Jet Noise Characteristics of Unsuppressed Duct Burning Turbofan Exhaust System

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Recent aeroacoustic tests of model coannular nozzles have shown that less noise is generated if the higher velocity jet is exhausted from the outer annular passage rather than from the primary nozzle. These findings are of particular significance to the duct burning turbofan engine being studied for application to an advanced supersonic transport airplane. Unlike conventional turbofan engines that have peak velocities from the primary nozzle, it is possible to design a DBTF engine to have a fan velocity higher than that of the primary flow. In this paper are presented the results of a model test program that covers a range of fan to primary area ratios from 0.75 to 1.2, and a range of fan-to-primary velocity ratios from 0.4 to 2.8. Correlations are presented that relate radiated sound power to fan velocity, fan-to-primary velocity ratio, and fan-to-primary area ratio. Corresponding exhaust plume velocity traverse data are presented which suggest that the observed noise benefits may be because of the more rapid decay of the annular flow caused by shear stresses on the inner surface which result from the lower velocity primary flow.

Nomenclature

AST	= advanced supersonic technology
DBTF	= duct burning turbofan
FAR 36	= federal aviation regulations, part 36, noise limits
IVP	= inverted velocity profile
M_i	= ideally expanded jet Mach number
m	= velocity ratio exponent
OASPL	= overall sound pressure level, db, re., 0.0002 dynes/cm^2
P	= pressure
PNL	= perceived noise level in PNdB
PR	= total to static pressure ratio P_t/P_a
PWL	= acoustic power level re. 10-12 W
R	= radius
SPL	= one-third octave band sound pressure level, dB, re. 0.0002 dynes/cm^2
T	= temperature
V	= velocity
X	= distance
ω	= density exponent, a function of velocity defined in Ref. 1
ρ	= density
θ	= angle relative to the upstream jet axis

Subscripts

a	= ambient
F	= fan stream
j	= jet
M	= mixed conditions
P	= primary stream
T	= stagnation property

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Introduction

A DUCT burning turbofan engine for an advanced supersonic technology (AST) transport can be designed to have a fan exhaust velocity that is substantially higher than the primary stream exhaust. This results in a velocity profile across the exit plane that is "inverted" compared to those of conventional turbofans that have fan-to-primary velocity ratios less than 1.0. Although procedures have been developed which predict the jet noise of turbojets and conventional turbofans, no method was available to predict the jet noise characteristics of inverted exit profile jets. Earlier efforts to develop more precise prediction methods focused on the turbojet (flat velocity profile) and conventional turbofan (higher primary velocity) cases because of their wide range of application. The noise produced by a single jet exhausting to atmosphere through a circular, converging nozzle at subcritical pressure ratios, i.e., such that $M_i < 1.0$, is characterized by the relationship between the overall sound pressure level and jet velocity and by the sound pressure level spectra. One aspect of the jet noise spectra of circular subsonic jets is that the sound pressure level is a continous function of frequency and has a single maximum level at a frequency that depends on velocity, nozzle size, and far field angle, as shown in Fig. 1. The Society of Automotive Engineers (SAE) has prepared a procedure to predict the noise of a single jet[1] which has been found to compare very well with measured levels. Methods to predict the far field noise characteristics of coannular jets, where $V_f/V_p < 1$, also have been documented accurately by SAE.[1] The presence of a secondary stream was shown to decrease noise at high frequencies and to increase noise at low frequencies. The net result on overall sound pressure level (OASPL) is to reduce the noise of a coannular jet below that of the original primary jet for low and moderate fan-to-primary velocity ratios, and to increase the OASPL at the higher velocity ratios. Both effects are accentuated with increasing fan-to-primary area ratio. These characteristics are illustrated for a typical coannular jet in Fig. 2. No provisions are included in the SAE procedure to quantify the noise of coannular jets having an inverted velocity profile, i.e., with a fan-to-primary ratio greater than

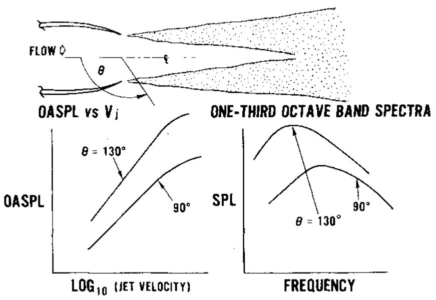


Fig. 1 Jet noise characteristics of single-stream turbojet exhaust.

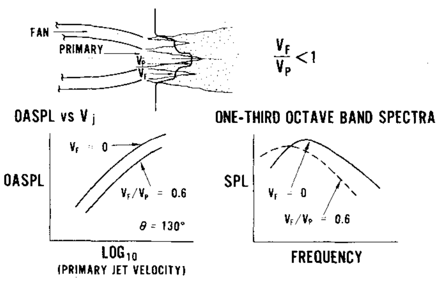


Fig. 2 Jet noise characteristics of conventional turbofan exhaust.

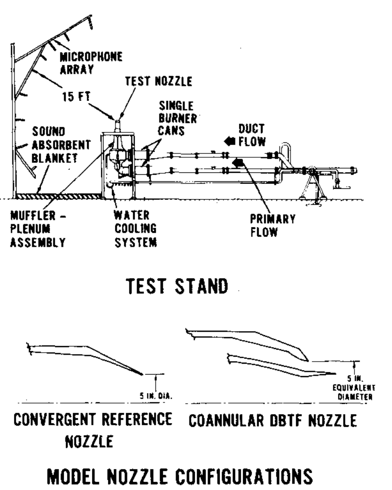


Fig. 3 Experimental set-up.

one. This is the type of velocity profile that is produced by some duct burning turbofan (DBTF) engines being studied for use on advanced supersonic transports.

Since jet noise levels largely are determined by the engine size and cycle parameters, the selection of an efficient cycle for a supersonic transport powerplant which satisfies aircraft noise certification rules requires accurate noise prediction methods. An important need was thus established for methods to define the noise characteristics of inverted velocity profile (IVP) exhausts. One goal of the test program reported in this paper was directed towards meeting this requirement.

Prior to the results presented in this paper, the noise of an inverted profile jet was estimated by adding predicted noise levels for two circular jets operating independently at the primary and fan stream conditions. This method assumed no interaction between the two flows. This "simple" method was shown to be inaccurate by the results of the test program. The results of this program therefore are being used as a data base in the generation of a new empirical procedure to predict more accurately the noise of inverted velocity profile (IVP) jets.

Experimental Program

Under the experimental program, two 5-in. equivalent diam scale model coannular exhaust nozzles were tested over a large range of fan and primary conditions (velocities from 1000 to 2000 fps in the primary, and 870 and 2800 fps in the fan stream). One nozzle had a fan-to-primary nozzle exhaust area ratio of 0.75 and the other had an area ratio of 1.2. In addition to the coannular nozzles, a 5-in. diam single stream circular convergent nozzle was tested at each coannular nozzle fan and primary stream circular convergent nozzle was tested at each coannular nozzle fan and primary stream operating condition in order to provide a base of data for the simple prediction method described in the previous section. The nozzle models were tested at an outdoor "free-field" jet noise test facility, which is described in detail in Ref. 2. Figure 3 shows schematic drawings of the facility and of the single and coannular nozzles tested during the program. The model acoustic data were scaled using convential Strouhal methods for level and frequency to represent the jet noise of a full size duct burning turbofan (DBTF) engine ten times the model size. Acoustic power levels were calculated by assuming symmetry of noise generation about the jet axis, and perceived noise levels were calculated using scaled noise spectra extrapolated to 2128-ft sideline, using the procedure of Ref. 3.

The acoustic results obtained during the tests can be segregrated into 3 categories: 1) single circular jet, 2) coannular jet for fan-to-primary velocity ratios less than 1.0 (conventional turbofan), 3) coannular jet for fan-to-primary velocity ratios greater than 1.0 (duct burning turbofan). The first two categories provided data that could be compared to predicted levels using the SAE procedure mentioned previously. These comparisons are presented in the next section and show good agreement between measured and predicted levels. These results verify the accuracy of data generated by the test facility and establish a basis for validity of the test results obtained in category 3 for the $V_f/V_p > 1.0$ inverted velocity profile (IVP) coannular nozzles.

Data Validity

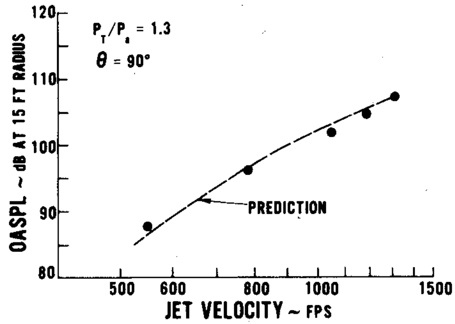
Model scale spectra measured for the single convergent nozzle are shown in Fig. 4 for subsonic conditions, along with corresponding spectra predicted using the SAE method shown as a dashed curved on the figure. The measured spectra can be observed to compare well with the predicted spectra. Also shown in Fig. 4 is a comparison of the measured and predicted OASPL vs jet velocity. The comparisons are limited to subsonic pressure ratios, because there is no accepted method for predicting the jet noise of convergent nozzle jets at supersonic pressure ratios (i.e., underexpanded flows containing shock waves). Since the SAE prediction method has been found to be accurate for a wide range of applications, the good agreement between measured and predicted values indicates that the test facillity produces valid data.

The convergent nozzle data also were compared with results of a new prediction procedure developed by Stone.[4] The data agreed slightly better with the Stone method at high temperatures and velocities, and showed slightly better agreement with the SAE predictions at the lower temperature and velocities. More extensive comparisons of the data with both prediction methods are contained in Ref. 5. The single nozzle data are used as input for the "simple" coannular prediction method mention earlier.

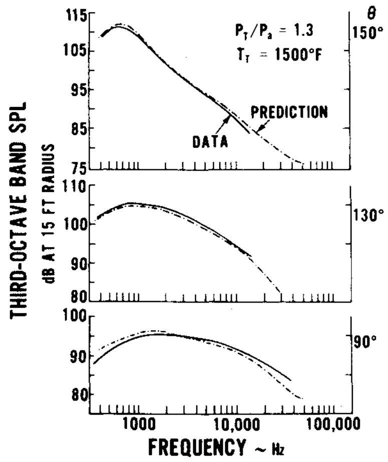
A further check on the validity of the test results is provided by a comparison of scaled coannular nozzle data for $V_f/V_p < 1$ with levels predicted using the SAE procedure. Figure 5 presents these comparisons. The agreement between the test results and predictions shows that the coannular nozzle at $V_f/V_p < 1$ produces noise typical of that produced by conventional turbofan exhausts.

Inverted Velocity Profile Results

The coannular nozzle operating as an IVP (i.e., $V_f/V_p > 1$ produced noise characteristics substantially different from the noise produced by single jets or by conventional coannular stream turbofan exhausts. As was mentioned earlier, a

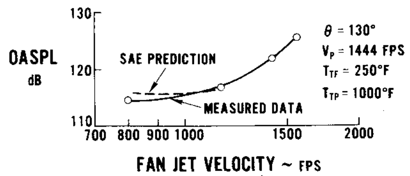


a) OASPL as a function of jet velocity

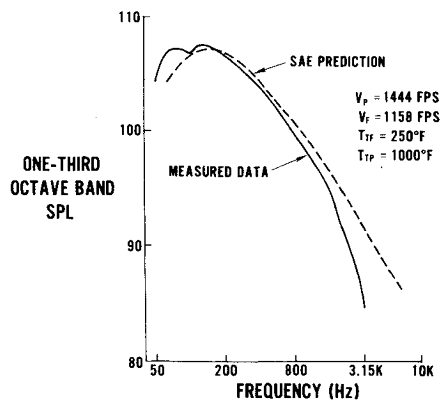


b) Third-octave band SPL spectra

Fig. 4 Comparison of convergent reference nozzle model scale data noise with SAE prediction.



a) Overall sound pressure level

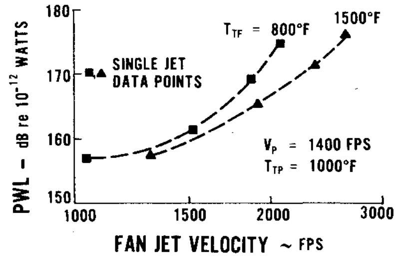


b) Sound pressure level spectra

Fig. 5 Comparison of measurement and predicted jet noise of coannular nozzle for $V_f/V_p < 1.0$.

"simple" prediction method was devised based on the assumption that the noise would be equal to the sum of the noise from two independent circular jets at the respective operating conditions and exit areas of the coannular nozzle primary and fan streams, i.e., (power level)$_{syn}$ = 10 log [$\log^{-1}$ (PWL/10)$_p$ + $\log^{-1}$(PWL/10)$_f$] and perceived noise level (PNL)$_{syn}$ = 10 log [$\log^{-1}$(PNL/10)$_p$ + $\log^{-1}$ (PNL/10)$_f$]. This concept will be referred to as the coannular noise

Fig. 6 Synthesized acoustic power of coannular nozzle based on measured single jet data.



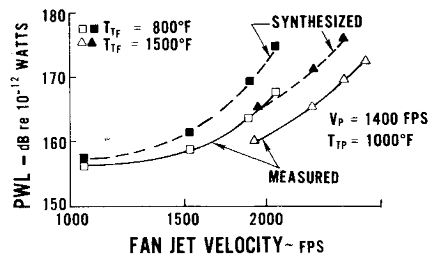


Fig. 7 Comparison of measured and synthesized acoustic power of coannular nozzle.

synthesis. Further, since no method was available to predict accurately the noise of convergent nozzles operating supercritically ($M_i > 1.0$), the input to this prediction method was provided by the results of the reference convergent nozzle tested during this program. By use of this procedure, acoustic power levels were "synthesized" for each coannular nozzle test condition. The noise levels for this case and for the rest of the paper have been scaled to an engine having 50 in. total nozzle diameter. Figure 6 illustrates the power level predictions based on the synthesis for one primary velocity over a range of fan stream conditions. Note that at fan velocities lower than V_p the predicted levels are affected little by increasing fan velocity, indicating that the primary jet is the dominant noise source. At high fan velocities, however, the noise increased rapidly with increasing fan velocity, showing that the fan jet becomes the dominant noise source. In this synthesis, no attempt was made to account for acoustic or aerodynamic interactions between the coannular streams.

The overall noise power levels of the coannular nozzle are compared with the synthesized levels in Fig. 7. This comparison shows that, when the fan velocity is greater than the primary velocity, the measured noise levels are significantly lower than the synthesized levels. Similar results were found for the other primary velocities tested.

A comparison is presented in Fig. 8 of the measured and synthesized one-third octave band SPL spectra for two cases, one with supersonic fan jet and the other with a subsonic fan jet. In both cases, the fan jet velocity is substantially larger than the primary jet velocity. The synthesized spectrum, as would be expected, is similar to that of a single circular jet operating at the fan stream conditions of the coannular nozzle. (The noise of the primary jet was predicted to be much less than that of the fan jet, and thus had little influence on the synthesized spectrum.) The measured spectrum, however, is much lower in the low and mid-frequency regions with high-frequency levels basically the same. This results in a "double-humped" spectra that is characteristic of spectra from multielement suppressor nozzles used on turbojets exhausts. The double-humped spectrum shape is much more apparent in the aft angle SPL than in the power spectrum shown in Fig. 9. The detailed spectra are contained in Ref. 5. The results in Ref. 5 also show that, at very low frequencies, below the audible range for a full-size engine but measured in model scale during the program, the SPL levels of the coannular nozzle and the synthesized levels are the same. In Ref. 5, it is shown that the noise reductions are similar to those achieved with suppressor nozzles, indicating that the IVP jet has a suppressor like noise behavior.

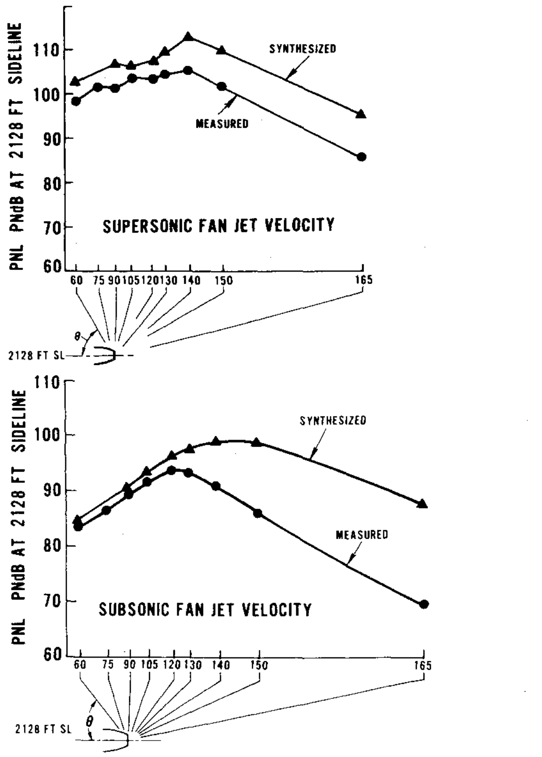


Fig. 8 Comparison of measured and synthesized perceived noise level directivity of coannular nozzle.

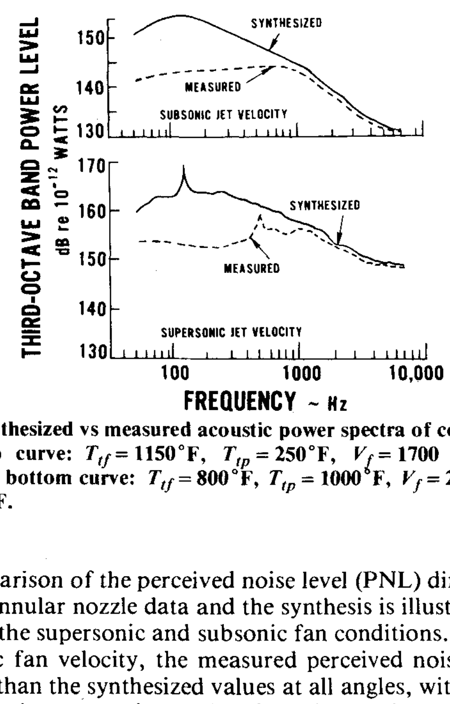


Fig. 9 Synthesized vs measured acoustic power spectra of coannular nozzle—top curve: $T_{tf} = 1150°F$, $T_{tp} = 250°F$, $V_f = 1700$ fps, $V_p = 1000$ fps; bottom curve: $T_{tf} = 800°F$, $T_{tp} = 1000°F$, $V_f = 2050$ fps, $V_p = 1400°F$.

A comparison of the perceived noise level (PNL) directivity of the coannular nozzle data and the synthesis is illustrated in Fig. 8 for the supersonic and subsonic fan conditions. For the supersonic fan velocity, the measured perceived noise levels are lower than the synthesized values at all angles, with larger noise reductions occurring at the aft angles. In the case of the subsonic fan, however, significant noise reductions are seen to occur only at the aft angles. These results are typical of the other subsonic and supersonic fan conditions tested.

Figure 10 shows the noise spectra at a variety of fan conditions for a constant primary velocity. At the lowest fan velocity, $V_f/V_p = 0.74$, the spectrum, with peak levels centered at 100 Hz, is typical of that from a conventional turbofan. As the fan velocity is increased, a slow increase in low-frequency noise levels is seen to occur, whereas high-frequency noise, centered at 1000 Hz, increases at a more rapid rate. This leads to a "double-humped" spectra at large values of fan-to-primary velocity ratio. The discrete tone present at the highest fan velocity is associated with the noise

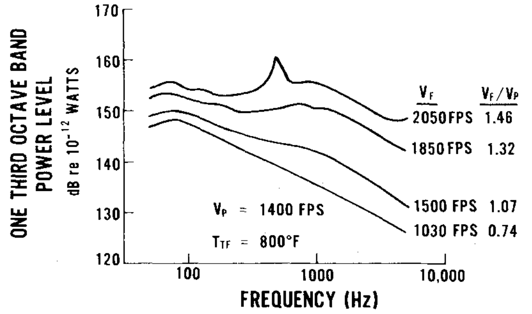


Fig. 10 Noise spectra of coannular nozzle.

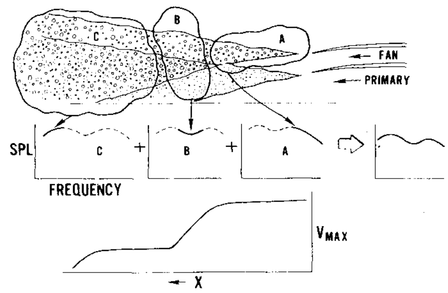


Fig. 11 Suggested model of inverted velocity profile jet noise generation.

due to the presence of shock waves in the supersonic fan exhaust. The double-humped spectral characteristic supports the existence of two regions of noise generation in the IVP jet exhaust, a high-frequency generation region near the nozzle, where the fan stream velocity is not yet mixed, and a low-frequency noise generation region downstream of the nozzle, where the two jet flows are mixed.

A conceptual model of the noise generation process, illustrated in Fig. 11, has been proposed for the case in which $V_f/V_p > 1$, based upon the previous rationale. The model relates the characteristics of the jet plume flowfield to the spectral character of the noise. Below the jet plume schematic are shown the results of a coannular jet flowfield calculation, based on the work of Harsha (described in Ref. 6), applied to the inverted velocity profile jet, assuming fully expanded flow at the exits of the coannular nozzle. From this calculation, the jet plume is seen to be composed of two initial potential cores, a circular primary core extending downstream of the primary nozzle for 4-10 primary nozzle diameters, and an annular fan stream core extending downstream of the fan nozzle for probably 4-10 fan annulus heights. The fan potential core is surrounded on the outside by ambient air to product a mixing layer of high turbulence intensity. Another mixing layer is developed at the interface of the primary and fan streams. The turbulent velocity levels in this inside mixing layer are expected to be considerably lower than those in the outer mixing region because of the lower relative velocity that exists between the fan and primary flows.

The outer mixing layer of the annular jet is considered to be more important for noise generation than the inner mixing layer, since the turbulence level is significantly higher. Thus the noise generated by the inner mixing layer is neglected. The outer mixing layer is similar to the one that exists on a single jet having the same outer diameter. Thus, the high-frequency noise generated in the shear region aft of the nozzle exit up to the end of the fan potential core is expected to be the same as that generated by the same region of a single circular jet. However, the coannular jet exhibits a rapid velocity decay downstream of the fan jet potential core, which results in a reduction in the noise at mid and low frequencies compared to a single circular jet whose potential core extends much farther downstream. Following the rapid mixing of the fan and

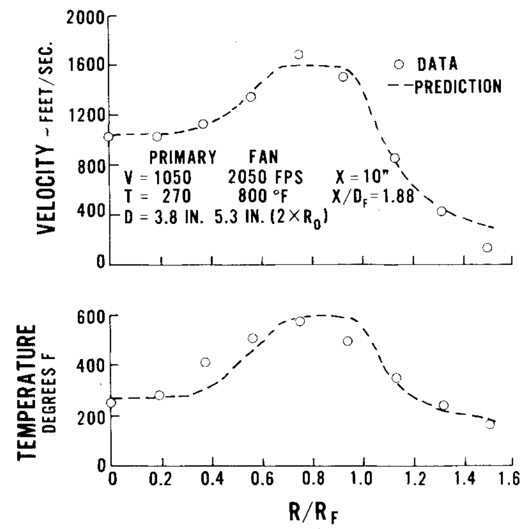


Fig. 12 Comparison of measured and predicted velocity and temperature profiles in jet plume.

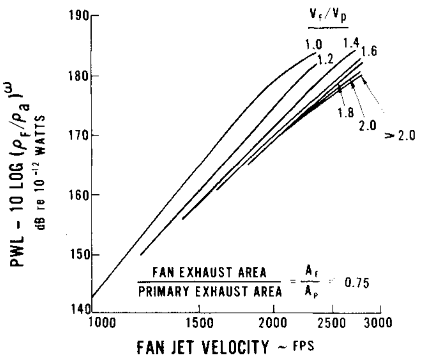


Fig. 13 Acoustic power correlation from inverted profile coannular jet data.

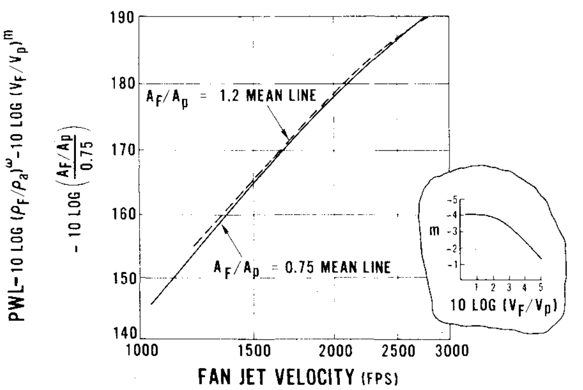


Fig. 14 Correlation of unsuppressed coannular nozzle power levels including area ratio and velocity ratio normalization.

primary streams, a large diameter region results that has a relatively uniform axial velocity profile. The mixing aft of this region would be expected to develop and generate noise in a manner similar to the flow from a single jet having the same velocity.

A check on the validity of the flowfield calculation was made by comparing a calculated velocity profile with the corresponding profile at one axial position, as shown in Fig. 12. The close agreement between measured and calculated profiles substantiates the method used to predict the flowfield, and in particular the rapid velocity decay in the transition region. Figure 11 also illustrates the spectra that would result from the postulated model of noise generation. The general shape of the postulated spectra is in agreement with the measured data. More complete measurements of the coannular flowfield are necessary, however, before the noise generation model can be verified fully.

Correlation of Acoustic Power

A correlation was developed which empirically relates overall acoustic power with inverted velocity flow features, using the data obtained from all of the test points for which $V_f/V_p > 1$. The step-by-step development of the correlation is contained in Ref. 4, and only the final results are included here. The data included six different primary velocities from 1000 to 2000 fps, at temperatures from 250° to 1500°F. Fan velocities varied from 1000 to 2800 fps, fan pressure ratios covered the range from 1.3 to 4.1, and fan temperatures ranged from 250° to 1500°F. The acoustic power was normalized for the effects of density by the factor 10 $\log(\rho_f/\rho_a)^{\omega}$, where ω was obtained from Ref. 1.

Noise level vs fan velocity data are presented as a family of curves, one for each value V_f/V_p, as shown in Fig. 13. It can be seen from this figure that the fan-to-primary velocity ratio is a major factor affecting the noise of an inverted velocity profile jet. As an example, this correlation shows that, for a fan velocity of 2000 fps, a coannular jet with $V_f/V_p = 1$ generates 10 dB more noise than an inverted profile jet with $V_f/V_p = 2.0$. From this correlation, it is apparent that the power level decreases as V_f/V_p increases between the ranges of 1 and 2. For a given value of V_f, however, reductions in V_p to cause V_f/V_p to increase above 2.0 appear to offer only negligible additional noise suppression at the area ratio shown. By introducing the additional normalization parameter $10\,(V_f/V_p)^m$, where m is a decreasing function of V_f/V_p, which accounts for the effect of fan to primary velocity ratio, further collapse was achieved of the family of constant velocity ratio noise curves, as shown in Fig. 14. In order to complete the correlation, results were incorporated from a fan-to-primary area ratio 1.2 coannular nozzle tested during the program. The same velocity ratio normalizing factor used for the 0.75 area ratio nozzle was used for the 1.2 area ratio nozzle data, and an additional normalization factor was introduced to account for the effect of area ratio. Because of the limited number (2) of area ratios tested, the correlation curve in Fig. 14 should not be used for area ratios outside the 0.75 to 1.2 range.

DBTF engine studies originally were conducted using noise estimates based upon the synthesis prediction method. Those studies have indicated that a moderate amount of fan stream jet suppression would be required in order to meet FAR 36 noise levels. Based on the results of this program, it now appears possible to meet FAR 36 throught the inherently lower noise of the inverted velocity profile (IVP) characteristic of the DBTF cycle, as mentioned in Refs. 2 and 7. Thus, it may be possilbe to meet noise regulations without the use of a suppressor nozzle with the attendent penalties of weight, thrust loss, mechanical complexity, and expense.

Comparison of IVP Coannular Jet with Mixed Jet

It has been a common assumption that the noise of a coannular jet is minimized when the two streams are fully mixed internally to produce a single jet at the mixed velocity and temperature. For conventional turbofan exhausts ($V_f/V_p < 1$), substantial noise reductions have been achieved by using internal mixing devices. For typical duct burning turbofan conditions ($V_f/V_p > 1$), however, the results are just the opposite. For example, a duct burning turbofan exhaust containing an internal mixer designed for constant momentum mixing and the same static pressure before and after the mixing region will result in a uniform jet, whose noise level is higher than that of the original unmixed exhaust. This is illustrated in Fig. 15 for conditions typical of a duct burning turbofan cycle. Power spectra for the IVP jet

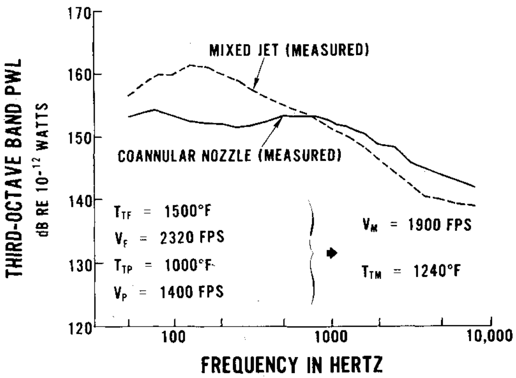


Fig. 15 Acousitc power spectra of inverted profile coannular jet compared to equivalent mixed single jet.

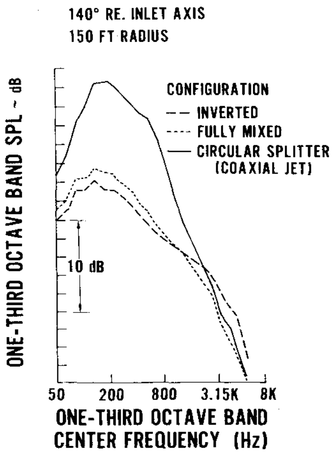


Fig. 16 JT8D jet noise spectra for fully mixed and partially mixed/inverted streams at 140 deg from the inlet axis.

generates slightly more high-frequency noise, but also significantly less low-frequency noise, with the net result being less total acoustic power generated for the IVP jet. Extrapolation of the SPL spectra for this condition to distances relevant for sideline noise certification indicated 5-PNdB reduction in peak perceived noise level (PNL).

Application to Conventional Turbofan Engines

The jet noise produced by a conventional turbofan engine is dominated by the high-velocity primary stream. For example, a prediction using the SAE procedure indicates that large noise reductions would result from mixing the primary and fan exhaust within the engine tailpipe. Test results recently obtained by Pratt & Whitney Aircraft on a scale model JT8D refan exhaust system have shown that the noise level predicted by the SAE method for a single jet is representative of a fully mixed coannular stream. Such mixed flow conditions can be approached by use of an internal mixing device, which produces a nearly uniform velocity profile at the tailpipe exit plane. This mixing results in significant noise reductions relative to the noise level of the unmixed case. The results of the IVP test program were used in a study to determine if additional noise reduction could be obtained by inverting the primary and fan flows (i.e., by causing the primary stream to exit the tailpipe near the outer diameter, thereby surrounding the fan stream) as opposed to fully mixing the flows internally. The results of the study indicated that approximately the same amount of noise reduction would result for fully inverting the stream as fully mixing the streams. However, one of the results obtained during the testing of various internal mixing devices indicated that, for this particular cycle, a device that partially mixed the streams while at the same time causing a flow inversion produced less noise than if the streams were fully mixed. Figure 16 presents comparisons of the one-third octave band sound pressure levels for the baseline unmixed case, fully mixed, and inverted velocity profile cases. These limited results indicate that, for conventional turbofan cycles, the use of partial mixing and flow inversion may result in lower noise levels than fully mixing the streams internally, and this should be investigated further as a means of reducing jet noise for this class of engines.

Conclusions

The following conclusions were obtained during the study described in this paper:

1) The noise generated by a coannular nozzle having an inverted velocity profile ($V_f/V_p > 1$) is less than that predicted by synthesizing the noise of this type of jet as the sum of the noise of individual circular jets representing the fan and primary streams.

2) A DBTF engine, having an inverted velocity profile, applied to an AST airplane may not need a mechanical jet noise suppressor to meet FAR 36 noise limits.

3) The noise spectra of the inverted velocity profile jet exhibits a double-peaked shape, similar to a multielement suppressor nozzle, and is traceable to the aerodynamic mixing characteristics of the jet flowfield.

4) The acoustic power generated by an inverted velocity profile at fan-to-primary area ratios of 0.75 and 1.2 were correlated, with the fan-to-primary velocity ratio being an important correlating factor.

5) The inverted profile coannular nozzle, as used on a typical AST DBTF ($V_f/V_p > 1$), generated less noise than an equivalent single jet of the same exit area, airflow, and thrust.

6) The principle of the inverted velocity profile can be used on conventional turbofan engines to reduce the jet noise below the level obtainable with complete internal mixing.

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