78-241

Acoustic and Flow Characteristics of Cold High-Speed Coaxial Jets

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Far-field noise of model coaxial supersonic cold jets exhausting from a coplanar convergent two-nozzle coaxial configuraton was investigated. The pressure ratio (velocity) of the outer annular jet was maintained higher than the inner round jet. For each outer-jet pressure ratio, the inner-jet operating pressure ratio for the "minimum" radiated noise was established. Experimental results on the noise reductions and the modifications of the shock structure and velocity distribution of coaxial jet flows at the "minimum" noise conditions are presented and are compared with those of a single convergent underexpanded round and annual jet at a wide range of operating pressure ratios.

Nomenclature

a = speed of sound, ft/s
A = area, in.^{2}
C = constant
D = nozzle diameter, in.
D_{i1}, D_{i2}, D_{o1}, D_{o2} = refer to Fig. 1
f = noise frequency, Hz
ℓ = characteristic length
M = ratio of flow velocity to local speed of sound (flow Mach number)
m = mass flow rate, lbm/s
OAPWL = overall acoustic power level, dB, re 10^{-13} W
OASPL = overall sound pressure level, dB, re 2×10^{-4} μbar
P_a = ambient pressure, psia
P_R = reservoir pressure, psig
PWL = acoustic power level, dB, re 10^{-13} W
S = shock cell length, in.
SPL = sound pressure level, dB, re 2×10^{-4} μbar
St Strouhal number
T = thrust, lbf
t = lip thickness, in.
T_R = reservoir temperature, °R
U = calculated jet velocity based upon the calculated thurst per mass flow rate, ft/s
V = jet flow mean velocity, ft/s
W = acoustic power, W
w = width of annular jet, in.
X = distance downstream of the nozzle exit, in.
Y = radial distance, in.
ρ = density, lbm/ft^3
ω = density exponent
ξ = pressure ratio, i.e., reservoir absolute pressure/ambient pressure
θ = angle between the direction of sound emission and the axis in the downstream direction, deg
ϕ = jet spread angle, deg
ψ = pointed needle cone angle, deg

Subscripts

ISA = International Standard Atmospheric conditions
m = mean
e = exit conditions
1 = inner nozzle parameter
2 = outer nozzle parameter
t = total flow condition
0 = ambient condition
j = fully expanded jet conditions
th = nozzle throat
ref = reference

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I. Introduction

FROM an operational standpoint, noise is one of the biggest stumbling blocks in the development and use of high-speed jet aircraft for civilian transportation. The use of coaxial multinozzle exhaust configurations appears promising as an effective supersonic noise abatement approach. The supersonic jet noise reductions achieved earlier by the use of such coaxial high-speed cold jets issuing from an inner (round) and outer (annular) nozzle, where the annular nozzle was operated at a higher pressure ratio (therefore at a higher flow velocity) than that of the round jet, were reported.[1-4]

The interaction of such coaxial coflowing jet flows downstream of the exits of the component round and annular nozzles results in striking flow modifications and significant noise reductions. In the combined coaxial jet flows, the cellular shock structure of the individual annular and round supersonic jets essentially is modified to a "composite" shock structure[1,4] located just downstream of the nozzle exit $X/D_{i2} \doteq 0.16$. Such coaxial supersonic jet flows operated at the minimum noise condition are observed to become sonic much closer to the nozzle exit than is normally the case in a single underexpanded free round jet of equal exit area and specific thrust.[4,5] Such coaxial jet studies have been extended to where the outer (annular) jet was heated.[6,7]

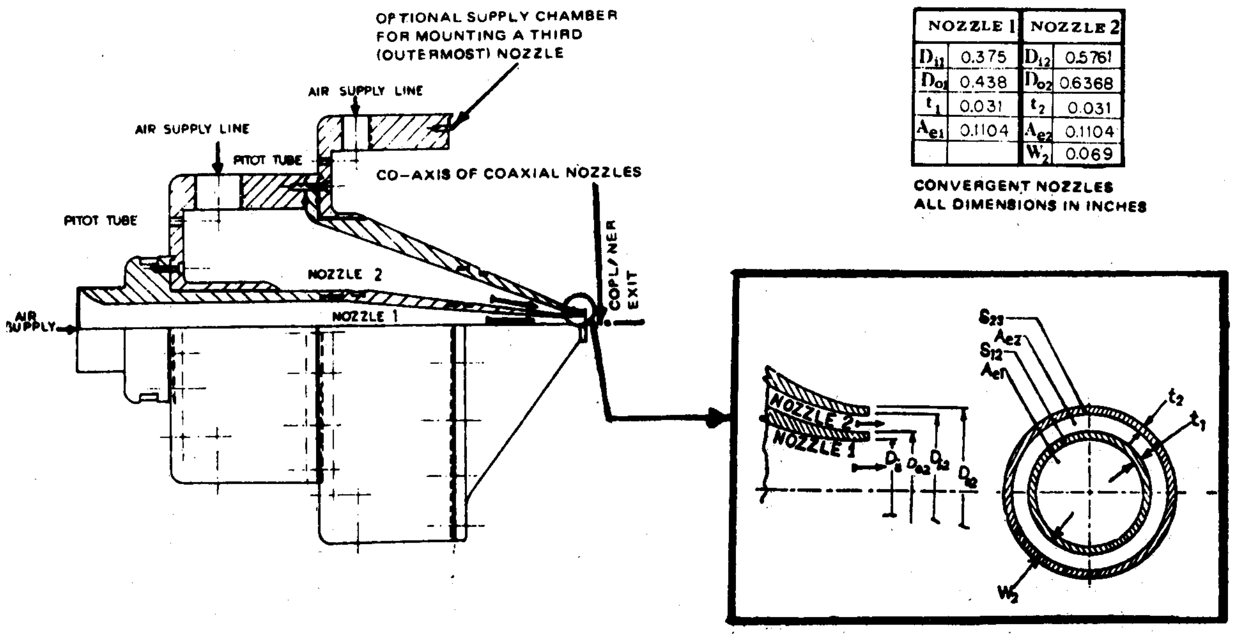


Fig. 1 Two-nozzle coaxial configuration and specifications.

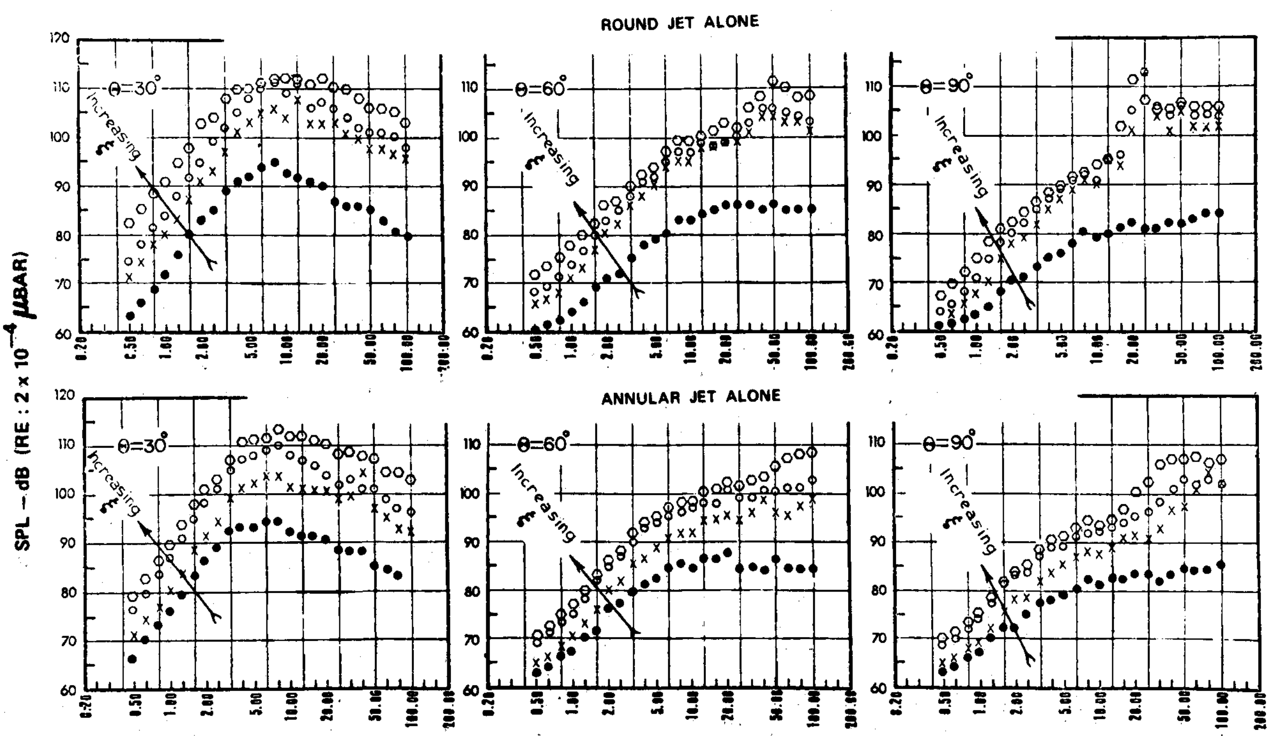


Fig. 2 Variation of ⅓-octave SPL spectra at $\theta = 30$, 60, and 90 deg with the operating pressure ratio ξ for convergent single round jet (nozzle 1) and single annular jet (nozzle 2), each having the same exit area (•:$\xi = 2.02$; ×:$\xi = 3.04$; o:$\xi = 3.88$; ⬡:$\xi = 5.12$; $T_{R1} = T_{R2} = 530°$R).

Recently, the use of coaxial jets as a noise suppression approach has been explored by both Pratt and Whitney Aircraft[8] and General Electric Company[9] for its possible adoption in the exhaust systems of the proposed duct-burning turbofan engine and the advanced supersonic variable-cycle supersonic turbojet engine. At NASA Lewis Research Center,[10] parallel aeroacoustic studies of model coannular nozzles suitable for supersonic cruise aircraft applications also have been conducted. In all of these studies with heated flows, substantial noise reductions have also been reported, and noise reductions from coaxial jets with inverted operating conditions when one or both jets are heated are similar in nature to those from cold coaxial jets.

In previous studies with cold coaxial jets,[2,3] the operating pressure ratio of the annular jet was fixed at $\xi_2 = 3.04$ because the then-proposed turbojet engine for the supersonic transport was designed around this operating pressure ratio. However, in view of the promise of coaxial interacting supersonic jet flows as a potential noise abatement approach, it was of interest to establish whether or not the observed noise reductions from coaxial supersonic jets occur at other operating pressure ratios of the annular jet as well. Moreover, the correspondence between the radiated noise from individual as well as coflowing coaxial jets and the changes in their respective flows needed to be examined. It is to accomplish both of these objectives that a systematic and detailed survey of the far-field noise and flow studies (shock structure and its modifications, Mach number distribution, and general mean flow behavior and changes) of the coaxial jets were performed at a wide range of operating conditions.[5]

II. Experimental Facilities and Test Procedures

A. Two-Nozzle Arrangement and Controls

The configuration of the coaxial nozzles used in these experiments and their pertinent dimensions are shown in Fig. 1. Both nozzles are convergent with finite but thin-lip thickness, coplanar exits, and equal exit areas. The compressed air system and controls are described in Ref. 5. It suffices to add that both coaxial coflowing jets could be operated continuously, and the operating reservoir pressure of each could be controlled independently.

B. Acquisition of Acoustic Data

One-third-octave sound pressure levels of the far-field noise of coaxial jets were recorded in an anechoic chamber (size approximately 10 × 13 × 9 ft) at eight azimuthal positions 15 deg apart, from 15 to 120 deg on an arc of 6-ft radius. The acoustic data were analyzed in ⅓-octave bands of 200 Hz-100 kHz. These data then were corrected for microphone pressure response, the free-field effects, and the atmospheric absorption.[11] OASPL's, ⅓-octave PWL's, and OAPWL's were calculated from the corrected ⅓-octave SPL data. In order to insure the absence of unwanted upstream noise sources and the accuracy of the subsequent jet noise measurements, validation tests were conducted in the facility, and the dominance of jet mixing noise was demonstrated.[5]

C. Optical and Flow Measurements

A pointed needle (cone angle $\omega = 4$ deg) was traversed through the coaxial flows operated at the minimum noise condition ($\xi_1 = 2.02$ and $\xi_2 = 3.04$), and extensive shadowgraphs of the coaxial jet flows were recorded at different radial and axial positions of the pointed needle. From the presence or the absence of the attached conical shock, it was possible to determine if the local flow was supersonic (oblique shock attached to the needle) or subsonic (no shock). Total pressure survey with a pitot tube was also conducted. The physical dimensions of the pitot tube were o.d. = 0.02 in., and i.d. = 0.01 in. For further details see Ref. 5.

III. Acoustic and Flow Characteristics of the Individual Component (Round and Annular) Jets of the Coaxial Nozzle Configuration

In order to understand the changes that occurred in the coaxial jet flows and therefore in the noise generated by such flows, it is helpful to study both the flows and the noise fields of the individually operated single (component) round and annular jets.

A. Acoustic Characteristics

Comparisons of ⅓-octave SPL spectra, at different azimuth angles ($\theta = 30$, 60, and 90 deg), for a convergent round jet (nozzle 1) and an annular jet (nozzle 2) for different operating pressure ratios ($\xi = 2.02$, 3.04, 3.88, and 5.12) are presented in Fig. 2. At the same location or angle, a gradual change in the spectral shape occurs with increasing operating pressure ratio (Fig. 2).

The spectral behavior of round and annular jets is compared at the same ξ and θ in Figs. 3 and 4. The low-frequency noise levels of the single annular and round jets are identical at pressure ratios of $\xi = 3.04$, 3.88, and 5.12. However, at a pressure ratio of $\xi = 2.02$, the low-frequency noise levels of the annular jet are somewhat higher. Since at a given downstream location the diameter of the annular flow operated at this pressure ratio is observed[5] to be larger than that of the round jet, and since the low-frequency noise emanates from flows farther downstream of the nozzle exit, the noise levels at low frequencies are likely to be higher.

The contribution to the high-frequency noise radiation is dominated by acoustic sources in flows closer to the nozzle exit. In both annular and round underexpanded cold jet flows, the shock-associated noise increases with the increasing azimuthal angle. It is particularly evident in the sideline spectra, i.e., at $\theta = 90$ deg. The fundamental shock or screech tone frequency[12] f_M in jet noise spectra is proportional to $a_0/\ell\sqrt{\xi - 1.89}$ for $\xi > 1.89$. The jet diameter for a round jet and annular nozzle width W for an annular jet are taken to be the characteristic length ℓ of the respective jet flows. At the same operating conditions, the following relations were reasonably valid for the present study, as well as other experiments[6,13]: f_M (round jet) α $1/D$, and f_M (annular jet) α $1/W$.

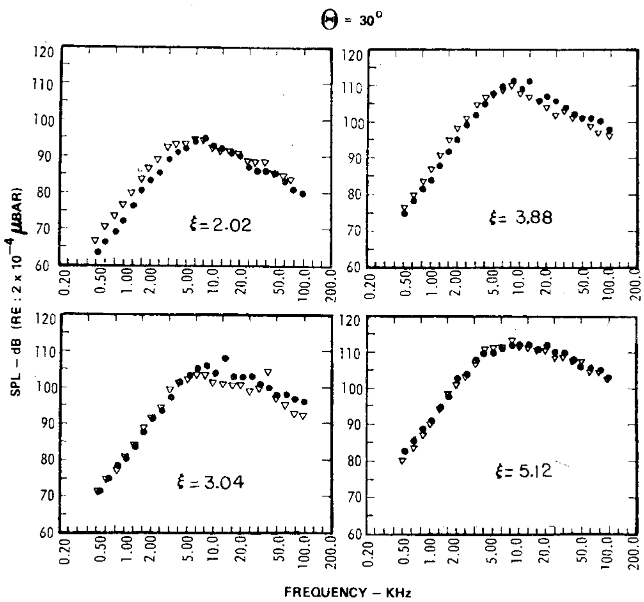


Fig. 3 Comparison of ⅓-octave SPL spectra at $\theta = 30$ deg for convergent round jet (nozzle 1) and annular jet (nozzle 2), each having the same exit area ($\xi = 2.02$, 3.04, 3.88, and 5.12; •: round nozzle; ∇: annular nozzle; $T_{R1} = T_{R2} = 530°$R).

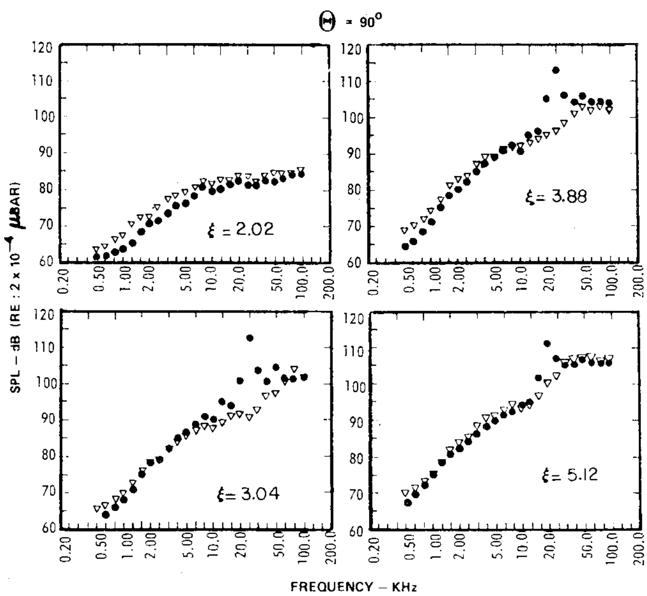
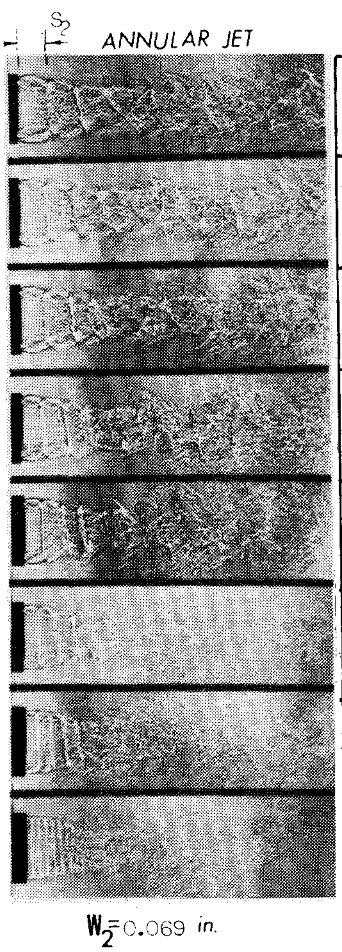


Fig. 4 Comparison of ⅓-octave SPL spectra at $\theta = 90$ deg for convergent round jet (nozzle 1) and annular jet (nozzle 2), each having the same exit area ($\xi = 2.02$, 3.04, 3.88 and 5.12; •: round nozzle; ∇: annular nozzle; $T_{R1} = T_{R2} = 530°$R).

In general, the annular jet generates lower noise levels over the entire frequency range covered here than those of the round jet at different θ and ξ (except for $\xi = 2.02$ at $\theta = 90$ deg). This observation is illustrated clearly from the spectral data (⅓-octave SPL) presented in Figs. 3 and 4. Because of the small width of the annular nozzle, the high-frequency components in the acoustic spectra (due to high-speed flows, narrow shear layers, and small shock cell size) are dominant, especially at $\theta = 90$ deg, and also somewhat at $\theta = 60$ deg in Fig. 2. At other locations ($\theta = 15$, 30, 45, 105, and 120 deg), dominant narrow-band peaks were not recorded[5] (also see Fig. 3). The OAPWL was calculated by integrating the sound levels at these eight azimuthal locations. The main contributors[5] to the OAPWL were the levels at $\theta = 30$ and 45 deg. Therefore, the fraction of the acoustic energy at higher frequencies (>100 kHz) of $\theta = 60$ and 90 deg, not considered in calculating the OAPWL, was negligible. Moreover, from earlier studies[14] with similar-model coaxial nozzles where spectral data up to the 200-kHz band were recorded, the sound levels in the frequency range of 100 to 200 kHz decreased rapidly with frequency at all locations.

B. Flow Characteristics of Single Round and Annular Jets

The effect of the reservoir operating pressure ratios ξ on the shock structure and the spreading of the annular jet flows can be seen in the typical set of spark shadowgraphs presented in Fig. 5. Corresponding to this operating pressure range of $\xi = 2$ to 5.12, the variation of the nondimensionalized length of the primary shock cell S/W_2 with ξ is plotted in Fig. 6. The variation of S/W_2 vs ξ for the annular underexpanded jet ($W_2 = 0.069$ in.) is a faired straight line.



	P_R psig	ξ_2	U ft/sec
a	60	5.12	1500
b	54	4.7	1470
c	48	4.29	1440
d	42	3.88	1405
e	36	3.465	1365
f	30	3.04	1310
g	24	2.625	1240
h	15	2.02	1070

Fig. 5 Shadowgraphs showing shock structure of single annular convergent jets at different reservoir pressure ratios.

The nature and the behavior of single annular underexpanded jet flows are discussed in Ref. 4 and 5. Because of high shear, with the ambient air mixing and spreading of the annular jet, and because of the smaller W_2 and larger flow circumference, it decays to sonic speeds faster than a round jet of equivalent exit area and operating conditions. Therefore, the annular jet is less noisy than an equivalent round jet, as discussed earlier.

When an annular nozzle is operated alone, a dead-air region exists downstream of the inner round nozzle. The effect of this region in the fluid mechanics and noise radiation was not investigated in the present study. However, since the addition of a low-velocity inner jet flow reduces the noise from the annular jet, it is reasonable to assume that the radiated noise from the annular jet is higher than it would be if the dead-air region were not there.

IV. Coaxial Jets from Two-Nozzle Configurations

A. Selection of Minimum Noise Conditions

For two-nozzle coaxial jets of a given geometry and configuration, it has been shown consistently by Dosanjh et al.[1,2,4,7] that, for a fixed outer reservoir pressure ratio ξ_2, if the inner jet pressure ratio ξ_1 is varied in controlled steps, the OAPWL's decrease with increasing ξ_1 attaining a minimum value. This is called the "minimum-noise" condition for the given coaxial nozzle configuration operated at a fixed ξ_2. For the same ξ_2 but higher ξ_1, the OAPWL's increase. Since ξ_1 is varied with ξ_2 fixed such that $\xi_2 > \xi_1$, the total thrust from coaxial jets also varies. Therefore, in assessing the noise performance of coaxial jets, the total thrust also should be considered, and the selection of the operating conditions for minimum-noise mode of operation should be based upon the consideration of the acoustic efficiency, where[5]

$$\log_{10}\eta = \frac{\text{OAPWL(dB)}}{10} - \log_{10}\frac{T^2_{\text{total}}}{\dot{m}_{\text{total}}} + \text{const}$$

The acoustic efficiency relation takes into account both the thrust and the mass flow rate. The efficiency $\log\eta$ vs ξ_1 plot given in Fig. 7 exhibits a minimum in radiated noise. Therefore, based on these results, for a fixed ξ_2, combination sets of the operating pressures ratios (ξ_1, ξ_2) for the minimum-noise mode of a given nozzle configuration can be derived experimentally for a wide range of ξ_2.

It also is observed that, for each of the annular jet operating pressure ratios ξ_2, the minimum condition persists within less than 1 dB for a small range of inner-jet operating pressures ratios ξ_1. The nearly minimum noise conditions are as follows: 1) with $\xi_2 = 3.04$, they are attained with operating pressure ratios of $\xi_1 = 1.82$, 2.02, and 2.22; and 2) with

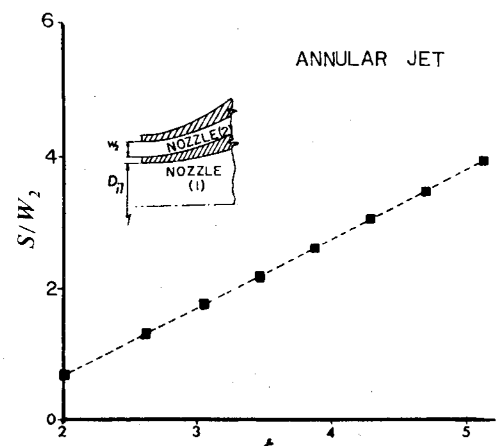


Fig. 6 Variation of the nondimensionalized primary shock cell length of an annular jet from a convergent annular nozzle with operating pressure ratio.

$\xi_2 = 3.88$, they are attained with ratios of $\xi_I = 2.02$, 2.22, and 2.42. Therefore, for the nozzle configuration used here (Fig. 1), the pressure ratio of the inner jet ξ_I needed for the minimum noise condition tends to shift slightly to higher values with higher ξ_2.

B. Prediction of OAPWL of Coaxial Supersonic Jets at Minimum-Noise Mode of Operation and Its Comparison with Single Jet Data

In the combined coaxial jet flows at the minimum noise condition, primarily the shock structure is confined to just downstream of the nozzle exit, beyond which only weak shock fronts are evident. Moreover, the outer boundary of coaxial flow downstream of this composite shock structure is straight, and therefore it is reminiscent of a fully expanded single jet flow.[5] Therefore, one reasonably may assume, for predicting, that the noise radiated from coaxial flows at their minimum-noise mode of operation may be considered similar to that from a single nearly fully expanded jet flow. Therefore, the normalization of the overall acoustic power levels (OAPWL's) from coaxial jets operated at minimum noise conditions may be attempted on the basis of Lighthill's relation for radiated acoustic power.[15] Also, using the Hoch et al.[16] modification for the density term $(\rho_j/\rho_{ISA})^{\omega}$, where the value of ω is defined experimentally as a varying function of V_j/a_o, the normalized sound power level can be written as

$$\mathrm{PWL} - \log_{10}\left[A_j\left(\frac{\rho_j}{\rho_{ISA}}\right)^{\omega}\left(\frac{a_o}{a_{ISA}}\right)^{3}\left(\frac{\rho_{ISA}}{\rho_o}\right)\right] = 10\log_{10}\left(\frac{V_J}{a_o}\right)^{8} + \text{const}$$

Since coaxial supersonic cold convergent jets are operated such that $\xi_2 > \xi_I$, the effective velocity $(U_2 = T_2/\dot{m}_2)$ of the outer jet was used to compare the normalized noise levels for the coaxial jets operated at the minimum noise conditions. For a discussion of various possible options for representative U and ρ and the use of this assumption, see Ref. 4 and 5.

The normalized OAPWL's against log U/a_o, where $U = U_2$ and $\rho_j = \rho_{j2}$, are presented in Fig. 8, and the following conclusions can be drawn:

1) OAPWL's calculated from the acoustic data acquired in the present studies of single convergent round underexpanded jets are in good agreement with other similar studies.[17]

2) An annular jet is less noisy (5 dB, where $\xi = 3.04$) than the round jet, but both the annular and round jets are noisier than an equivalent fully expanded round jet.

3) Coaxial interacting supersonic jets produce substantially less noise than baseline noise radiated by a single convergent supersonic jet of equal exit area operated at a reservoir pressure ratio equal to that of the outer annular jet of the coaxial two-nozzle arrangement at minimum noise condition. The maximum reduction is observed to be approximately 12.5 dB with respect to the single round convergent jet and approximately 7.5 dB if comparison is made with respect to the single outer annular jet.

4) Moreover, such coaxial jets at this minimum noise mode at various ξ_2 radiate less noise than the corresponding equivalent fully expanded jet.[18] (The maximum difference of approximately 4 dB occurred at $\xi_2 = 3.65$.)

5) The minimum noise condition data for $\xi_2 = 2.62$ to 5.10 may be represented by the dotted lines a and b of different slopes. Line a ranges from $\xi_2 = 2.6$ to 3.5, whereas line b ranges from $\xi_2 = 3.5$ to 5.2.

V. Flowfield of Coaxial Jets Operated at Minimum Noise Conditions

The flowfield and shock structure of coaxial jets from the two-nozzle configuration (Fig. 1), which is operated at the minimum noise conditions, are illustrated in Fig. 9. For further details, see Refs. 4 and 5. On the basis of the shadowgraphic observations of traversing a pointed needle through coaxial jets at minimum noise conditions ($\xi_I = 2.02$, $\xi_2 = 3.04$), the subsonic flow downstream of the composite

FOR COAXIAL JET AT MINIMUM NOISE CONDITIONS

ξ_2	U_2 ft/sec.	ξ_1	U_1 ft/sec.	$(U_2/U_1)_{min.}$
□ 2.625	1240	2.02	1070	1.16
X 3.045	1310	2.02	1070	1.22
■ 3.465	1365	2.02	1070	1.28
○ 3.88	1405	2.02	1070	1.31
▲ 4.29	1440	2.22	1140	1.26
○ 5.12	1500	2.42	1190	1.26

$T_{R1} = T_{R2} \doteq 530\ ^{\circ}K$

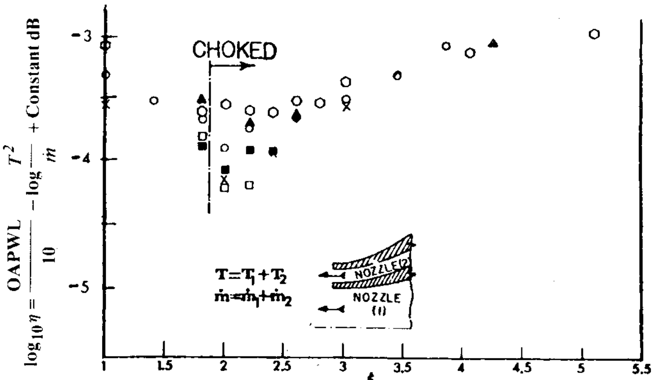
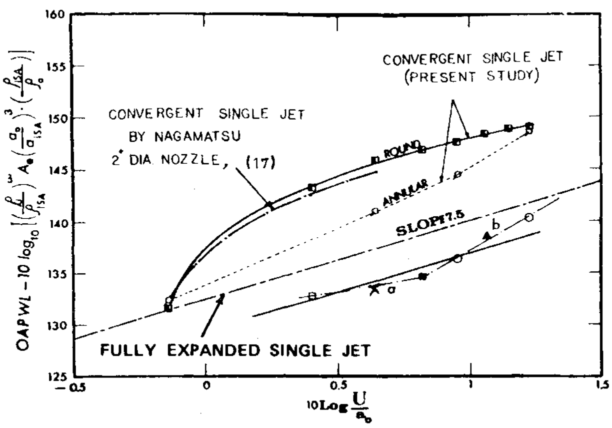


Fig. 7 Variation of acoustic efficiency with inner jet pressure ratio ξ_I from two-nozzle coaxial configuration.



FOR COAXIAL JETS : $U = U_2$

FOR COAXIAL JET AT MINIMUM NOISE CONDITIONS

ξ_2	U_2 ft/sec.	ξ_1	U_1 ft/sec.	$(U_2/U_1)_{min.}$
□ 2.625	1240	2.02	1070	1.16
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○ 5.12	1500	2.42	1190	1.26

$T_{R1} = T_{R2} \doteq 530\ ^{\circ}K$

Fig. 8 Variation of normalized OAPWL with normalized jet velocity.

shock along the central axis of the coaxial jets becomes supersonic at approximately $X/D_{i2}=3$, and the entire flow becomes subsonic at approximately $X/D_{i2}=8$ (note that $D_{i2}/W_2=8.35$). The locations of these two sonic points along the jet flow central axis are observed to be dependent upon the relative pressure ratios ξ_2 and the corresponding ξ_I at which the minimum noise condition is observed.

VI. Velocity Profiles and Mach Number Distribution of Coaxial Jet Flows

The mean velocity profiles and Mach number distributions of the coaxial jet flows were investigated 1) to obtain a better understanding of the interaction of coaxial jet flows and the favorable flow modifications and their correspondence with the resulting substantial noise reductions; and 2) to check the validity of the proposed semiempirical schemes for predicting noise from coaxial jets at their minimum noise conditions, as discussed earlier, where the normalized calculated specific thrust or flow velocities were used as representative of the combined coaxial jet flows.

Pitot pressure surveys of the combined coaxial jet flows operated at the minimum-noise mode of operation ($\xi_I=2.02$ and $\xi_2=3.04$) were conducted. Total pressure data were recorded at different axial and radial locations downstream of the nozzle exits. Downstream of the normal shock stem located at the central region of the inner flow (see Fig. 9), the static pressure was calculated from the normal shock relations. Linear interpolation or extrapolation of the variation of the static pressure with distance was used to calculate the static pressure at locations where such data were not recorded. The reservoir temperatures of the inner and outer jet flows were nearly equal to the ambient temperature. With these assumptions, the local static temperatures, flow Mach numbers, and velocities were calculated. Details of the methods of calculations and assumptions used are available in Ref. 5.

The velocity profiles and Mach number distributions at different axial locations of $X/D_{i2}=0.408$, 4, and 8 ($X/W_2=3.4$, 33.5, and 67, respectively) for the minimum noise condition ($\xi_I=2.02$ and $\xi_2=3.04$) are given in Fig. 10. It is worthwhile to notice that the maximum outer-jet velocity

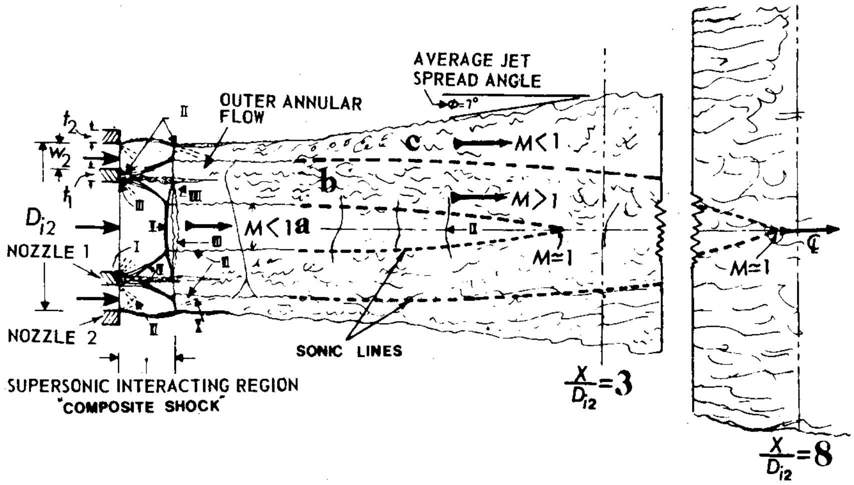

Fig. 9 Illustration of shock structure and flow details of two coaxial jet flows at minimum noise condition (both nozzles convergent). I Base region between inner and outer jets, II Outer jet boundaries, III Inner jet boundaries, IV Oblique shocks due to turning of interacting flows, V Normal shock front in the inner flow, VI Slip streams, VII Projection of annular oblique shocks fronts of IV, VIII Mixing interface between two jets, IX Projection of weak shocks in the supersonic flow region, X Expansion waves in annular jet, XI Prandtl-Meyer expansion (P.M.).

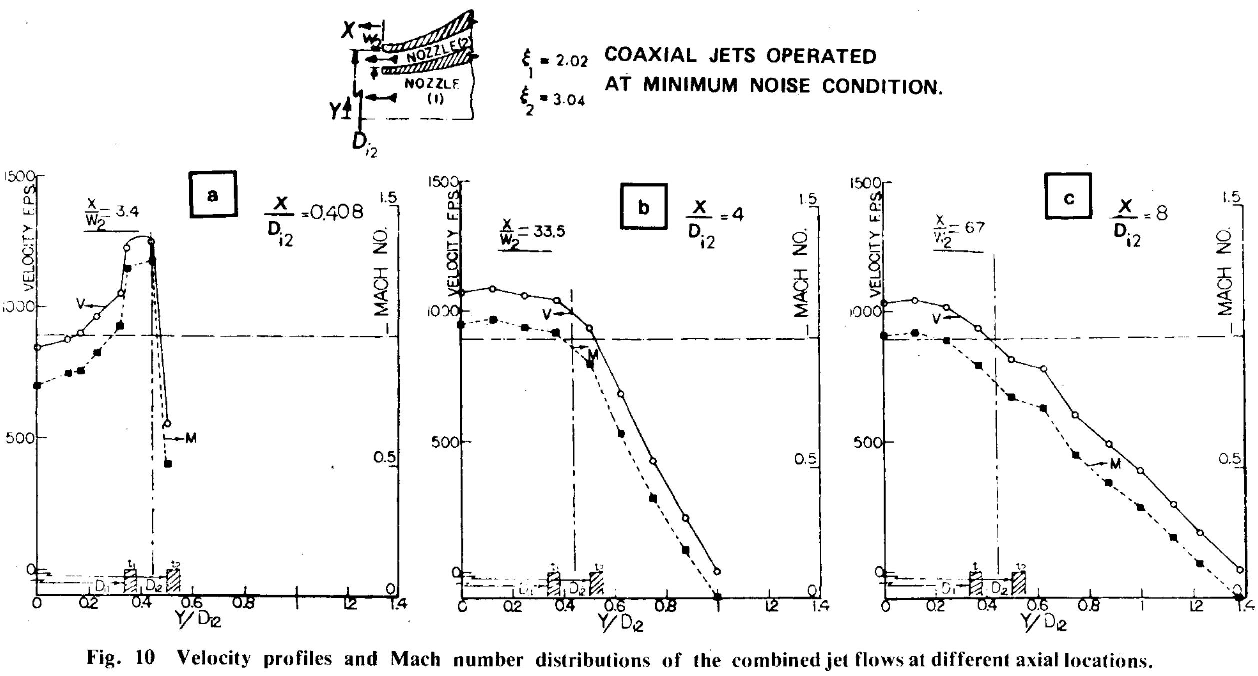

Fig. 10 Velocity profiles and Mach number distributions of the combined jet flows at different axial locations.

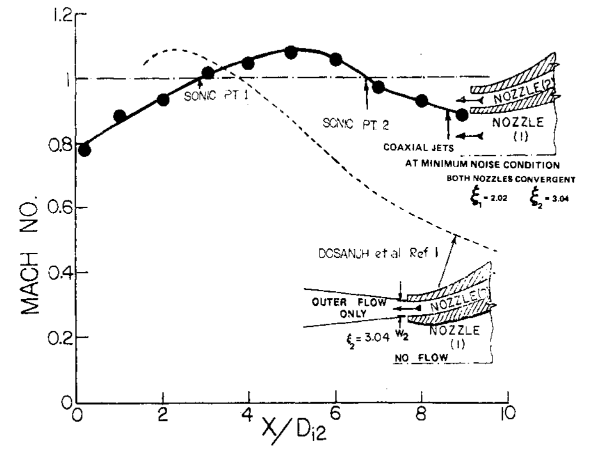

Fig. 11 Axial Mach number distributions of coaxial (minimum noise condition) and convergent jet at same ξ_2 (---): single annular convergent jet of Ref. 1 ($D_{i2}/w = 11.56$); -●-: coaxial jet at minimum noise condition ($D_{i2}/w = 8.35$) of the present study.

V_{j2} did not occur along the centerline of the annulus and that it is shifted slightly toward the combined jet flow centerline (see Fig. 10a). With increasing X/D_{i2}, the maximum velocity V_{j2} of the outer flow region shifts toward the center (see Figs. 10b and 10c). It also is interesting to note that the radial extent of the inner supersonic region of the jet flow narrows with increasing values of X/D_{i2}. The Mach number distributions at different X/D_{i2} are, in general, similar in trend to the velocity profiles at the same locations.

Axial Mach number distribution of the combined jet flows also was calculated and compared to that of the outer converging annular jet alone[1] operated at $\xi_2 = 3.04$, as shown in Fig. 11. The axial Mach number distribution for a coaxial jet from the two-nozzle arrangement (Fig. 1) operated at $\xi_2 = 3.04$ and $\xi_1 = 2.02$ is entirely subsonic for $X/D_{i2} < 2.7$ ($X/W_2 < 22.5$). Downstream of this location, the axial Mach number increases to $M > 1$ (supersonic), reaching a maximum value, and then further downstream becomes sonic and then decreases to $M < 1$ (subsonic).

Step-by-step calculations of the axial flow Mach number are available in Ref. 5. Therefore, as a result of the interaction of the two coflowing coaxial jets operated at the minimum noise conditions with the annular jet operating pressure $\xi_2 = 3.04$, the combined jet flow exhibits two sonic points at $X/D_{i2} = 2.7$ ($X/W_2 = 22.5$) and 7.5 [$X/W_2 - 62.5$] along the centerline. For illustration of the flow, see Fig. 9. For comparison, it may be pointed out that the axial Mach number in the outer jet alone is supersonic for $X/D_{i2} < 3.75$ ($S/W_2 < 43$) and, as compared to the combined jet flows, the Mach number distribution for this operating condition for $X/D_{i2} < 3.75$ ($X/W_2 < 43$) decays more rapidly.

VII. Conclusions

1) Spectral shapes of annular and round jets are a function of the nozzle geometry (nozzle width for the annular, and nozzle diameter for the round jet) and the operating pressure ratios. Annular jets produce less noise than round jets of the same exit area when operated at the same pressure ratio (i.e., the same mean flow density and velocity). The shock structure and mean flow velocity of an annular jet decay faster with downstream axial distances; i.e., subsonic flow is achieved over a shorter distance downstream of the nozzle exit than that for a round jet of the same exit area and operating pressure ratio.

2) On the basis of a striking similarity observed in optical records between flows downstream of the composite shock just downstream of the nozzle exits with two-nozzle coaxial supersonic jets operated at minimum noise conditions and a single nearly fully expanded jet, semiempirical schemes for prediction of coaxial jet noise have been developed for predicting OAPWL.

3) The most interesting finding about the nature of the combined coaxial jet flows operated at the minimum noise condition $\xi_2 = 3.04$ and $\xi_1 = 2.02$ is that, along the centerline of the combined jet flows, two distinct sonic points occurred at $X/D_{i2} = 3$ and $X/D_{i2} = 8$, respectively.

4) Noise reductions of up to 12.5 dB were observed between the single round convergent jet and coaxial jets operated at the minimum noise conditions. Normalized OAPWL's are up to 4 dB lower than those for the fully expanded jets when plotted against log $T/\dot{m}a_0$ where the highest value of $T/\dot{m}$ existent in the coaxial jets is used.

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