Reduction of Noise from Supersonic Jet Flows

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Acoustic characteristics and flow behavior of interacting coaxial supersonic jets have been investigated experimentally. A number of arrangements of the inner and outer coaxial nozzles were used. Far field acoustic measurements were made for each nozzle arrangement. Preliminary near field measurements were also made for one typical nozzle arrangement. Substantial reductions in both peak sound pressure and total radiated power were obtained over a range of operating conditions of the coaxial jet flows. Spark-shadowgraphs recorded at these operating conditions revealed the consistent appearance of a characteristic pattern of shock structure which effectively eliminates the usual repetitive shock cells associated with super sonic jet flows. The corresponding velocity profiles deduced from pitot-pressure surveys of coaxial jet flows indicate that the large mean shear at the inner boundary of the outer annular jet as well as the mixing are favorably modified owing to the interaction of inner and outer jet flows. The dependence of the measured noise reduction on the observed flow changes is discussed.

Introduction

THE use of turbo-jet engines for powering high-speed aircraft has focused attention on the need for suppressing the intense noise generated from the associated supersonic exhausts. The possible noise sources in supersonic flows are: 1) supersonic and subsonic flow turbulence; 2) eddy Mach wave emission; 3) shock-turbulence interaction; and 4) shock oscillation and flow resonance. In the absence of any definitive theoretical analyses which either predict the over-all noise radiation or the relative contributions of each of the different type of acoustic sources in supersonic (with shock structure) turbulent jet flows, the noise abatement methods for supersonic jet noise are still mostly innovations based on concepts which are extrapolated from some of the more successful subsonic jet noise theories and abatement practices. Supersonic jet noise abatement techniques investigated so far by various research groups fall into three main categories.

1) Use of external noise-suppressing flow modification at the nozzle exit using mechanical devices: for example, a) Westley and Lilley[1] used teethed-exit nozzles and wire gauze extension at nozzle exit to diffuse or eliminate shock waves normally present in the flow downstream of the exit; b) work on center plug nozzle by Pernet[2] and its extension by Moore and Clinch[3] to hot jets and full size jet engines; c) more recently use of rods in the nozzle exhaust by Nagamatsu et al.[4] to induce bow shock waves and thus reduce mean velocity near the nozzle exit; and d) any other mechanical devices such as the multitubed arrangements which may be inserted at a suitable location in or as an extension of the nozzle to modify some of the noise sources in supersonic exhaust flows, may also be considered to fall into this category. However, these mechanical techniques and devices often result in severe thrust penalties.

2) Use of ejector shroud: the purpose of this technique is to enhance the entrainment flow and mixing so that at the exit of the ejector, the main jet and the secondary entrainment flows are almost completely mixed and uniform. The shielding of noise sources by the ejector shroud is also a favorable factor. A fairly complete account on noise suppression by the use of ejectors can be found in Ref. 5. Nagamatsu et al.[4] have also investigated noise suppression by using shroud and its induced flow. This method is generally advantageous where an additional improvement in the performance of an otherwise successful noise suppressing approach is desired. However, passive entrainment through ejector shroud by itself (i.e., in the absence of forced and controlled flow interaction with the main supersonic jet flow) perhaps will not suffice as an effective primary noise suppression technique for supersonic jets over an extended range of operating pressure ratios.

3) Use of flow interaction methods: a secondary subsonic and/or supersonic jet flow is used to interact with a primary supersonic jet flow. The interaction of a supersonic free jet just downstream of the nozzle exit with a secondary free supersonic jet flow does not disturb the upstream flow at or inside the nozzle exits, excluding perhaps some second-order effects through the subsonic turbulent boundary, and any changes in the entrainment flow due to interaction. If this interaction between a primary and a secondary jet leads to the elimination or weakening of the shock related acoustic sources, mixing enhancement and reduction of the supersonic region of the jet flows, noise reduction should result. Therefore, the investigations of impingement and/or interaction, between two coaxial supersonic jet flows where both flows are thrust producing, were recently initiated by Dosanjh, Abdelhamid and Yu.[6] Preliminary results have shown this approach to be quite promising. Earlier Pernet[2] had also investigated far noise field of center core flow nozzle where both the inner core flow nozzle and outer annular nozzle were convergent. Both flows were operated at the same reservoir to ambient pressure ratios. Pernet concluded that over the subsonic flow range, the acoustic performance of center core flow nozzle is poor, as compared to a convergent nozzle based on mass flow rate per unit area, and that favorable acoustical performance of the center core flow nozzle operated at higher than the critical pressure ratios is obtained only when the inner nozzle protrudes further down-

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Index categories: Aerodynamic and Powerplant Noise (Including Sonic Boom); Jets, Wakes, and Viscid-Inviscid Flow Interactions; Supersonic and Hypersonic Flow.

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Table 1 Important specifications of the nozzle arrangements (NA)

NA	D_o, in.	D_t, in.	D_i, in.	A_{oe}, in.^{2}	A_{ot}, in.^{2}	α_0, deg.	d_e, in.	d_t, in.	A_{ie}, in.^{2}	A_{it}, in.^{2}	α_i, deg.	$\frac{A_{oe}}{A_{ie}}$
1	0.665	0.665	0.550	0.110	0.110	0	0.482	0.375	0.182	0.110	12	0.605
2	0.678	0.665	0.550	0.123	0.110	2	0.482	0.375	0.182	0.110	12	0.675
3	0.800	0.800	0.550	0.265	0.265	0	0.482	0.375	0.182	0.110	12	1.657
4	0.800	0.800	0.438	0.352	0.352	0	0.375	0.375	0.110	0.110	0	3.200
5	0.678	0.665	0.438	0.210	0.196	2	0.375	0.375	0.110	0.110	0	1.908

stream relative to the outer annular nozzle exit. No experimental observations of the corresponding flowfield were reported by Pernet. More recently Williams et al[7] conducted acoustical and flow studies of coaxial jet flows operated in the subsonic flow range. Different reservoir pressures were used for inner jet and outer jet, thus producing a nonzero relative velocity at the interface of the two interacting jets. Contrary to Pernet's earlier observations, substantial noise reductions were achieved when certain values of relative velocities between two subsonic jets were maintained. Furthermore, preliminary results reported by the present authors, from the interaction of coaxial supersonic jet flows,[6] where inner and outer nozzle exits are aligned in the same plane, indicate that flow interaction approach provides substantial noise reduction. Clearly for any arrangement of the impinging and/or interacting supersonic free flows to be successful as an effective and practical approach for noise abatement, it should meet all or at least some of the following objectives: 1) The net total thrust of the interacting jets should, in the limit, be equal to the sum of the thrusts produced by the individual jets, i.e. any thrust loss should be the least possible. This can be best realized only if all of the interacting jets are thrust producing and if flow interaction between free supersonic flows take place downstream of nozzle exits. 2) The shock structure in the free supersonic jet flow should be modified and weakened. 3) The extent of the individual supersonic flow regions should be shortened in the combined interacting jet flows. This may be achieved by inducing strong shocks as a result of the mutual impingement and/or interaction of two or more jets, and thus expediting the change of the freejet flows from supersonic to subsonic speeds. 4) The effective mean shear near the exit of each jet flow should be reduced owing to interaction. 5) The net effectiveness of the mixing region as a noise source should be diminished. Commonly this is achieved by accelerating mixing and thus shortening the extent of the mixing region provided turbulence levels do not rise such as to negate the advantage. 6) The "shielding" of the noise sources in the inner jet flow should be enhanced by the use of the outer jet flow. To accomplish some or all of these desirable flow changes and thus achieve expected noise reduction, systematic investigations of noise from two interacting coaxial free supersonic turbulent jet flows have been undertaken by the authors and some important experimental findings are reported and discussed here.

Experimental Facility and Procedure

Coaxial Nozzle Arrangements

The important features of the nozzle arrangements used in these investigations are shown in Fig. 1. The basic arrangement consists of a) an outer annular nozzle either convergent or convergent-divergent and b) an inner nozzle also either convergent or convergent-divergent. Important specifications of the five nozzle arrangement (NA 1 to NA 5) used in these experiments are summarized in Table 1 where A_{oe} and A_{ie} are the exit areas of the outer and inner nozzles, respectively. The relative locations of the inner and outer nozzle exits are adjustable as illustrated by the double arrow in Fig. 1. The two jet flows are supplied through separate settling chambers and are individually controlled. The compressed air and its control system is described in Ref. 8. The stagnation pressure in the settling chamber of the inner jet is measured by a combination of four pitot tubes. For the outer annular jet the stagnation pressure is measured in the buffer reservoir (Fig. 1). The stagnation temperatures of both jets were measured to be very nearly equal to ambient temperature. For most of the experimental results reported here the outer annular jet was operated at a somewhat higher pressure ratio than the inner jet and the inner and outer nozzle exits were aligned in the same plane, i.e. $X/D = 0$ where X is the axial distance measured downstream of the nozzle exits. (Fig. 1).

In NA 1, 3 and 4 the outer annular nozzle was operated in the underexpanded mode ($\xi_0 = 3.04$) and although the flow Mach number at the nozzle exit is 1.0, the free jet flow Mach number was as high as 1.7.§ The outer nozzles in NA 2 and 5 were mostly operated at the design conditions, i.e. nozzle exit Mach number = 1.5.

Flow Measurements

Spark-shadowgraphs of coaxial interacting jet flows were recorded in a semi-hard room. The optical system is described in ref. 8. Total pressure surveys were conducted in both the subsonic and supersonic regions of coaxial jet flows. These total pressure data were used to determine the Mach number distribution and the velocity profiles at various cross-sections of the coaxial jet flows. Only typical results are presented.

Accoustical Instrumentation

Farfield over-all sound pressure and spectrum measurements of the radiated noise as well as preliminary near field sound pressure survey of the interacting jet flows were conducted in a fully anechoic chamber with design cut-off at 200 Hz. Detailed description of the anechoic chamber and the acoustical instrumentation is available in Ref. 8. Briefly, the acoustical measurement system, mostly Brüel and Kjaer instruments, comprised of a $\frac{1}{8}$-in. condenser microphone with appropriate cathode follower (frequency response flat from 30 Hz to 140

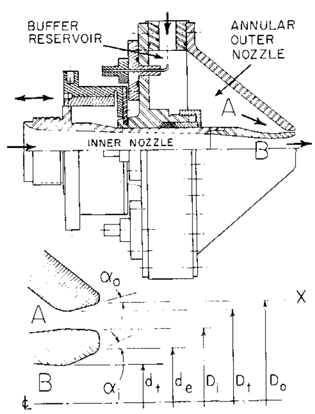

Fig. 1 Basic nozzle arrangement.

§ Determined from calculations by the characteristics method of the annular underexpanded axisymmetric flow.

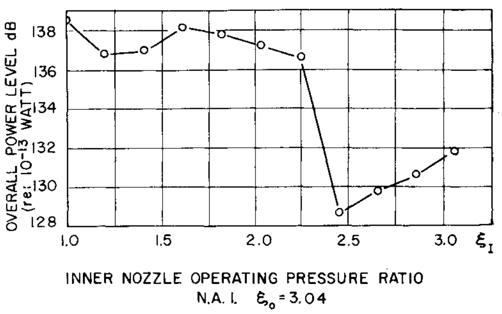

Fig. 2 Typical variation of over-all acoustic power level with inner nozzle operating pressure ratio.

kHz; dynamic range 76-184 db re 2×10^{-4} μbar), a microphone amplifier (frequency response flat from 10 Hz to 200 kHz, a $\frac{1}{1}$ and $\frac{1}{3}$ octave band filter set (center frequency from 25 Hz to 100 kHz) and a level recorder (frequency response flat from 10 Hz to 200 kHz; dynamic range 50 db).

For far noise field investigations, over-all sound pressure levels were recorded at eight equally spaced azimuthal positions, from 15° to 120°, relative to the downstream coaxial jet axis. Total emitted acoustic power and directional distribution of noise were computed by assuming the sound field to be symmetric. Sound pressure data at azimuthal positions greater than 120° were not recorded because of the limitation imposed by the size of the anechoic chamber. This neglect of sound pressures at azimuthal positions greater than 120° was found to affect the total acoustic power by less than 1 db. Spectrum analysis was undertaken for selected operating conditions of coaxial interacting jet flows. A detailed discussion of data reduction procedures are given in Ref. 8.

For near noise field survey, the axis of microphone diaphragm was oriented perpendicular to the centerline of coaxial jets. The boundary of measurements was determined from shadowgraphs recorded at the corresponding operating conditions, and its location was also confirmed by pitot pressure data taken in the vicinity of the coaxial jet boundary.

Results and Discussion

A summary of the major acoustic results for the different nozzle arrangements used in these experiments is given in Table 2. Detailed discussion of some aspects of typical experimental results for nozzle arrangements numbers 1 and 3 are reported here. For additional details and discussion of experimental results of other arrangements see Ref. 9.

Far Noise Field

For different annular convergent nozzle operating pressure ratios ξ_0,¶ the over-all acoustic power level and directionality

Table 2 Summary of acoustic results for different nozzle arrangements

NA	ξ_o	$\xi_I{}^a$	ΔSPL,[a] (30°)	ΔSPL,[a] (90°)	ΔPWL,[a] *db*	ΔPWL,[b] *db*
1	3.04	2.43	11.0	9.3	10.0	5.5
2	3.20	2.63	8.3	6.0	7.0	5.8
3	3.04	2.22	7.5	5.4	6.7	8.3
4	2.50	2.00	5.5	4.0	4.0	6.3
5	3.04	2.12	4.7	3.4	3.6	7.2

Range of operating conditions for
[a] Minimum noise when compared with the outer nozzle alone operating at the same ξ_o.
[b] Minimum noise when compared with a single convergent nozzle producing the same thrust.

¶ ξ_o, the ratio of outer jet reservoir absolute pressure P_{TO} (psi) and ambient pressure P_a.

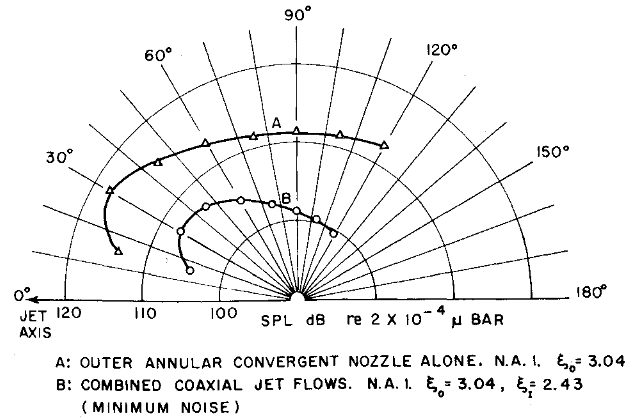

Fig. 3 Over-all sound pressure directionality.

of the interacting coaxial jet flows were determined at various inner jet operating pressure ratios ξ_I.** Significantly at each of the operating outer jet pressure ratios, the over-all acoustic power level of the sound emitted from the coaxial jet flows decreases gradually as the operating pressure ratio of the inner jet is increased and, at certain values of ξ_I, an abrupt reduction in total emitted noise occurred and at still higher ξ_I's a gradual increase in noise was observed. This typical variation of the over-all acoustic power level for $\xi_o = 3.04$ is shown in Fig. 2. For operating pressure ratios of 2.43 for the inner jet, the over-all acoustic power level of the combined coaxial jet flows reduced by 10 db below that of the outer jet alone. The total acoustic power of the outer jet alone was found to be equal to that of a single convergent nozzle of the same exit area as the outer nozzle, and operated at the same pressure ratio. Comparison between the directionality characteristics of the sound emitted from the outer jet alone and that from the combined coaxial jet flows at the minimum noise condition is shown as curves *A* and *B*, respectively, in Fig. 3. Nearly uniform reductions in SPL occur at all angular positions from 15° to 120°. The over-all sound pressure reduction along the direction of peak sound pressure (30°) is 11 db. Maximum reduction in SPL of 13 db occurs at 120°.

The over-all acoustic power level of the outer annular convergent jet flow alone and the minimum over-all power levels achieved with the interacting coaxial combined jet flows are compared in Fig. 4, for outer jet pressure ratios ξ_o ranging from 3.04 to 7.80. The inner jet pressure ratios ξ_I required to achieve these minimum acoustic power levels at different outer jet operating pressure ratios ξ_o are shown in Fig. 5. It is

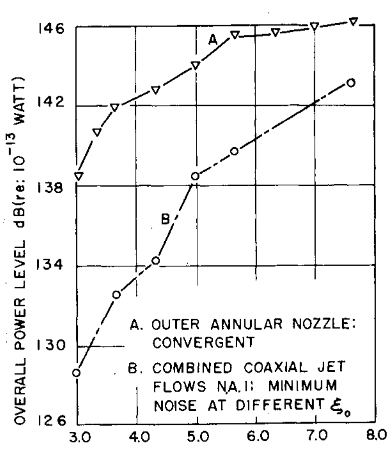

Fig. 4 Over-all power level at various operating pressure ratios.

** ξ_I, the ratio of inner jet reservoir pressure P_{TI} and ambient pressure P_a. $\xi_I = 1$ means that the inner jet is not operated.

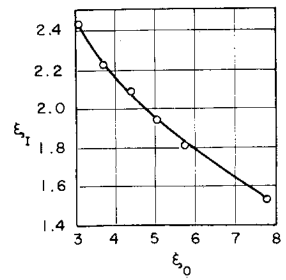

Fig. 5 Variation of inner nozzle pressure ratio, ξ_I, with outer nozzle pressure ratio, ξ_o, for minimum noise operation.

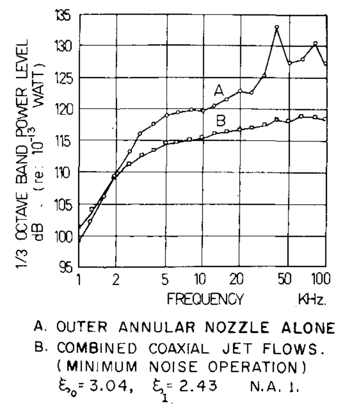

Fig. 6 1/3 octave band power spectra.

evident that significant noise reductions (of the order of 6 db and higher) are achieved for outer pressure ratios ξ_o up to 5.08. Furthermore it is worth noting that 1) at all inner jet operating pressure ratios indicated in Fig. 4, the total noise radiated by the combined jets is lower than that from the outer jet alone and 2) the required inner jet pressure ratios to achieve the minimum acoustical power levels decreases as the outer jet reservoir pressure ratio is increased (Fig. 5).

Spectral analyses of the noise radiated from the outer jet alone and from the coaxial interacting combined jet flows at operating conditions corresponding to the minimum over-all acoustic power level were recorded at $\frac{1}{3}$ octave band-width. Results are given in Fig. 6. For the outer annular jet flow alone ($\xi_I = 1$) operated at a pressure ratio $\xi_o = 3.04$, the power spectrum (curve A) exhibits two discrete peaks at 40 and 80 kHz. These discrete spectral peaks are eliminated (curve B) at operating condition ($\xi_o = 3.04$ and $\xi_I = 2.43$) corresponding to the minimum emitted noise from the interacting jet flows. More importantly, such use of the interacting inner jet flow attenuates the broad band noise over almost the entire spectral range, with somewhat greater attenuation at higher frequency bands. The frequency range of the acoustical instrumentation available limited the experimental observations to a maximum 100 kHz.††

Optical Observations

Shadowgraphs of the interacting jet flows from different nozzle arrangements when operated such that substantial noise reductions are achieved show similar flow behavior. A typical sequence of shadowgraphs showing the development of the shock structure in the coaxial interacting jet flows at different inner jet operating pressure ratios ξ_I for NA 3 (see Table 1 for details of nozzle specifications) are reproduced in Fig. 7a. At $\xi_o = 3.04$ and $\xi_I = 1$ (i.e., the outer annular jet was operated alone) six annular repetitive shock cells of approximately the same wavelength can be seen. As ξ_I is increased to 1.82, shock structure also appears in the inner jet flow. The annular shocks in the outer jet flow seem to be somewhat weakened; however, all the six shock cells are still identifiable. As ξ_I is increased to 2.22 at which minimum noise was achieved for this nozzle arrangement, the repetitive shock cells are replaced by a single composite shock structure. Further increase of ξ_I results in only minor changes in the appearance of this composite shock system.

From all the shadowgraphs at or near minimum noise conditions (Fig. 7b, NA.1) two distinct flow regions can be delineated:[6] 1) a flow region which extends from nozzle exits to about $X/D_o = 0.16$ downstream of the exits, where the composite shock structure terminates and 2) a flow region which extends downstream of the shock structure. The coaxial jet flows in the first region are supersonic and contain several shock fronts in the outer as well as in the inner jet flows. Downstream of the strong, almost normal shocks, the repetitive shock structures is practically eliminated and flow velocities are substantially reduced.

Since the inner nozzle flow is over-expanded in NA 1 (Fig. 7b) there is a conical shock wave which emanates from the inner nozzle exit. It is pertinent to stress, however, as discussed previously that similar noise reductions have also been

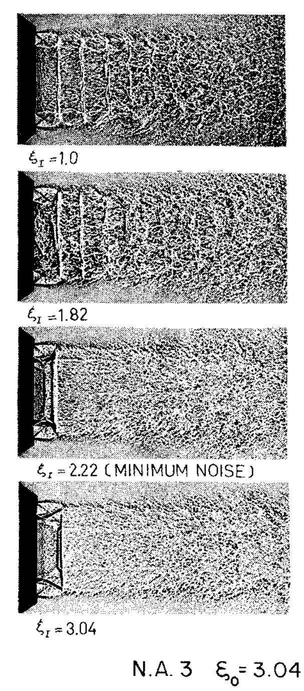

Fig. 7a Typical development of shock structure with different inner jet pressure ratios.

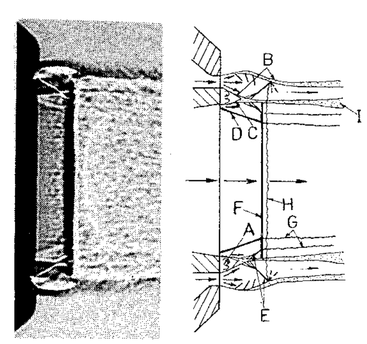

Fig. 7b Shock structure and flow details of interacting coaxial jet flows near nozzle exits: A) Cavity between inner and outer jet flows; B) outer jet boundary; C) inner jet boundary; D) oblique shock from inner nozzle; E) oblique shock due to deflection of interacting jet flows; F) strong shock; G) slip streams; and H) projection of annular shock wave in outer flow; I) mixing region between two jets. N.A. 1 (minimum noise). $\xi_o = 3.04$, $\xi_I = 2.43$.

†† The nature of the spectral characteristics of the emitted noise from the outer jet flow alone and from the combined jet flows, as shown in Fig. 6 did not change significantly when recently measurements were extended to frequencies up to 200 kHz.

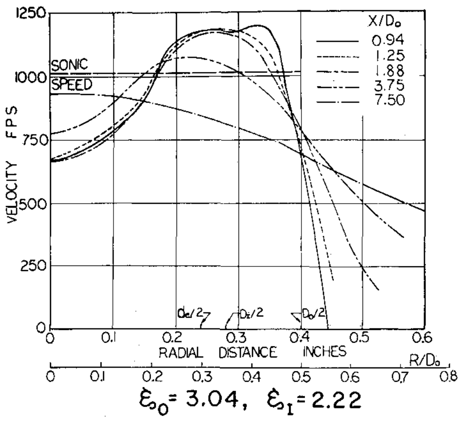

Fig. 8 Velocity profiles at various axial locations (minimum noise operation).

achieved when the inner nozzle flow is operated in the underexpanded mode in NA 3 (Fig. 7a) and NA 4 (see Table 2).

At all operating conditions of interacting coaxial jet flows where maximum noise reductions were achieved (Fig. 5), the parts of the inner and outer supersonic jet flows impinge at slightly oblique angles just downstream of the jet exits. The boundaries of the two jet flows therefore locally interact and the individual jet flows deflect, generating compression waves which coalesce to form additional shock waves, Fig. 7. The additional oblique shock in the outer annular supersonic jet flows extends to the sonic surface in the outer boundary of the jet flow and thus the jet flow Mach number (velocity) downstream of the oblique shock is reduced and the repetitive shock structure is practically eliminated. The additional oblique shock in the inner jet flow interacts with the reflected shock of the Mach disc in the inner jet flow. The interacting flows, different shock fronts and their interactions, and the influence of the small cavity between the inner and outer nozzles represent a rather complex flow system between the nozzle exit and the strong, almost normal shock front. Further analytical and experimental investigations are necessary to examine more thoroughly the details of this flow.

The outer jet boundary of the coaxial jet flows downstream of the composite shock structure seems to be fairly straight, indicating that the static pressure in this region is almost equal to the ambient pressure. The behavior of the outer jet boundary of the combined flows in this shock free region appears to be very similar to a properly expanded supersonic jet flow.

Velocity Profiles

Flow measurements which yield Mach number distributions and velocity profiles were made in an attempt to relate qualitatively the changes in the flowfield of coaxial interacting jets to the observed noise reduction. Typical velocity profiles at different X/D_o's for operating condition which yield maximum noise reduction using NA 3‡‡ are given in Fig. 8. It is noted that due to shear between the outer jet and ambient air, and at the interface between inner and outer jet flows, the velocity profiles smoothen out progressively with increasing value of X/D_o. At $X/D_o = 0.94$, slightly downstream of the strong shock system, the ratio between maximum outer jet velocity and inner jet velocity at the centerline is 1.8. With increasing X/D_o, the maximum velocity at every flow section reduces and shifts towards the center, while the velocity at the center increases; and eventually, the velocity profile becomes self-similar and assumes a fully developed state by $X/D_o = 7.5$. The sonic velocity is also indicated in Fig. 8. The maximum mean velocity of outer annular jet flow is supersonic from the nozzle exit to $X/D_o = 3.75$. However, the inner jet flow is subsonic at all flow cross sections downstream of the normal shock located at $X/D_o = 0.11$. For the outer jet alone, the maximum mean velocity is supersonic from the nozzle exit to $X/D_o = 4.0$.

The velocity gradients (or mean shear) corresponding to the velocity profiles given in Fig. 8, are presented in Fig. 9. The maximum mean shear occurs at two radial locations: 1) at the shear layer (the slipstream) emanating from the triple point of the inner Mach disc at $R/D_o = 0.2$, and 2) at the outer boundary of the outer annular jet at $R/D_o = 0.4$. The local maximum and minimum near $R/D_o = 0.37$ in the mean shear profile at $X/D_o = 0.94$ is caused by velocity deficiency in the interface shear layer between two jets.

The presence of a high mean shear region in turbulent flowfield is possibly an important source of noise.[10] Therefore, the observed gradual decay of the mean shear profile with increasing X/D_o's for the minimum noise operation (Fig. 9) would indicate the existence of an extended noise source. The near noise field survey conducted for NA 1 at minimum noise operation also supports this deduction. However, in order to compare the contributions of this extended shear region to radiated noise for different operating conditions of NA 3, the mean shear profiles for the annular jet alone operated at $\xi_o = 3.04$, $\xi_I = 1$ and interacting jets operated at $\xi_o = 3.04$, $\xi_I = 2.22$ (minimum noise), and $\xi_o = 3.04$, $\xi_I = 3.04$ are plotted for different X/D_o's (Figs. 10a and b). From comparative interpretation of the shear profiles in Figs. 9 and 10, the following deductions can be made: a) for $X/D_o = 0.94$, the maximum mean shear for the annular jet alone ($\xi_I = 1$) is higher than that for the interacting jet flows at minimum noise (Fig. 10a). However, the mixing at the inner boundary of the outer jet flow alone is very rapid and the velocity gradients smoothen out faster (see Fig. 10b for $X/D_o = 1.88$) than for interacting jet flows b) at all X/D_o's the maximum mean shear in interacting jet flows for operating conditions $\xi_o = 3.04$, $\xi_I = 3.04$ is appreciably higher than at the operating conditions $\xi_o = 3.04$, $\xi_I = 2.22$ (minimum noise).

The influence of a and b is reflected in the observed acoustic power radiated at different ξ_I's. The over-all acoustic power level from the outer annular jet alone ($\xi_o = 3.04$, $\xi_I = 1$) is about 6 db higher than for $\xi_o = 3.04$, $\xi_I = 2.22$ (minimum noise). Similarly the over-all power level for the interacting jets operated at $\xi_o = 3.04$, $\xi_I = 3.04$ is about 1.5 db higher than at the minimum noise operation. From the near noise field measurements conducted with NA 1, it has been de-

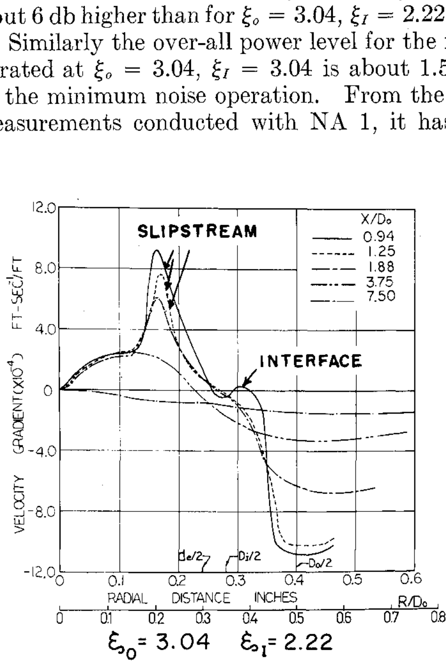

Fig. 9 Velocity gradients at various axial locations (minimum noise operation).

‡‡ The outer diameter of annular nozzle in NA 3 is larger than that in NA 1. Therefore experimental velocity profiles for NA 3 are used instead, as these are likely to be more accurate than those for NA 1. Both velocity profiles of the NA 1 and 3 essentially exhibit the same characteristics. However, for NA 3 the minimum noise condition was obtained at $\xi_o = 3.04$ and $\xi_I = 2.22$.

duced that the acoustic power contribution from the over-all mixing region for the minimum noise operation is considerably lower than the corresponding contribution from the outer annular jet flow alone (see Table 3) even when the extent of the mixing region for the minimum noise operation is comparatively larger than that for the outer jet alone.

Near Noise Field Survey

Sound pressure measurements were conducted in the near noise field for NA 1 with outer jet operated at $\xi_o = 3.04$ and inner jet operated at selected operating pressure ratios. To determine the boundary of the measurements both the shadowgraphs and Pitot pressure distribution near the outer boundary of the coaxial jets were used. The half-angle of spread of coaxial jets was found to be approximately 9°. It was established that the speudo-sound contribution to the measured sound pressure was negligible.[9] To further ensure that the near sound field measurement would not be affected by the intermittency of the coaxial jet boundary, a 10° boundary for sound pressure measurement was used from $X/D_o = 0$ to 8. For $X/D_o > 8$, boundary of measurement was selected to be 15°. In all the measurements the microphone axis was oriented perpendicular to the centerline of the coaxial jet flows.

The near field contours of over-all sound pressure level for the euter jet operated at $\xi_o = 3.04$ and the inner jet operated at $\xi_I = 1$ and 2.43 are given in Fig. 11a (for $\xi_I = 2.22$ see Ref. 9). With the exception of $\xi_I = 2.43$ (minimum noise), strong source of acoustic emissions are concentrated in the region where the repetitive shock structure is present in the

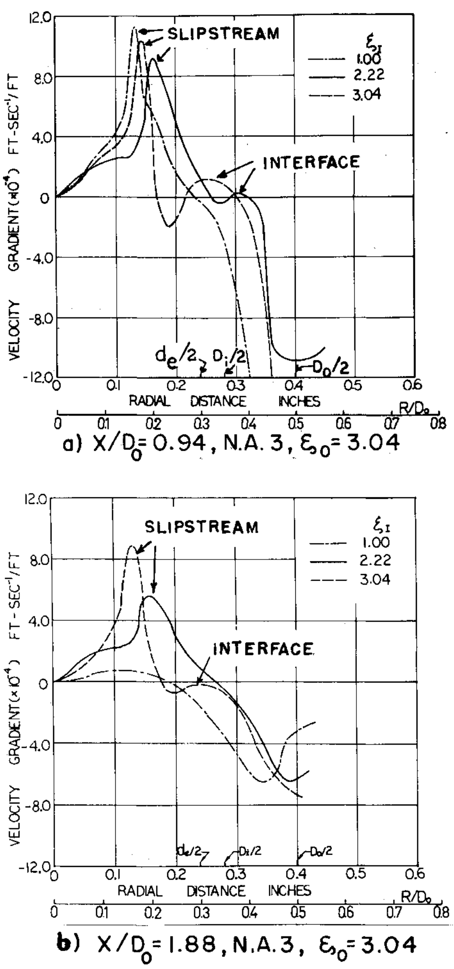

Fig. 10 Variation of velocity gradients with inner jet pressure ratio.

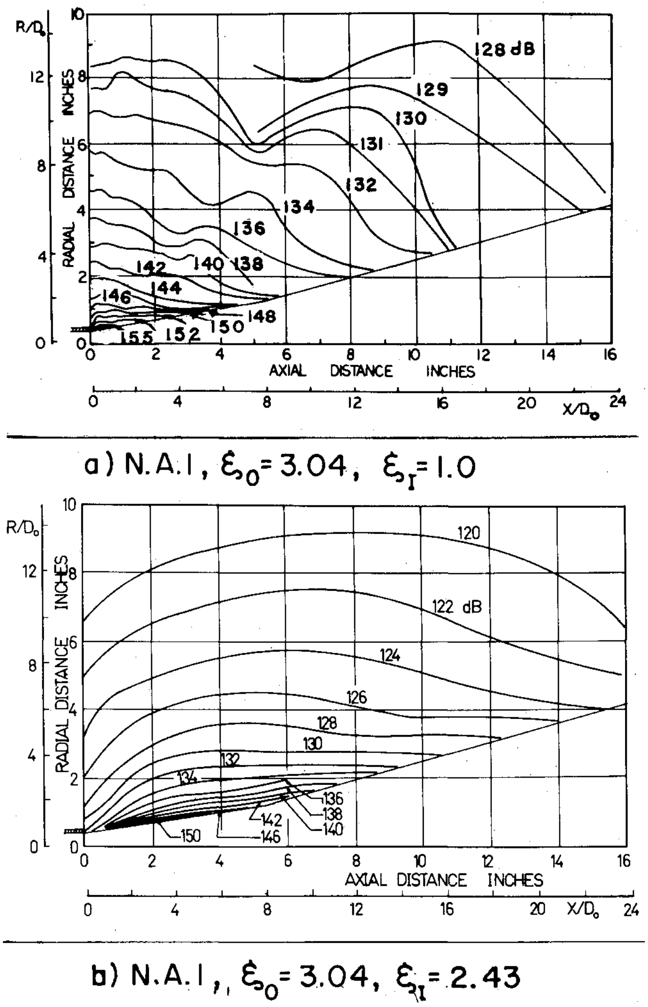

Fig. 11 Nearfield contour of over-all sound pressure level.

coaxial jet flows. The corresponding peak sound pressure level is about 164 db.

At an outer jet operating pressure ratio $\xi_o = 3.04$ and an inner jet operating pressure ratio $\xi_I = 2.43$ where the maximum noise reduction was observed, the contours of sound pressure in the near field exhibit a considerably modified pattern, (Fig. 11b). The sound field is generated mainly by an extended source region located downstream of the exit between $X/D_o = 1$ to 6.2. Its peak sound pressure level is about 150 *db*. The corresponding shadowgraphic data (Fig. 7b) reveal that, in the combined jet flows, the relative locations of the single annular shock in the outer flow and the strong shock in the inner flow are almost coplanar at $X/D_o = 0.16$. It indicates that the strong sources associated with repetitive shock region of the flows which were observed for $\xi_I = 1$ and 2.22, respectively, were replaced by an extended but reduced strength source region downstream of the strong shock system.

Acoustical power emission from different characteristic flow regions (shown in Fig. 12) of coaxial interacting jet flows operated at different conditions were calculated and the results are shown in Fig. 13, where the differential acoustic powers emitted at different downstream distances are plotted. For $\xi_o = 3.04$ and $\xi_I = 1$ or 2.22, the major sound producing regions are limited to $X/D_o \approx 3.0$ where the flow is supersonic and contains repetitive shock structure. For $\xi_o = 3.04$ and $\xi_I = 2.43$ at which maximum noise reduction is observed, it is seen that the major part of the over-all sound power is generated from the flow region extending from $X/D_o = 1.75$ to $X/D_o = 7.5$. It is important to point out that the flow region of the combined jets extending from the nozzle exits

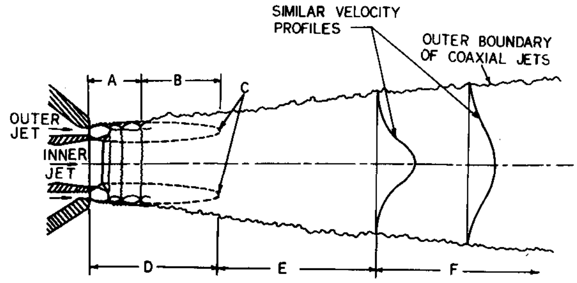

Fig. 12 Illustration of typical flow regions in coaxial supersonic jet flows: A) supersonic mixing region with shock structure; B) supersonic mixing region without shock structure; C) sonic boundary; D) supersonic mixing region; E) subsonic mixing region; and F) fully developed-turbulent region.

to one diameter downstream, in which a nonrepetitive composite strong shock system exists, contributes only a negligible amount to the total acoustic power.

The relative contributions from different characteristic flow regions to the over-all acoustic power emitted at three operating conditions of coaxial jet flows were deduced. This was done by integrating the measured sound pressure data along the coaxial jet boundary over the pertinent surface area of different flow regions. For details see Ref. 6. Important findings are summarized in Table 3. It is seen that the interaction between the inner and outer jet flows results in variations in percentage power distribution from different parts of the jet flows. These results indicate that: 1) shock waves in supersonic jet flows are responsible for a substantial portion of over-all noise which can be reduced and made relatively insignificant if shock locations, their spacings and strengths are suitable altered by jet flow interaction. 2) The noise contribution from supersonic mixing is reduced; however a relative increase in noise emitted by the subsonic mixing region is observed with the result that the over-all relative contributions from mixing is increased. 3) The emitted power from fully developed turbulent region remains the same for all operating conditions used and is somewhat lower than the 20% contribution commonly predicted by subsonic jet noise theory. For $\xi_I = 2.43$, the relative contribution from jet mixing is 90% and the possible shock contribution amounts to only less than one percent. However, it is interesting to note that on an absolute basis, the 90% contribution from an extended mixing region is still much lower than the corresponding contribution from shorter mixing regions for $\xi_I = 1$ or 2.22. These observations lead to the conclusions that by proper interaction between two supersonic jet flows, 1) shock related noise generating mechanisms are greatly suppressed, and 2) the absolute contributions from the mixing regions are reduced.

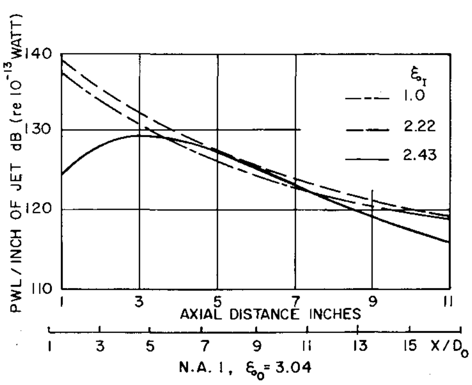

Fig. 13 Distribution of power emitted per unit length of interacting coaxial jet flows.

Table 3 Percent contributions of acoustic power emitted from prominent flow regions, ξ_o = 3.04 (NA 1)

Flow regions ξ_I	1	2.22	2.43
Supersonic mixing region with shock structure	37%	29%	<1%
Supersonic mixing region without shock structure	53%	47%	30%
Supersonic mixing region	62.5%	61%	30%
Subsonic mixing region	[a]	13%	60%
Over-all mixing region[b]	62.5%	74%	90%
Fully developed turbulent region[c]	10%	11%	9%
Total power emitted (w and db re 10^{-13}w)	11.5 w (140.6 db)	16.6 w (142.2 db)	3.5 w (135.4 db)

[a] For $\xi_I = 1$, mean velocity similarity was established at about the same location where the flow becomes subsonic; hence the extent of subsonic mixing region could not be determined.
[b] Defined as the region from nozzle exit to the location where the velocity distributions of the interacted flows become similar.
[c] Defined as the region in which the velocity distributions of the interacted flows are similar.

Thrust Considerations

The evaluation of the acoustical performance and the noise reductions achieved for each of the coaxial nozzle arrangements has been based on the comparison of the performance of the individual coaxial nozzle arrangement with that of the corresponding outer nozzle alone. This amounts to discounting the thrust produced by the inner jet flow alone. Since the inner jet flow is thrust producing and, for any successful jet noise abatement technique, the aim is to achieve maximum noise reduction at minimum possible thrust loss, it is more realistic to assess the acoustical performance of various nozzle arrangements based on thrust considerations. For this purpose the total radiated acoustic power/A_e (based on experimental data) and the total calculated thrust/A_e (based on one-dimensional flow assumption) produced by each coaxial nozzle arrangement were calculated at different operating conditions, where A_e is the total exit area of coaxial nozzles (if a single jet is used, A_e is the exit area of the single nozzle). Typical results for each of the five coaxial nozzle arrangements are given in Fig. 14. In the absence of well established reference standards, experimental noise data gathered with a single convergent (choked) jet were used for comparison.

It is noted that for nozzle arrangements 1 and 2, where substantial noise reductions (see Table 2) were obtained relative to the noise from the corresponding annular outer jet flows alone, an average reduction of only 5 db was obtained when compared with the performance of a single convergent nozzle based on the thrust criterion. On the other hand, for arrangements 3 and 4 the corresponding reductions on thrust basis are about 8 db while the direct comparison with the outer annular jet alone yielded lower levels (about 4 db) of noise re-

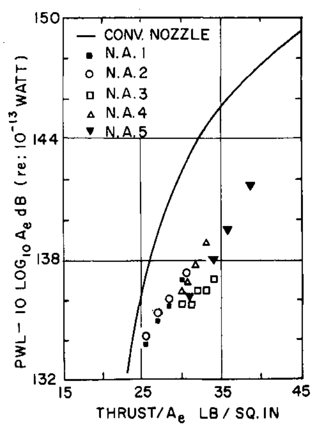

Fig. 14 Total acoustic power per unit area vs theoretical thrust per unit area.

duction. This behavior of the noise reductions deduced on thrust basis is understandable, when it is considered that in arrangements 1 and 2 the inner nozzle is operated in the over-expanded mode where the pressure term contributes negative thrust, thus reducing the total thrust of the combined jets. In NA 3, the relative effect of this negative thrust term is reduced because the outer annular nozzle exit area is comparatively larger. In NA 4 and NA 5 inner nozzles are convergent and underexpanded, and the negative thrust term is not involved.

Conclusions

It has been shown that interaction between two properly controlled coaxial supersonic jet flows results in substantial noise reduction. Furthermore, the observed noise reductions are well correlated with the appearance of a single characteristic composite shock structure in the combined coaxial jet flows just downstream of the nozzle exit plane. This results in the elimination of the repetitive shock pattern, usually present in high-speed jet flows, and modifications of mixing in the downstream flows. The present experimental findings indicate that the occurrence of the characteristic shock structure in the coaxial interacting jet flows, and hence the amount of noise reduction, depends strongly on the operating pressure ratios of both the inner and outer jets, their respective Mach numbers, half-angle divergence and exit area ratios. In order to predict the acoustic performance of the interacting coaxial jet flows and to assess their practicality for noise abatement, systematic investigations on the role of each of these parameters are indicated.

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