COANNULAR PLUG NOZZLE NOISE REDUCTION AND IMPACT

ON EXHAUST SYSTEM DESIGNS

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INTRODUCTION

Finding a satisfactory and practical method for reducing the noise generated by high velocity jets has confronted engine designers and acoustics workers alike for the past fifteen years. Figure 1 shows some of the jet noise suppressor configurations that have been investigated by General Electric in the past. With the exception of the early CJ-805 daisy suppressor nozzle which found successful application on the Convair 990 airplane, the others were developmental hardware at different stages of the effort in the past eight years - all aiming at potential supersonic cruise aircraft applications. We are happy to report here that some further significant progress has been made as the result of work supported by NASA and FAA in the past two to three years. This work pertains to the concept demonstration and scale model testing of coannular plug nozzles with inverted velocity profile, and to the preliminary study of its application to advanced variable cycle engines (VCE) appropriate for supersonic cruise aircraft.

COANNULAR PLUG NOZZLE NOISE INVESTIGATIONS AT GENERAL ELECTRIC

Two programs were carried out under the sponsorship of NASA (Lewis) from 1973 to 1976. The first program* aimed mainly at the investigation of multi-element suppressors added to the outer stream of the coannular plug nozzle for possible application to duct burning turbofan cycle. It included the study of two baseline (unsuppressed) coannular nozzles. Two configurations tested in this program are shown in figure 2. The second program** was confined to the unsuppressed coannular plug nozzle, but with extended range of configurations and test parameters such that possible applications of the unsuppressed coannular nozzle concept to variable cycle engine exhaust systems, with or without outer stream burning, can be fully evaluated. Performance tests as well as scale model acoustics tests were carried out in this program. Figure 3 shows a coannular plug nozzle installed in the NASA 8' x 6' wind tunnel for aero performance testing. All the acoustics testing was carried out in the new General Electric anechoic jet noise facility.

Eight configurations were investigated. Their general design outlines are shown in figure 4. The selection of these configurational designs were made with the view toward investigating the influence of the following geometric parameters on noise and takeoff performance: ratio of inner to outer areas, outer stream radius ratio, inner stream radius ratio, and plug shape. Test variables included velocity and temperature conditions of the two streams.

COANNULAR PLUG NOZZLE NOISE CHARACTERISTICS

The acoustical benefit associated with the interaction between the two streams issuing from an inverted coannular nozzle (high outer velocity and low inner velocity) can best be shown by comparing the measured noise characteristics of the coannular nozzle against that obtained by simply log summing the measured or known noise levels of two conical nozzles having the exit nozzle areas and flow conditions equal to those of the two exhaust streams of the coannular nozzle. The calculated noise level so obtained on the tacit assumption of no interaction between the two streams is hereinafter referred to as the synthesized conical or synthesized baseline noise level.

Figures 5 and 6 show such typical comparisons in terms of sound pressure spectrum at the 130° maximum sideline angle of several coannular configurations. Examination of these spectral comparisons and others not shown here indicate that the benefits due to interaction of the two annular streams in a coannular nozzle are: (a) concentrated mainly in the mid-frequency region, (b) increased sharply with increase in the ratio of inner area over outer area, and (c) dependent to some extent also on the outer nozzle radius ratio and the velocity ratio. The exact trend here, however, has not been fully pinned down at this time.

It was also observed that with the inner flow shut off ($v^i = o$) the noise level of the outer annular nozzle alone is still considerably lower than that of the equivalent conical baseline (same exit area and velocity). The extent of this inherent noise advantage of the annular nozzle (with a large base area) increases with increase in radius ratio.

The noise benefit of the coannular nozzle relative to the synthesized baseline is also quite evident, as would be expected, at other radiation angles and over a rather wide velocity range. This is illustrated by typical comparison plots of noise vs. angle and noise vs. outer velocity in figures 7 and 8. As will be discussed later, the noise advantage of the coannular nozzle shown at forward quadrants is partly due to shock noise reductions. Noise due to turbulent jet mixing alone associated with the inverted coannular nozzle is only slightly lower than that of the referenced synthesized baseline at forward quadrants.

COANNULAR PLUG NOZZLE NOISE CORRELATIONS

Based on noise data so far analyzed, exact generalization of how various geometric and flow variables govern the noise generation is not possible. It is nevertheless desirable to obtain an approximate engineering correlation that can put into perspective how the salient parameters would affect the overall noise levels of the coannular nozzle. Analogous to the well established fact that the noise of a simple conical nozzle is primarily the function of exhaust velocity, it is believed that the noise of a more complex coannular plug nozzle, at least to the first order of approximation, may also be primarily the function of some "characteristic" velocity. The selected "characteristic" velocity is the mass flow averaged velocity for the two coannular streams; thus,

$$V_{ave} = \frac{w^i v^i + w^o v^o}{w^i + w^o}$$

where w and v are mass flow and velocity, and superscripts i and o refer to inner and outer streams respectively. The correlations of normalized total sound power and normalized maximum sideline PNdB against this flow averaged velocity for all test data from the eight configurations and for all test conditions are shown in figures 9 and 10. Plotting of the relative maximum sideline PNdB and relative sound power were normalized for density and ideal thrust in the following manner:

$$\left. \begin{array}{l} \text{Relative PNdB} \\ \text{Relative PWL} \end{array} \right\} \alpha \left\{ \begin{array}{l} \text{PNdB} \\ \text{PWL} \end{array} \right\} - 10 \log(w^o v^o + w^i v^i) - 10 \log_{10} \left(\frac{\rho_m}{\rho_{isa}} \right)^{\omega-1}$$

where ρ_m (mixed density) $= \dfrac{2.7 \times \rho_{isa}}{T_{sm}}$

T_{sm} (mixed static temperature) $= T_{tm} - \dfrac{V_{ave}^2}{2gJc_p}$

T_{tm} (mixed total temperature) $= \dfrac{(T_t^o w^o + T_t^i w^i)}{w^o + w^i}$

T_t is total temperature

ω is SAE density exponent (ARP 876, July 75 revision)

The collapsing of all the test data within a band of about ± 2 dB to show a single trend band supports the reasonableness of the notion of a "characteristic velocity." This then provides a relatively simple basis for predicting the overall PWL and max sideline PNdB levels of the inverted coannular plug nozzle. Further work is needed to provide detailed spectral and directivity correlations.

It is recognized that the mass flow average velocity for a coannular nozzle is really the specific thrust of the engine exhaust system; namely, $\frac{F_{ideal}}{w_t} \times g$ (F is ideal total gross thrust, and w_t is total weight flow). The fact that the correlation curve (band) lies about 3 dB in sound power and about 5 dB in maximum perceived noise level lower than that of the conical nozzle for equal specific thrust is another way of showing the inherent jet noise advantage of inverted coannular nozzle. This, of course, suggests the very important conclusion; namely, for a bypass (e.g. VCE) engine, use of an inverted coannular plug nozzle system will produce significantly lower jet noise than that associated with the use of a fully mixed flow exhaust system, when compared under equal thrust and equal total flow conditions.

DETAILED AERO-ACOUSTIC MODELING AND THEORETICAL PREDICTION

A comprehensive aero-acoustic prediction method for complex jet flows is currently under development at General Electric. This effort is part of the High Velocity Jet Noise program sponsored by the FAA*. The primary objective of this effort is to gain fundamental understanding of the mechanisms of jet noise generation and reduction.

The aero-acoustic prediction procedure utilizes an extension of Reichardt's theory to predict the jet plume development, including mean axial velocity, temperature, and turbulence intensity distributions. It can accomodate arbitrary nozzle planform shapes. The acoustic characteristics are predicted based on the classical concepts of turbulent mixing noise, combined with recently developed analytic methods for modeling the acoustic/mean flow interactions, commonly termed fluid shielding. The prediction procedure is designed to predict absolute levels, as well as spectrum shapes and directivities.

Although the prediction method is still in a development stage, some useful preliminary information on predicted jet noise characteristics has been obtained. Predictions of the noise characteristics of several inverted flow coannular nozzles were performed and compared with available scaled model test data. A typical example is shown in figure 11. There is excellent agreement between predicted and measured noise spectra for the inverted coannular nozzle.

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*DOT Contract OS-30034

To demonstrate the advantage of an inverted dual flow nozzle system over the non-inverted or conventional bypass type (high velocity jet surrounded by a low velocity bypass stream), a prediction of the characteristics of the two types is shown in figure 12. It can be seen that the inverted flow nozzle noise is somewhat higher at high frequencies but considerably lower at mid and low frequencies, with significant net reductions in peak noise level for observer angles greater than 80°. To be noted also is the smaller slope to the directivity pattern relative to the conventional bypass nozzle as shown in figure 13. This is attributed to the more rapid plume decay (also predicted by the model but not shown here), resulting in smaller eddy convection speeds, and hence lower convective amplification. Further exercise of the theoretical prediction method will shed additional insight and physical understanding of the coannular nozzle noise characteristics.

COANNULAR NOZZLE SHOCK NOISE CHARACTERISTICS

Mixing jet noise advantage is but one important attribute of the coannular nozzle. Preliminary analysis of the data obtained indicate that shock noise (arising from the interaction of turbulence with shock; both tones and broadband) of coannular plug nozzles appear to be consistently lower than that of conical nozzles under comparable nozzle pressure ratios which has been generally established as the key variable affecting shock noise. Figure 14 shows typically significant reduction in shock noise – varying from 6 to 12 dB in the frequency range between 600 to 12,500 Hz – for a coannular nozzle. Both outer and inner stream pressure ratios are 2.79, and the outer and inner velocities are 2000 and 1340 feet per second respectively. The baseline conical nozzle was operated at the same pressure ratio and velocity as those for the coannular outer nozzle. This comparison was made at the 50° sideline angle. Figure 15 shows a comparison of the overall noise levels of a coannular nozzle operating at constant velocity, but at different pressure ratios. It is believed that, in the forward quadrant, the rising noise with increase in nozzle pressure ratio is associated with the increasing presence of shock noise. Even then, the projected shock noise at a nozzle pressure ratio of 3.96 is still about 5 dB less than that of the conical nozzle at the same pressure ratio.

The importance of shock noise and the even greater role it may play under flight conditions cannot be overestimated. More effort should be given to this subject in future jet noise technology work for supersonic cruise aircraft.

IMPACT OF COANNULAR NOZZLES ON EXHAUST SYSTEMS DESIGNS

The coannular plug nozzle can be fairly easily adapted to the exhaust system of a variable cycle engine. The desired inverted velocity profile can be

accomplished by ducting the bypass flow to the inner core nozzle, and permitting the main thrust producing, high velocity, and high temperature stream to issue as the annulus.

A preliminary design study comparing the uses of coannular nozzle and conventional retractable multi-element suppressor was carried out, and the key results are shown in Table I. It is seen that the coannular nozzle system enjoys significantly improved performance, reduced weight, and reduced complexity. Reduced complexity implies improved reliability and maintenance. Performance estimates shown were based on data obtained in the NASA (Lewis) 8' x 6' wind tunnel, showing $Cfg \approx .965$ and .92 for coannular nozzle and chute suppression, respectively, at about 3.5 Mach. The final estimated noise level of the coannular nozzle, though still above 3 EPNdB higher than that obtainable with a full suppressor, approaches the FAR36(1969) sideline limit for subsonic aircraft. The exact EPNdB noise level will depend on the engine size selection.

CONCLUDING REMARKS

An inherent noise advantage of coannular plug nozzle with inverted velocity profile has been demonstrated statically as the result of scale model acoustical testing. Application of this concept to variable cycle engine exhaust systems appears feasible. Relative to the use of conventional turbojet type mechanical suppressors, coannular plug nozzles have significantly lower weight for the total exhaust system, reduced complexity, and far less takeoff performance loss. Their impact on aircraft mission range and direct operating cost is expected to be favorable.

Although the research results described in this paper are believed to be significant from the viewpoints of both potential applications and basic knowledge on jet noise reduction, it is not my view that the acoustic technology needed to achieve airport acceptable noise levels for an economically viable supersonic cruise aircraft is already on hand. A great deal of additional technology development work is necessary in order to fully exploit the inverted coannular plug nozzle concept and to more realistically demonstrate its application to future advanced technology engines. Such additional technology work should include, as a minimum, (a) investigation of jet related shock noise and means for its control, (b) investigation of the effect of flight on both jet mixing and shock noise, (c) continued investigation of the possible use of advanced and mechanically simple suppressors, evolved around the basic inverted coannular plug concept (in order to test the feasibility of even lower noise limits, as required, and (d) full scale component demonstration and optimization of the nozzle design.

Work done so far on inverted coannular nozzles by General Electric and others is a significant step forward. Much work lies ahead.

TABLE I
IMPACT OF COANNULAR NOZZLE ON EXHAUST SYSTEM
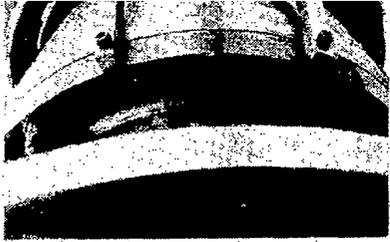### Four 266 880 N (60 000 lb) Thrust Engines

	MIXED FLOW BASELINE	MIXED FLOW PLUS CHUTE SUPPRESSOR	INVERTED COANNULAR
PERFORMANCE LOSS; T. O.	BASE	5 TO 6%	1.5%
NOZZLE WEIGHT	BASE	+ 31%	- 11%
COMPLEXITY	MODERATE	HIGH	MODERATE
NOISE; ΔEPNdB RELATIVE FAR 36 (1969) 649 m (2128 ft) SIDELINE	6 TO 9	-3 TO 0	0 TO 3
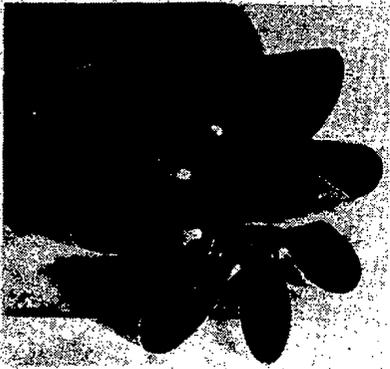
A. CJ805 DAISY (1960)
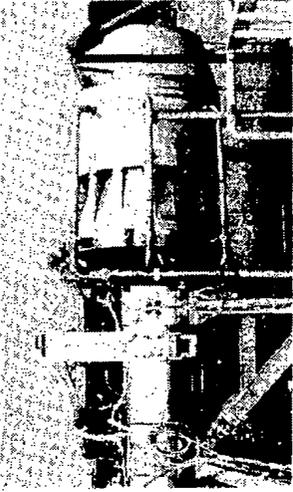
B. SST/GE4 ENGINE WITH TWO-STAGE EJECTOR NOZZLE (1968)

C. MULTI-T EJECTO
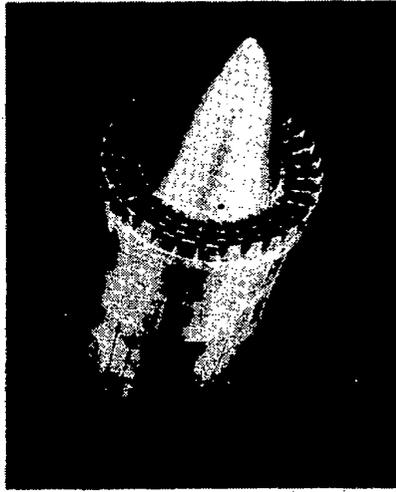
D. MULTI-CHUTE PLUG (1971)
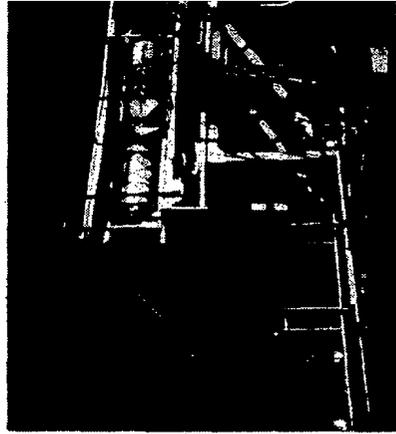
E. ADVANCED 32-CHU' PLUG (1975)

Figure 1.- Typical turbojet jet noise suppressor configurations 1960 – 1975
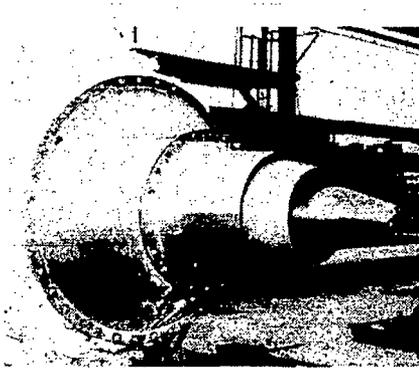
A. UNSUPPRESSED
COANNULAR PLUG
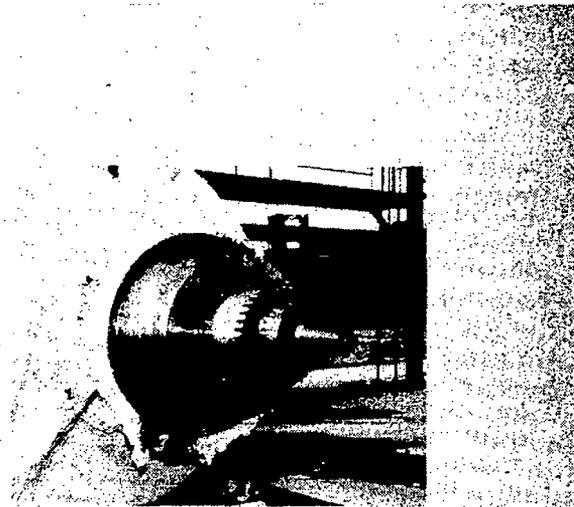
B. SUPPRESSED FAN
COANNULAR PLUG

Figure 2.- Advanced engine cycle coannular plug nozzle/suppressor
configurations - 1976 technology.
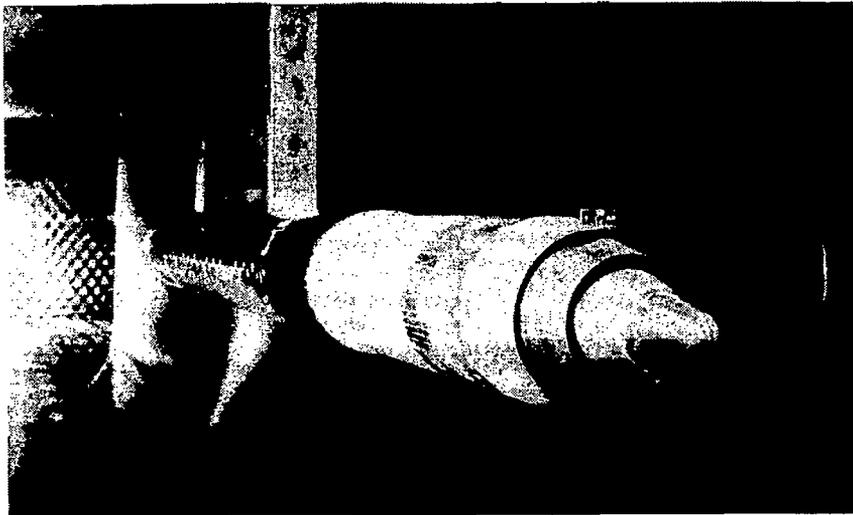
Figure 3.- High radius ratio coannular plug nozzle
installed in NASA Lewis 8' x 6' wind tunnel.

PARAMETER \ CONFIGURATION	1	2	3	4	5	6	7	8
R_r^o	.902	.902	.902	.902	.853	.926	.853	.853
R_r^i	.673	.800	.902	.800	.800	.800	.902	.800
A^i/A^o	1.530	1.030	.530	1.030	.630	1.420	.330	.630
TYPE TEST — ACOUSTIC	X	X	X	X	X	X	X	X
TYPE TEST — AERODYNAMIC	X	X	X	X	X	X	X	X

CONFIGURATION #1   CONFIGURATION #2   CONFIGURATION #3   CONFIGURATION #4

CONFIGURATION #5   CONFIGURATION #6   CONFIGURATION #7   CONFIGURATION #8
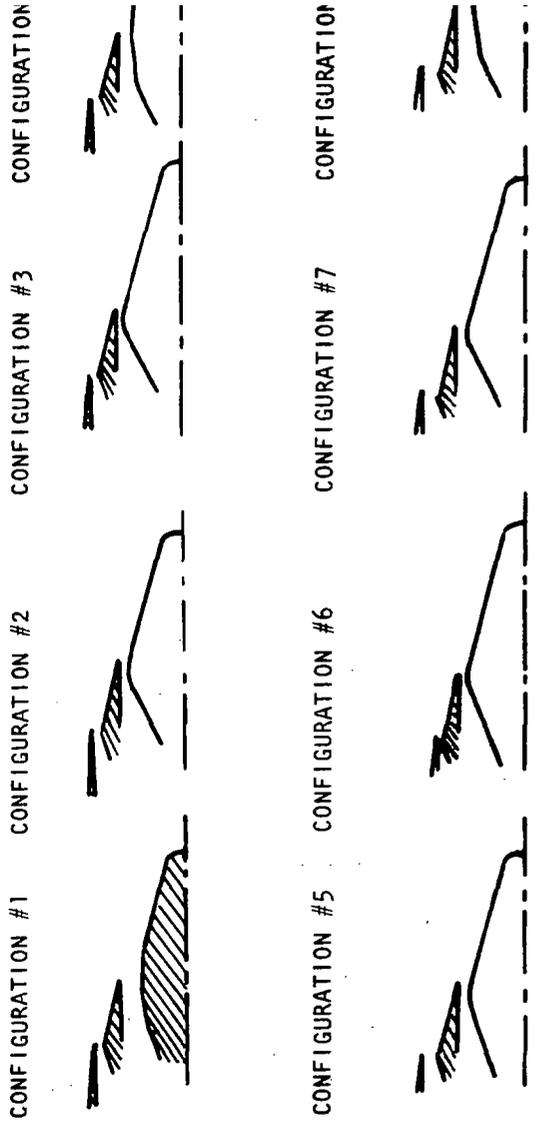
Figure 4.– Summary of configuration and key geometric parameters.
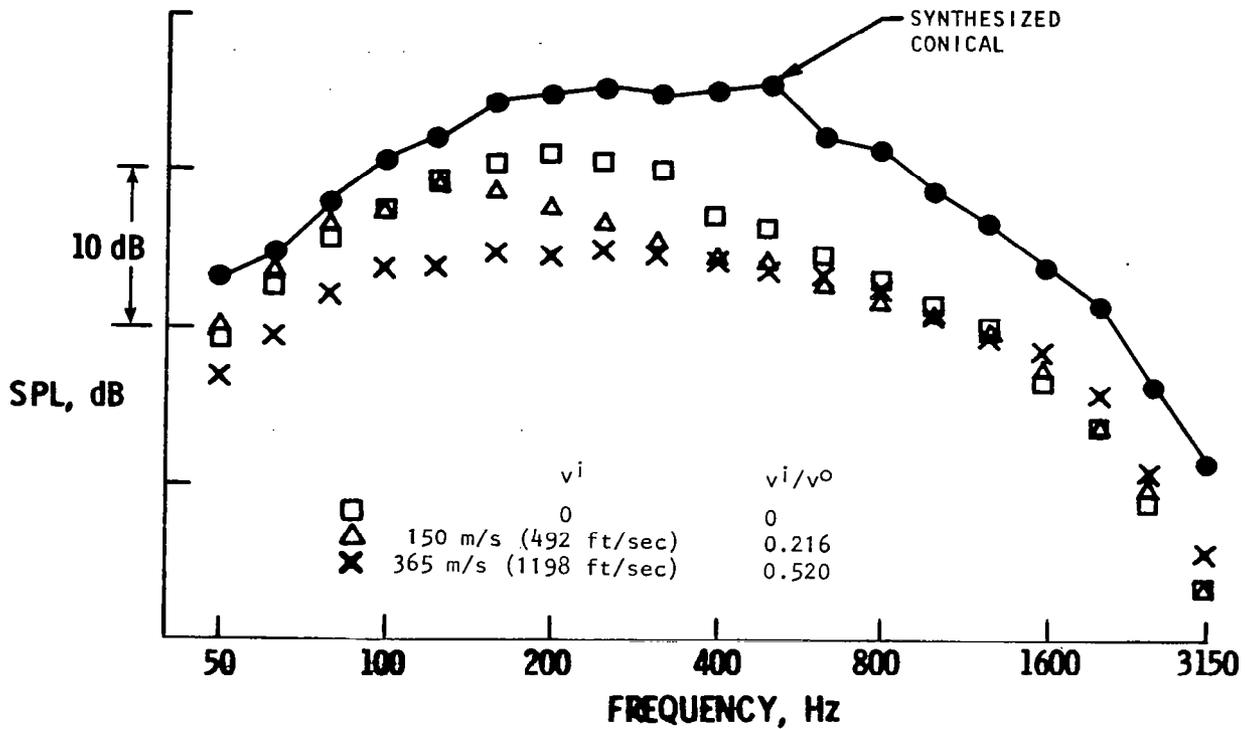
Figure 5.- Typical inverted coannular plug nozzle spectral characteristics. 732 m (2400 ft) sideline; data scaled to .33 m^2 (513 in^2); V^o = 701 m/s (2300 ft/sec); T_T = 967 K (1740° R); θ_I = 130°; configuration No. 3; A_R = .53.
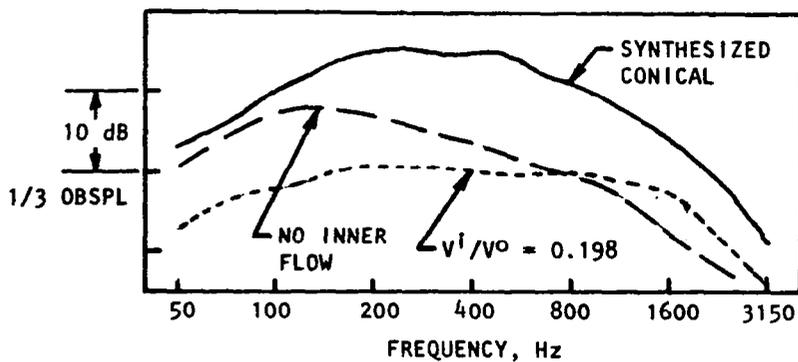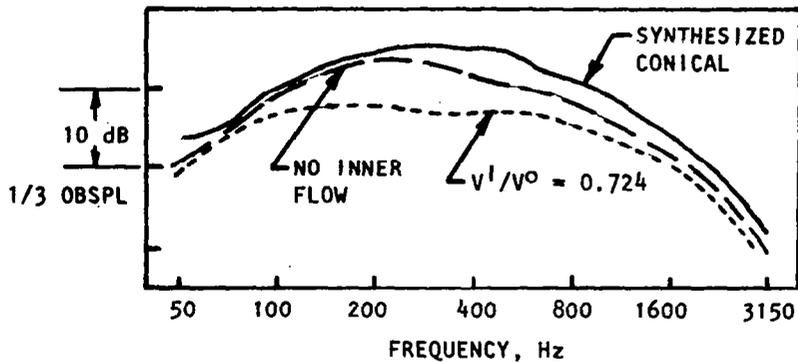
Figure 6.- Additional typical inverted coannular plug nozzle spectra. 732 m (2400 ft) sideline; data scaled to .33 m^2 (513 in^2); $\theta_I = 130^o$; $V^o = 701$ m/s (2300 ft/sec).
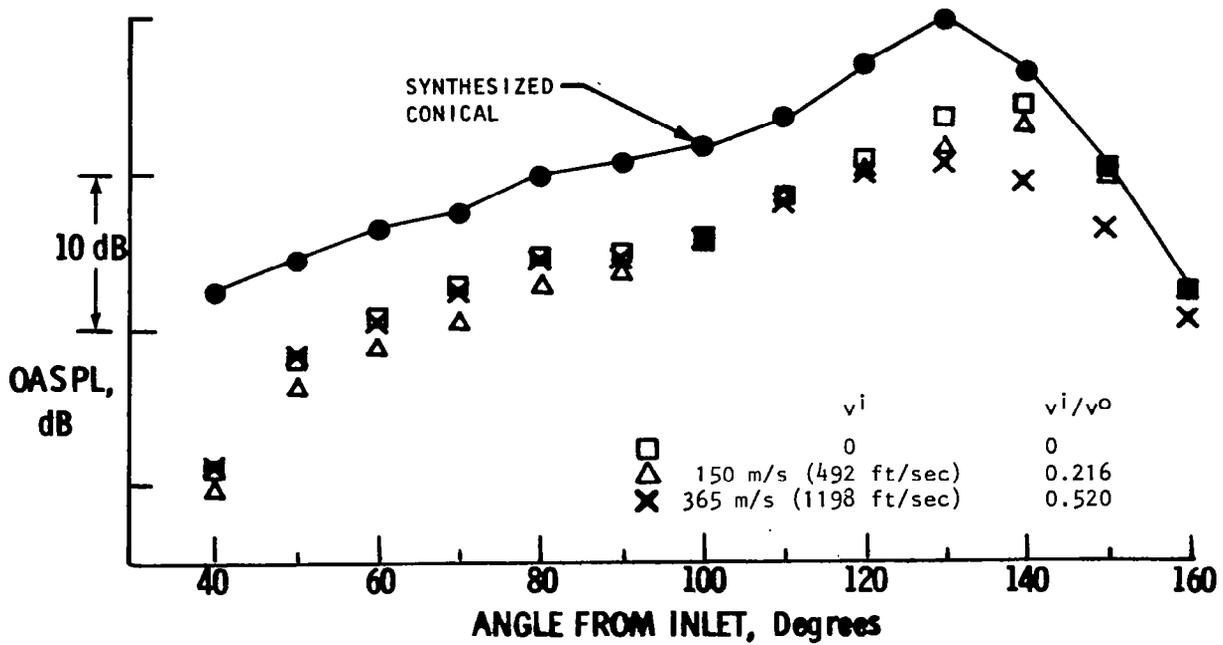
Figure 7.– Typical inverted coannular nozzle directivity characteristics. 732 m (2400 ft) distance; data scaled to .33 m^2 (513 in^2); V^o = 701 m/s (2300 ft/sec); T$_T$ = 967 K (1740° R); configuration No. 3; A$_R$ = 0.53.
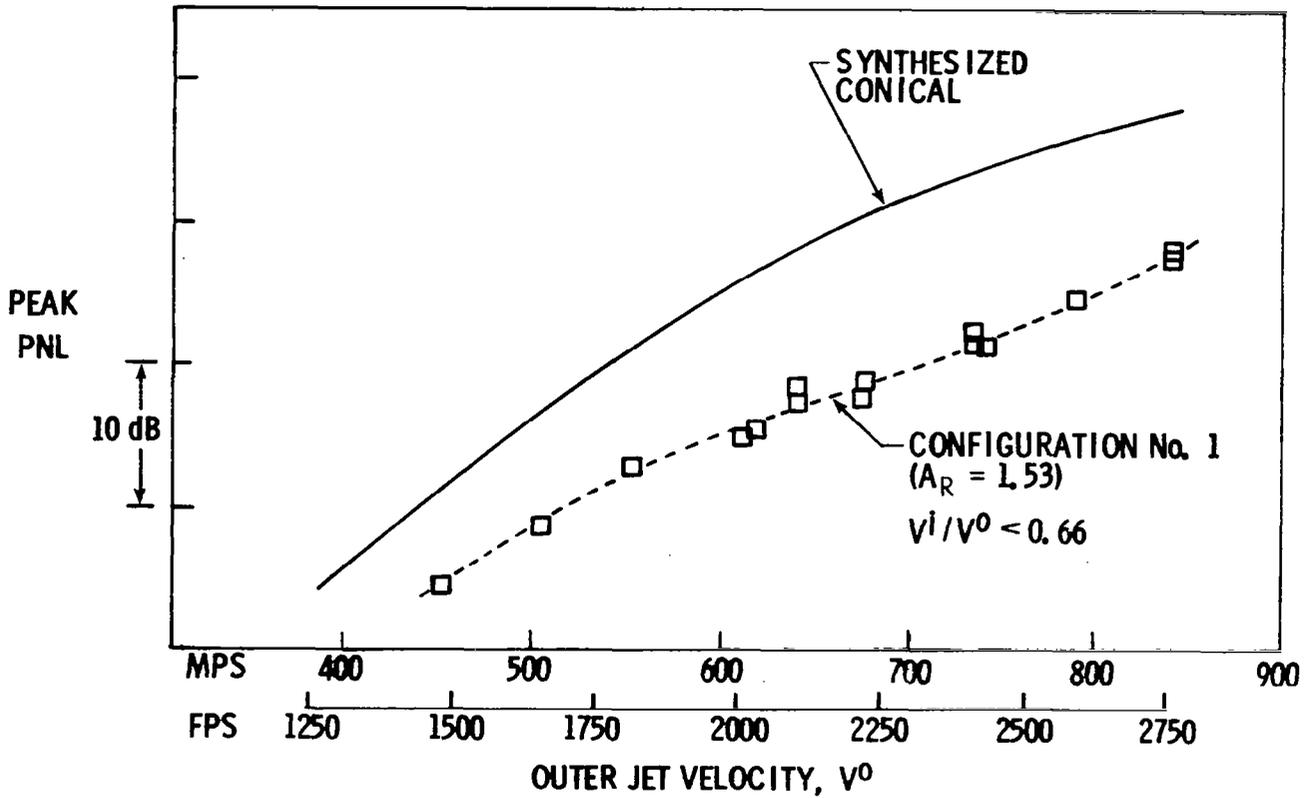
Figure 8.- Typical inverted coannular nozzle noise reduction relative to a synthesized conical nozzle as a function of outer velocity. 732 m (2400 ft) distance; scaled to .33 m^2 (513 in^2); static.
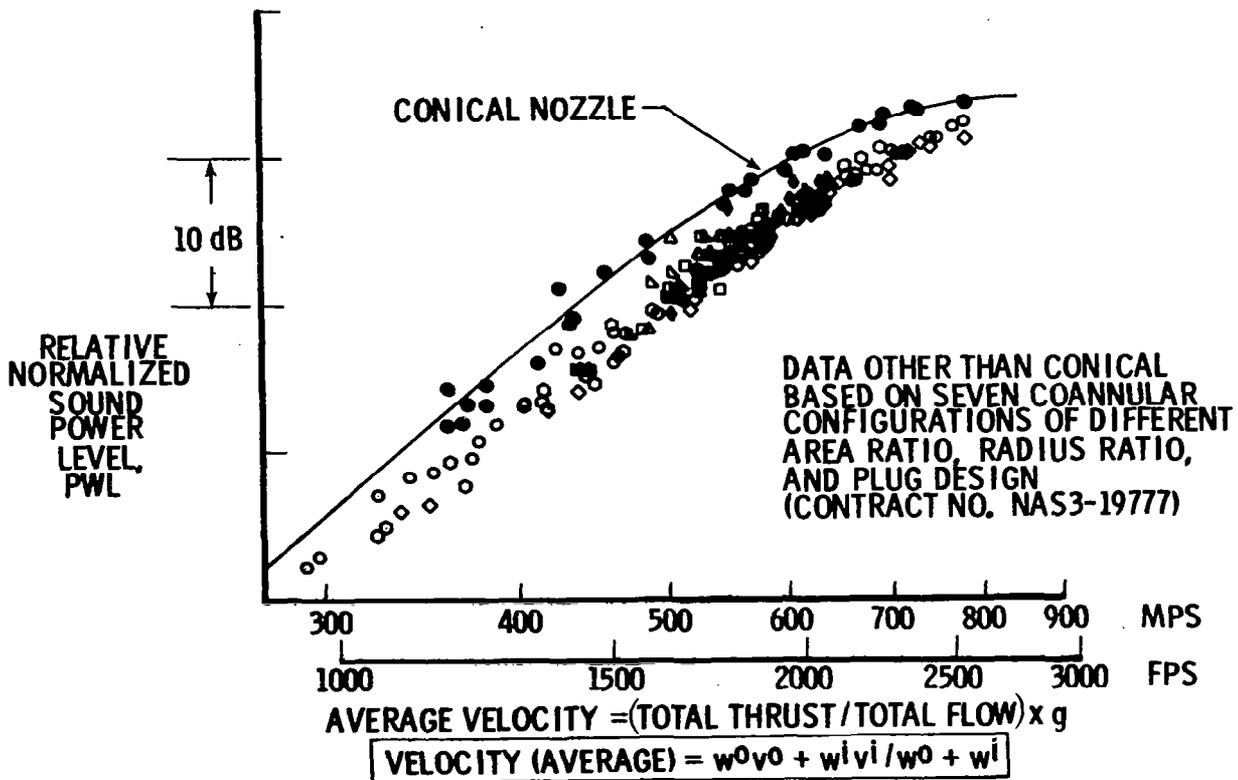
Figure 9.- Coannular nozzle sound power level (PWL) correlation. PWL normalized for density and thrust (ideal); .33 m^2 (513 in^2) nozzle area.
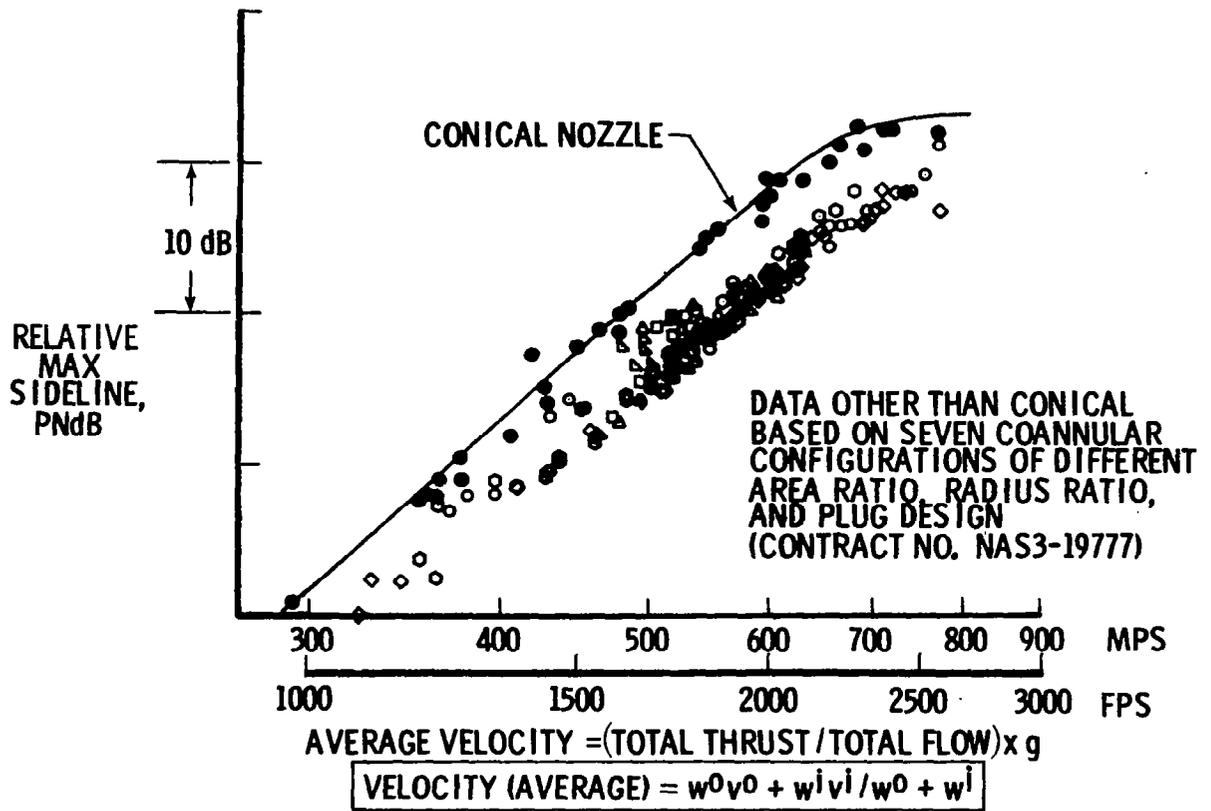
Figure 10.- Coannular nozzle maximum perceived noise level (PNdB)
    correlation. PNdB normalized for jet density and thrust (ideal);
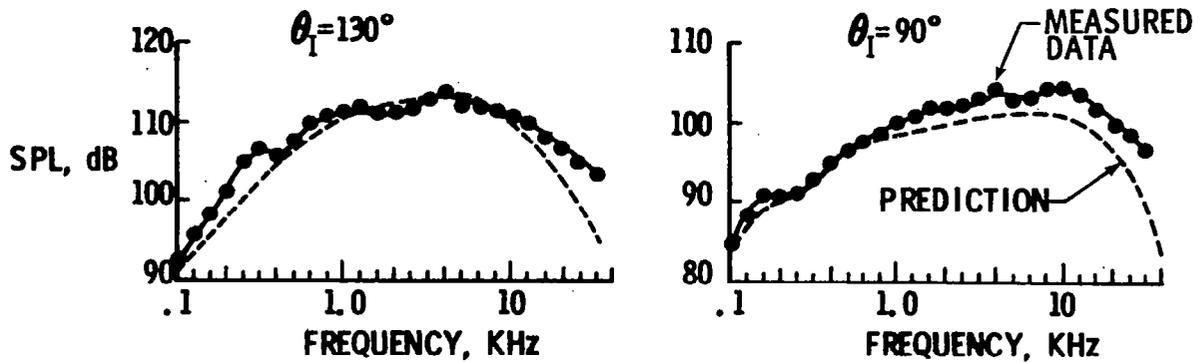   732 m (2400 ft) distance; .33 m² (513 in²) nozzle area.

Figure 11.- Comparison between measured and predicted spectra for
inverted coannular nozzle. See figure 12 for area and flow
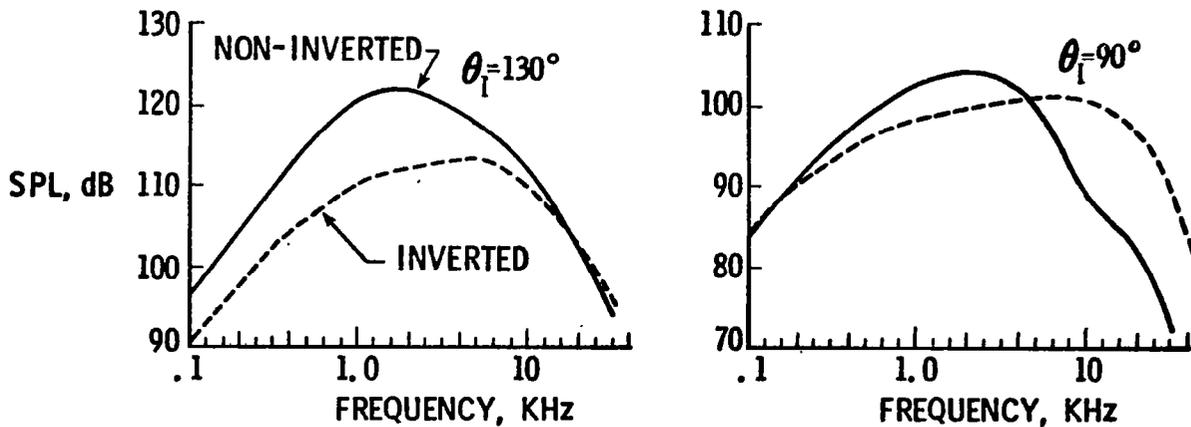conditions.

Figure 12.- Theoretical predictions of spectral characteristics of
inverted versus non-inverted (conventional bypass) coannular
nozzles. (Predictions based on preliminary results from work
supported by FAA contract DOT OS 30034.) Scale model size; high
velocity stream: V = 721 m/s (2366 ft/sec); low velocity stream:
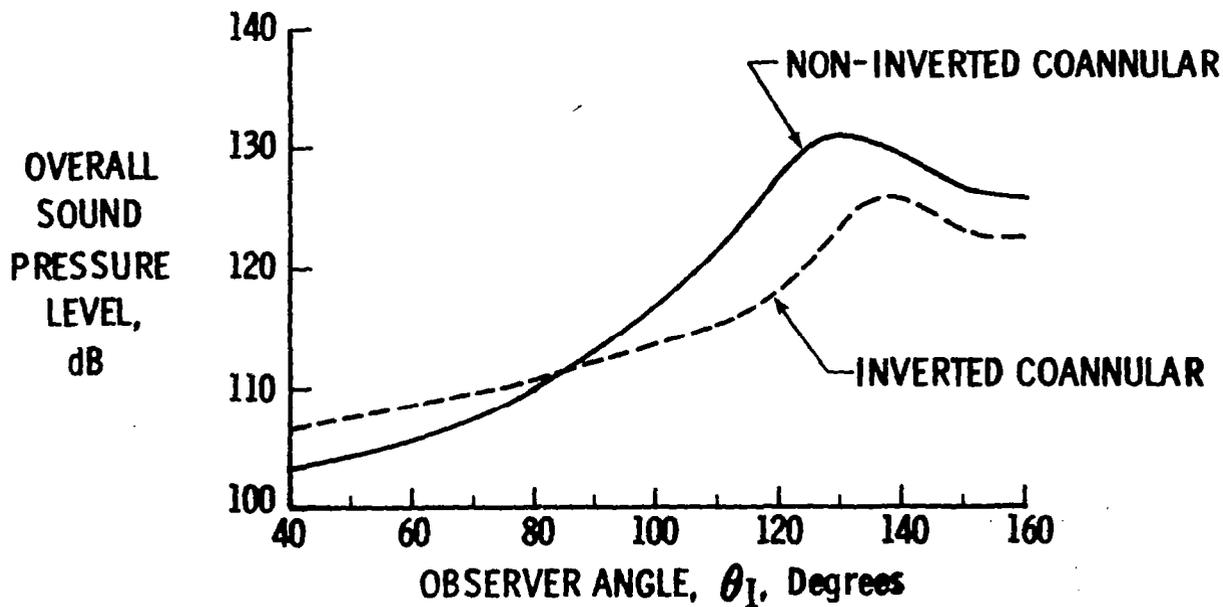V = 372 m/s (1219 ft/sec); 12.2 m (40 ft) arc.

Figure 13.- Theoretical prediction of directional characteristics of inverted and non-inverted (conventional bypass) coannular nozzles. (Prediction based on preliminary results from work supported by FAA contract DOT OS 30034.) See figure 12 for area and flow conditions; scale model size; 12.2 m (40 ft) arc.
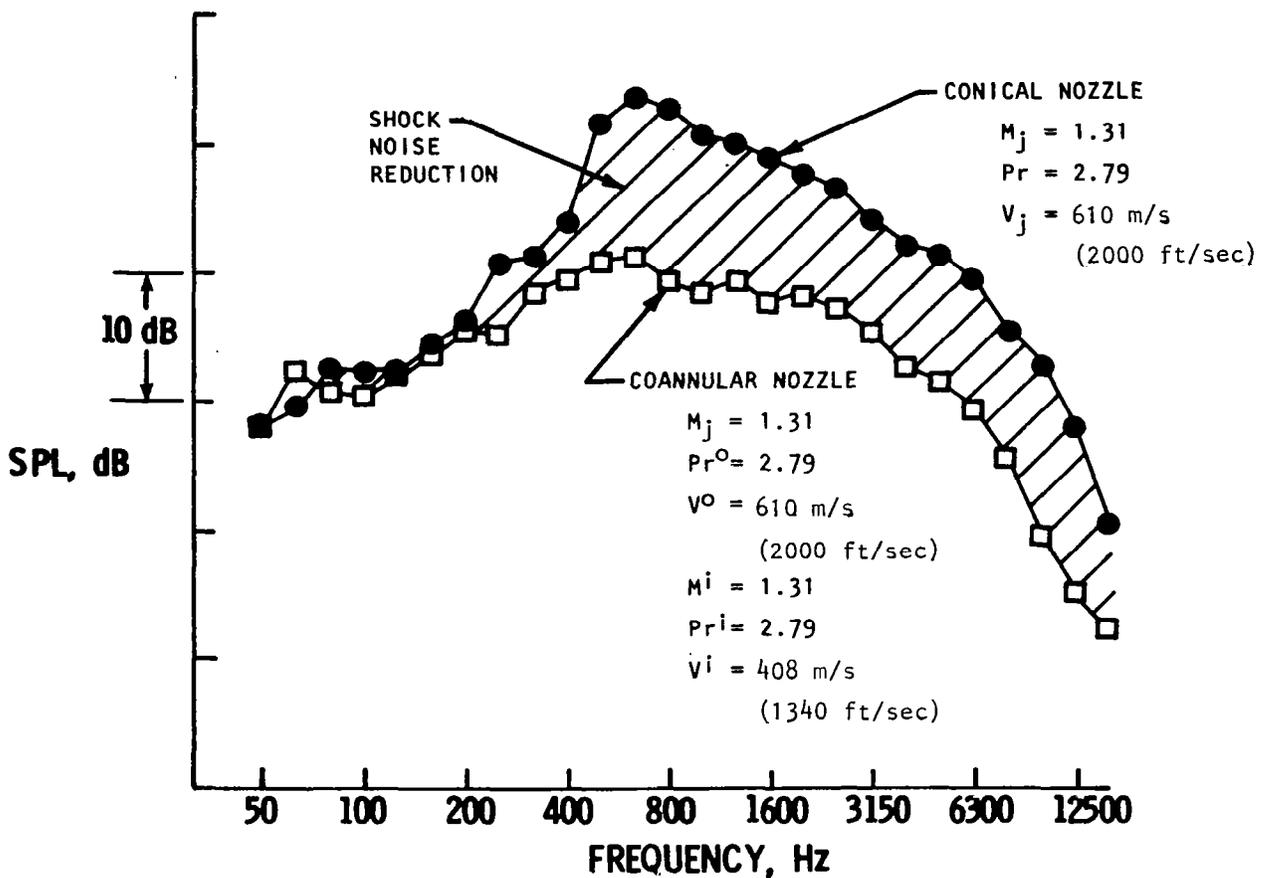
Figure 14.- Inverted coannular nozzle shock noise spectral characteristics relative to a conical nozzle, configuration 7. 91 m (300 ft) sideline; data scale to .33 m^2 (513 in^2); θ_I = 50°.
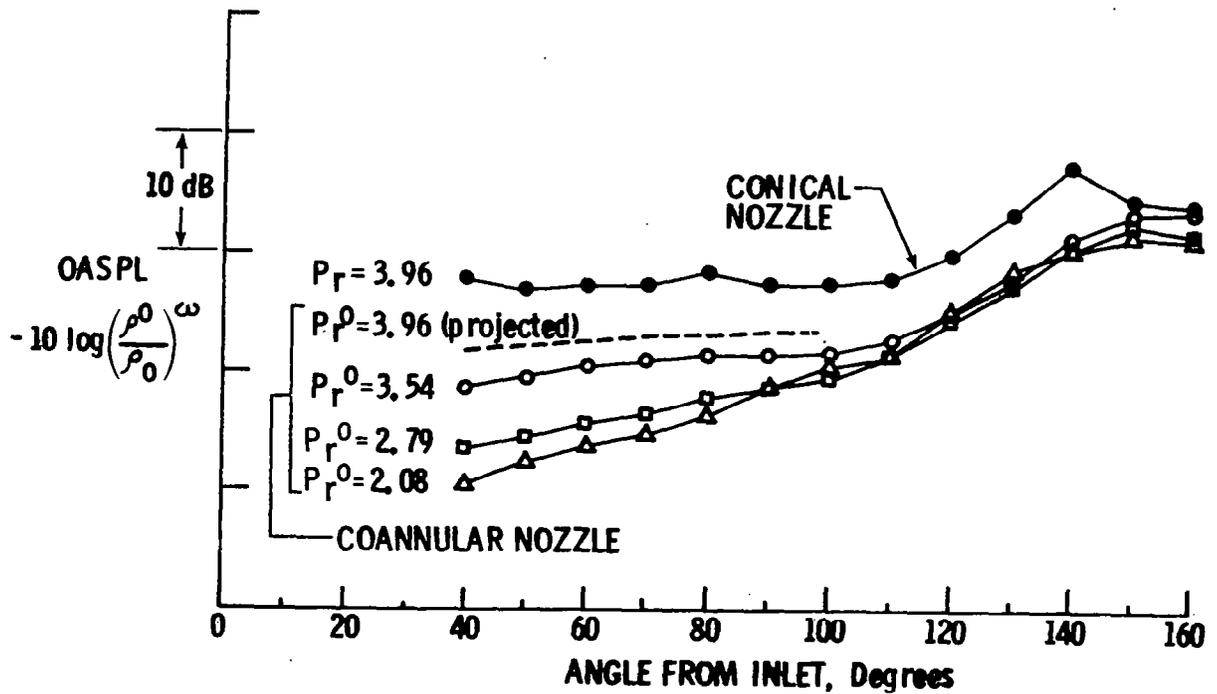
Figure 15.- Inverted coannular nozzle shock noise directivity characteristics relative to a conical nozzle. 45.7 m (150 ft) arc; data scaled to .33 m^2 (513 in^2); $V_j = V^o = 610$ m/s (2000 ft/sec) for all cases; $V^i = 414$ m/s (1360 ft/sec); $P_r^i = 2.8$ for all cases; configuration No. 7.