_l). As a result of these different velocity decay rates, a nonsymmetric velocity profile is developed; e.g., at $X/D_l = 5$ (which will be the tip of the potential core and a strong noise-producing region for the large jet), the velocity profile in the plane of the jet axes is clearly nonsymmetric. Thus, two different-size jets starting with the same nozzle exit condition will produce a nonsymmetric profile at a downstream noise-producing location. Thus, the noise reduction on the preferential quiet side can be related to a nonsymmetric profile producing a reduced velocity gradient on the quiet side.

The results for twin nozzles with dissimilar flows can be summarized as follows:

1) The noise levels at 120 to 160 deg from the inlet depend very strongly on the part of the velocity profile which can be "seen" directly by the observer.

2) The noise levels at 90 to 110 deg from the inlet depend on peak jet velocity.

3) The observed noise reductions can be related to nonsymmetric mean velocity profiles.

4) The noise reduction potential depends on the velocity and temperature ratios because a) lower-velocity jet noise becomes the noise floor, and b) jet noise refraction and interaction depend on the velocity and temperature ratio.

IV. Applications

In the present study, the effect of geometric and flow parameters on noise radiated by two jets is investigated. Two jets can be considered the fundamental building block of a multitube nozzle. Thus, the results of the present study can be used for designing acoustically improved multitube nozzles for jet noise suppression. Results of a fundamental study of this type could lead to new jet noise suppression concepts which could be better acoustically while minimizing performance, weight, and cost penalties. The results of this study also can be applied to multiengine configurations when two or more engines are placed together.

V. Conclusions

The acoustic characteristics of two parallel-flow jets have provided some insight into the jet noise suppression mechanisms of a multitube nozzle. The following specific acoustic results were obtained in the plane of the jet axis and in the region of flow conditions of typical interest:

1) Two parallel-flow jets with dissimilar flows can be quieter than the equivalent fully mixed single-flow jet.

2) Two parallel-flow jets with the same flow can be up to 3 dB quieter than the equivalent single-flow jet.

3) Two parallel-flow jets become quieter than the equivalent single-flow jet with reduction in the lateral spacing between jets, with streamwise staggering of the jet nearer the observer, and with the smaller-diameter jet placed nearer to the observer.

4) The noise reduction potential of two parallel-flow jets with dissimilar flows depends on their velocity and temperature ratios.

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