

AEROACOUSTIC STUDIES OF COANNULAR NOZZLES SUITABLE FOR SUPERSONIC CRUISE AIRCRAFT APPLICATIONS

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SUMMARY

Research programs have been conducted to investigate experimentally the aeroacoustic characteristics of scale-model, inverted-velocity-profile coannular nozzles. These programs include studies of unsuppressed configurations with and without center plugs over a variety of radius ratios and area ratios. Also included in these studies have been suppressed configurations, the effect of ejectors, and some simulated flight effects. Unsuppressed inverted-velocity-profile coannular nozzles seem to allow jet mixing noise compliance with present FAR-36 regulations when applied to supersonic cruise aircraft engine cycles. Simulated flight tests suggest that the aeroacoustic benefits of the inverted-velocity-profile coannular nozzles would be maintained in flight.

INTRODUCTION

The results of aeroacoustic studies of inverted-velocity-profile coannular nozzles suitable for supersonic cruise aircraft applications are briefly reviewed. These studies have been conducted over the past 3 years by the General Electric Company and the Pratt & Whitney Aircraft Division of United Technologies Corp. under contract to the NASA Lewis Research Center.

Mission analysis studies under the supersonic cruise aircraft research (SCAR) program (refs. 1 and 2) have identified low-bypass-ratio turbofan engines as likely candidates for use in future supersonic cruise aircraft. Two engine concepts of this type are shown in figures 1 and 2. Both concepts feature exhaust systems consisting of two unmixed coaxial streams at takeoff conditions, with the outer stream operating at a higher velocity than the inner stream. The concept shown in figure 1 yields a higher outer-stream velocity by over-extracting the core stream and augmenting the fan stream through burning in the fan duct (duct-burning turbofan (DBTF)). In the concept shown in figure 2, the inverted profile is obtained by ducting the higher velocity core flow outward and ducting the lower velocity, cooler fan air inward. The fan air then surrounds the center plug (double-bypass, variable-cycle engine).

The inverted-velocity-profile exhaust concept should introduce acoustic benefits during the takeoff and landing portions of the mission. These expected benefits, associated with the small radial height of the high-velocity stream, are as follows: (1) peak noise generation at higher frequency, which

is more amenable to dissipation through atmospheric absorption or, in the case of an ejector, to application of acoustic liners to the ejector walls; and (2) the easier application of mechanical suppressors because the narrow height of the outer stream would allow easier stowing of the hardware for those portions of the mission where noise generation is unimportant. However, insufficient information was available in the literature to allow evaluation of the actual noise characteristics of the inverted-velocity-profile coannular nozzles, with or without the use of mechanical suppressors.

The work described herein is the result of NASA-sponsored programs dedicated to filling that void. Under these experimental research programs, static aeroacoustic data have been obtained for a variety of inverted-velocity-profile coannular nozzles covering a wide range of geometric configurations, temperature and pressure ratios, and velocity conditions. The scale-model test nozzles were 13 to 15 centimeters in equivalent diameter. The scale-model nozzles included unsuppressed coannular nozzles, with and without center plugs; suppressed fan stream configurations (including multitube, convoluted, and multichute suppressors); and the application of lined and unlined ejectors. The effect of varying area and radius ratios on the unsuppressed coannular nozzles was also investigated. Data were obtained at stream temperatures from ambient to 1090 K, pressure ratios from 1.3 to 4.0, and velocities from 170 to 870 meters per second. In addition, simulated flight studies were made with smaller, 5.5-centimeter-equivalent-diameter, unsuppressed coannular nozzles over a reduced range of operating conditions.

The principal results obtained to date in these programs are summarized herein. These results and the continuing studies are characterized by very favorable acoustic and aerodynamic (high thrust coefficient) performance obtained with the unsuppressed coannular nozzles. These results could lead to the design of a practical supersonic cruise commercial aircraft.

COANNULAR NOZZLES

A simplified sketch of a coannular nozzle showing the inner, or core, nozzle surrounded by the outer, or fan, nozzle is shown in figure 3. The two exhaust streams form three regions of turbulence that are important to the generation of jet noise: region I, where the inner flow and outer flow mix; region II, where the outer flow mixes with the ambient air; and region III, where the merged jets mix with the ambient air. Each region generates noise. Their relative importance to the overall jet noise signature of a particular coannular nozzle depends on the relative sizes and velocities of the two streams.

The velocity profile characteristics of conventional subsonic coannular nozzles are shown in figure 4. These nozzles have large outer-stream to inner-stream area ratios A_o/A_i with outer-stream to inner-stream velocity ratios V_o/V_i of the order of 0.7 to 0.8. In this type of coannular nozzle, the inner-stream/outer-stream and merged-jet/ambient-air mixing regions (regions I and III, respectively, in fig. 2) are the significant noise-producing parts of the jet. These nozzles are applicable to high-bypass-ratio turbofan engines suit-

able for conventional and short-takeoff-and-landing (STOL) aircraft applications. Sufficient experimental work (e.g., refs. 3 and 4) has been conducted on nozzles of this type covering a wide enough variation in area ratio, velocity ratio, and exit plane offset to permit the generation of prediction curves. These prediction curves have already been incorporated into design procedures such as the NASA aircraft noise prediction program (ref. 5) and the currently proposed SAE prediction procedure.

Coannular nozzles that operate with inverted velocity profiles (outer-stream velocity greater than inner-stream velocity) have become primary candidates for application to low-bypass-ratio turbofan engines being considered for use in future supersonic cruise aircraft. This type of nozzle, shown schematically in figure 5, is characterized by a small A_o/A_i ratio (of the order of 1) and a V_o/V_i ratio in the range of 1.5 to 2.0. With this type of nozzle, the outer-stream/ambient-air and merged-jet/ambient-air mixing regions (regions II and III, respectively, in fig. 2) are the dominant sources of jet noise. The prediction methods based on conventional coannular jet data, where the inner-stream/outer-stream and merged-jet/ambient-air mixing regions are dominant and V_o/V_i ratios are less than 1, do not apply. To fill this gap in jet mixing noise technology, the Lewis Research Center sponsored experimental studies over the last 3 years with Pratt & Whitney Aircraft and General Electric to determine the noise characteristics of inverted-velocity-profile coannular nozzles.

The jet noise prediction method for coannular jets published by the SAE in 1965 (ref. 6) was used to establish a noise-level reference for the inverted-velocity-profile nozzles. This method, herein referred to as "synthesis," recommends that the coannular noise be synthesized by adding antilogarithmically the noise levels produced by two convergent nozzles with areas and jet velocities corresponding to each stream as if it were acting alone. This SAE procedure for synthesizing coannular noise is shown schematically in figure 6 and is used in this paper as an arbitrary reference against which to compare experimental results. The synthesis method does not account for the effect of stream interaction on jet noise generation.

INVERTED-VELOCITY-PROFILE COANNULAR NOZZLE INVESTIGATIONS

The experimental work conducted to date under this program has covered the following:

- (1) Static performance of basic unsuppressed coannular nozzles
- (2) Static performance of suppressed coannular nozzles
- (3) Effect of geometric variables on unsuppressed coannular nozzles
- (4) Simulated flight effects on unsuppressed coannular nozzles

Basic Unsuppressed Configurations

The two basic unsuppressed nozzle configurations tested in the contractor scale-model studies are shown in figure 7. A coannular nozzle without a plug,

with an area ratio of 0.75, and with an outer-stream radius ratio R_1/R_2 of 0.76 is shown in figure 7(a). (This radius ratio is defined as the ratio of the outer-stream inner radius to the outer-stream outer radius.) The nozzle shown in figure 7(b) is a coannular nozzle with a central plug, an area ratio of 0.67, and an outer-stream radius ratio of 0.90. These test nozzle configurations had equivalent total diameters of 13 and 15 centimeters, respectively.

Results from the experimental research programs are plotted in figure 8 as peak perceived noise level (normalized for jet density effects)¹ as a function of outer-stream velocity for cases where the outer-stream velocity was at least 1.5 times the inner-stream velocity. The jet noise levels for the coannular nozzles are 6 to 10 PNdB lower than the synthesized value calculated by the method shown in figure 6 (both jets exhausting through separate conical nozzles). The configuration with a central plug, which had a higher outer-stream radius ratio, showed a 2-PNdB-greater noise reduction than the nozzle without a plug, which had a lower outer-stream radius ratio. The measured thrust losses are about 1.5 to 2.0 percent (referred to an ideal nozzle).

In figure 9 the unsuppressed coannular acoustic power level (PWL) spectrum has been scaled up to engine size and compared with the spectrum for a mixed turbofan (single convergent exhaust nozzle) with the same total flow rate and thrust. As shown in figure 9 the unsuppressed coannular nozzle at these operating conditions is about 5 to 6 decibels lower in overall PWL than the mixed-turbofan exhaust nozzle at equal flow and thrust conditions.

Suppressed Annular Configurations

In addition to these basic unsuppressed coannular configurations, configurations with mechanical suppressors were also tested by adding chutes, convolutions, or tubes to the outer stream and, in some cases, including ejectors. These suppressed configurations are shown in figure 10. The coannular configuration without a plug was tested with multitube and convoluted suppressors; the nozzle with a center plug incorporated multitube and multichute suppressors. In both cases, tests were made with and without ejectors, and the ejectors were tested with and without acoustic liners. In all cases the total flow area and the A_o/A_i were the same as for the corresponding basic unsuppressed coannular nozzle.

Noise data. - In figure 11 the acoustic results obtained for the suppressed configurations are presented in terms of normalized peak perceived noise level as a function of outer-stream velocity. The crosshatched areas represent the suppressed coannular results. The dashed lines are a reproduction of the synthesized and unsuppressed coannular nozzle results already presented in figure 8. At the higher velocities the suppressed configurations yield an additional 3 to 7 PNdB reduction in noise but at the expense of rela-

¹The exponent on the fan jet density is based on conical nozzle results, and for the range of velocity shown here varies from 1.0 at 373 m/sec to 2.0 at velocities above 540 m/sec.

tively large thrust losses (as much as 8 percent greater than with the unsuppressed coannular nozzles).

Comparisons of suppressed and unsuppressed configurations. - The axial velocity decays for suppressed and unsuppressed coannular plug configurations are compared in figure 12. These data were taken with a laser velocimeter at supersonic outer-stream conditions in order to help establish the relation between velocity decay and total noise generation for future analytical coannular jet noise models. In addition to the coannular plug nozzle data, a typical conical nozzle decay curve is shown. The velocity of the unsuppressed coannular nozzle decays much more rapidly than that for the conical nozzle, which is consistent with the lower noise generation shown in figure 8. Both suppressed coannular nozzles shown in figure 12 have about the same velocity decay characteristics, but both have a more rapid decay rate than the unsuppressed coannular nozzle. This trend agrees with the larger noise reductions shown in figure 11 for the suppressed configurations.

The jet noise reductions obtained from suppressed and basic unsuppressed inverted-velocity-profile coannular nozzles are compared in figures 13 and 14 by means of bar graphs. In these figures, the PNL reductions with relation to the synthesized value for the basic unsuppressed configurations without ejectors are given for one outer-stream and one inner-stream velocity in the range of application to supersonic cruise engines. In figure 13 the results of the configurations without plugs are covered, with the reductions ranging from 7 decibels for the unsuppressed coannular nozzle to 15.5 decibels for the multitube coannular nozzle with treated ejector. Similar results are shown in figure 14 for the configurations with center plugs for approximately the same fan velocity as in figure 13. For these configurations the reductions ranged from 10 decibels for the unsuppressed nozzle to 17.7 decibels for the multitube coannular nozzle with treated ejector.

Geometric Variations of Unsuppressed Coannular Nozzles

A study was also conducted of the effect of several geometric variations on the static aeroacoustic performance of the unsuppressed coannular nozzle with center plug. The geometric effects investigated were primarily the radius ratio and area ratio effects. At the same time the velocity ratio effect was expanded over a wider range, reaching the extreme low point where the inner stream was completely shut off. This study used variations of the basic unsuppressed coannular nozzle with center plug shown in figure 7(b). The geometric characteristics of the variations investigated are described in table I.

The effects of velocity ratio on the noise reduction for two different-area-ratio coannular plug nozzles with constant outer-stream radius ratio are shown in figure 15. The noise level relative to the synthesized level predicted for noninteracting jets is plotted as a function of V_1/V_0 ratio for constant outer-stream operating conditions. (The inner-stream velocity was changed by varying both temperature and pressure.) Over this range, the A_0/A_1 ratio has very little effect on the noise. Maximum noise reduction occurs between V_1/V_0 ratios of 0.3 and 0.5. As the inner flow is reduced to very low values, less

noise reduction is obtained, which could be attributed to the lack of sufficient inner flow to promote rapid velocity decay in the energetic outer stream. When the inner flow is increased above a velocity ratio of 0.5, less noise reduction is again obtained, in this case because the inner stream affects the jet noise generated in the merged-jet/ambient-air mixing region (fig. 3).

The effects of outer-stream radius ratio on aeroacoustic performance are shown in figure 16. As the radius ratio is increased (fig. 16(a)), the noise reduction is also increased, indicating the desirability, from an acoustic viewpoint, of designing engine nozzles with a high outer-stream radius ratio. The effect of outer-stream radius ratio on the aerodynamic characteristics is shown in figure 16(b). For a V_i/V_o ratio of 0.5, static thrust losses were between 1 and 2 percent relative to a convergent nozzle. Increasing the outer-stream radius ratio increased thrust losses, indicating the need, from a designer's point of view, to trade off the thrust losses with the noise reduction in order to select the optimum nozzle radius ratio for an engine exhaust system.

Simulated Flight Effects

The acoustic information presented so far on the inverted-velocity-profile coannular nozzles has been static data. However, a most important consideration is whether these noise reductions relative to a convergent nozzle are maintained under flight conditions. Consequently, the acoustic program has also included experimental investigations of some models under simulated flight conditions in an acoustic wind tunnel by Pratt & Whitney Aircraft under NASA Lewis contract. The nozzles used for this part of the program were similar to the unsuppressed coannular nozzle without a plug described in figure 7(a), except that the models were 5.5 centimeters in equivalent diameter due to size limitations imposed by the wind tunnel. Typical results obtained with subsonic velocities in both streams ($V_o/V_i \sim 1.5$) are shown in figure 17. The data are presented in terms of overall sound pressure level (OASPL) as a function of the radiation angle from the nozzle inlet. The wind tunnel results have been corrected for the shear layer and sound convection effects of the tunnel stream and converted to a flight frame of reference by the methods of reference 7. The dashed curve represents the static conditions, and the dash-dot and solid curves show directivities at free-stream Mach numbers of 0.18 and 0.30, respectively. Reductions in jet noise were obtained throughout the measured arc from 70° to 150° from the inlet axis. The peak noise reduction was 5 to 7 decibels below the static case. The most significant result was that the noise reduction due to forward velocity was the same as for a convergent nozzle, indicating that the noise reduction benefit evident for static conditions would be maintained in flight.

Similar results are shown in figure 18 for a case where the outer stream was supersonic (pressure ratio, 2.5). The subsonic inner-stream conditions are the same as for figure 17, producing a V_o/V_i ratio of 1.9 here. The results are very similar except that the peak noise reductions are somewhat smaller in magnitude (by about 1.5 dB) and that in the forward quadrant there is an actual increase in noise level. These changes from the subsonic case are caused by shock-generated noise. However, this forward-quadrant effect does not change

the noise reduction during flight relative to a convergent nozzle because the convergent nozzle is similarly affected. For the 0.30 Mach number data shown, the thrust coefficient losses were increased by an additional 1 percent over those measured for static conditions. As in the subsonic case, the most significant result is that the noise reduction benefit evident for static conditions would be maintained in flight.

CONCLUDING REMARKS

Aeroacoustic experimental investigations on inverted-velocity-profile coannular nozzles have been carried out by the General Electric Company and Pratt & Whitney Aircraft under contract to the NASA Lewis Research Center. The results available to date indicate that this type of coannular nozzle, without the use of mechanical suppressors, generates less noise than two independent convergent jets of equal velocities and areas in the absence of interaction effects. The results also show that at high velocity levels the noise generated is lower than that from an equal-flow and equal-thrust internally mixed turbofan nozzle. Mission analysis studies suggest that the jet mixing and shock noise levels attainable with the unsuppressed coannular nozzles, coupled with the low thrust losses involved (~ 1.5 to 2 percent), are sufficiently low to permit the design of practical supersonic cruise commercial aircraft that will meet present FAR-36 noise requirements.

Mechanically suppressed inverted-velocity-profile coannular nozzles produce larger reductions in noise but are accompanied by significant thrust losses.

The unsuppressed inverted-velocity-profile coannular nozzles generate less noise under simulated flight conditions than under static conditions. This reduction in noise appears to be of the same magnitude as that experienced by convergent nozzles. Therefore, the coannular noise benefits experienced statically should be maintained, for the most part, in flight.

These programs have generated an extensive data base for inverted-velocity-profile coannular nozzles with and without center plugs, over a variety of area ratios and radius ratios, at an extensive combination of velocities, pressures, and temperatures. This data base also covers mechanically suppressed coannular nozzles as well as the effects of lined and unlined ejectors.

APPENDIX

SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations are used in the table and figures.

A_i	inner-stream area, cm^2
A_o	outer-stream area, cm^2
C_v	thrust coefficient, dimensionless
D	ejector diameter, m
D_{ref}	reference diameter, 1.523 m
h_i	inner-stream height, m
L	ejector length, cm
PNL	perceived noise level, PNdB
PNL _{pk}	peak perceived noise level, PNdB
PNL _{syn}	PNL for synthesized coannular nozzle, PNdB
PWL	acoustic power level, dB re 10^{-12} W
OASPL	overall sound pressure level, dB re $20 \mu\text{N}/\text{m}^2$
$R_{1,i}$	inner radius of inner stream, m
$R_{1,o}$	inner radius of outer stream, m
$R_{2,i}$	outer radius of inner stream, m
$R_{2,o}$	outer radius of outer stream, m
SPL _i	sound pressure level for convergent nozzle with area and velocity equal to those of inner stream, dB re $20 \mu\text{N}/\text{m}^2$
SPL _o	SPL for convergent nozzle with area and velocity equal to those of outer stream, dB re $20 \mu\text{N}/\text{m}^2$
SPL _{syn}	SPL for synthesized coannular nozzle (antilogarithmic sum of SPL _i and SPL _o), dB re $20 \mu\text{N}/\text{m}^2$
T_i	inner-stream total temperature, K
T_{mix}	internally mixed turbofan jet total temperature, K
T_o	outer-stream total temperature, K
V	local peak axial velocity, m/sec
V_i	inner-stream velocity, m/sec
V_{mix}	jet velocity of internally mixed turbofan nozzle, m/sec
V_o	outer-stream velocity, m/sec
V_{ref}	reference velocity, 304.8 m/sec
X	axial distance from nozzle exit, cm

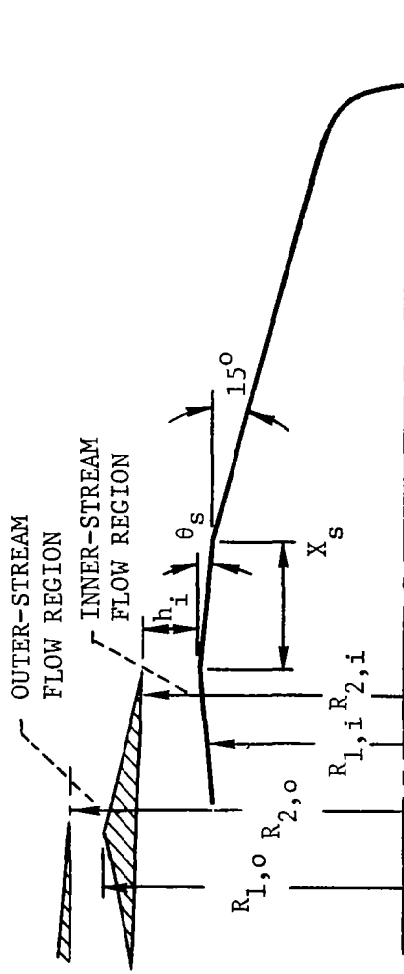
X_s distance from inner-stream exit to plug inflection point, cm
 θ angle from nozzle inlet axis, deg
 θ_s ramp angle of inner plug, deg
 ρ_{isa} ambient density at standard conditions, kg/m^3
 ρ_o outer-stream density, kg/m^3
 ω density correction exponent

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TABLE I. - SUMMARY OF GEOMETRIC CHARACTERISTICS OF VARIATIONS TESTED FOR UNSI

COANNULAR NOZZLE WITH CENTER PLUG



Configuration	Step height, h_i , cm	Outer stream radius ratio, $R_{1,0}/R_{2,0}$	Inner stream radius ratio, $R_{1,i}/R_{2,i}$	Outer stream area, A_o , cm^2	Inner stream area, A_i , cm^2	Area ratio, A_o/A_i	Ratio of inner exit to inflect to step X_s'
1	2.63	0.902	0.673	71.3	111.3	0.65	18.
2	1.61	↓	.800	↓	73.2	.97	0
3	.79	↓	.902	↓	37.9	1.88	0
4	1.61	.853	.800	116.4	73.2	.97	9.
5	1.61	.926	.800	51.7	73.2	1.59	0
6	1.61	.853	.902	116.4	73.2	.71	0
7	.79	↓	↓	↓	37.9	3.07	0

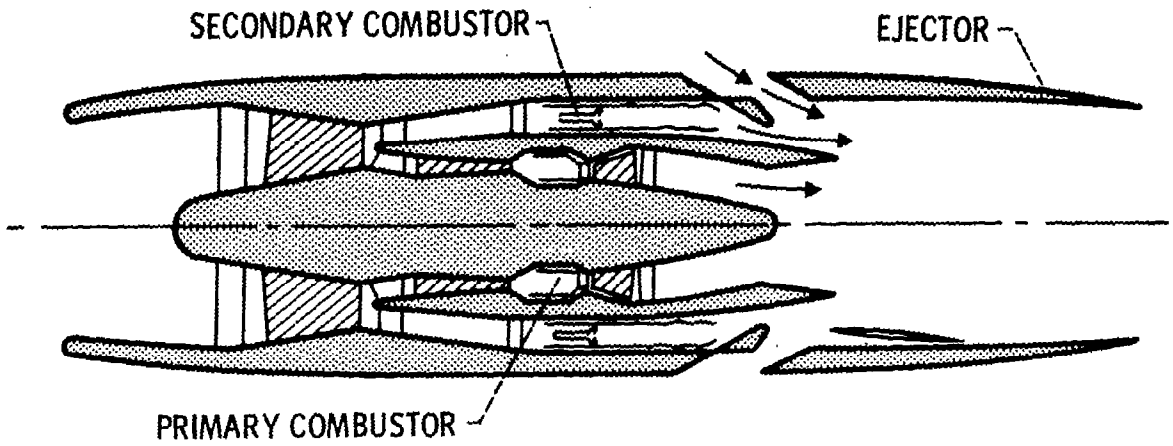


Figure 1.- Low-bypass turbofan concept - duct-burning turbofan (DBTF).

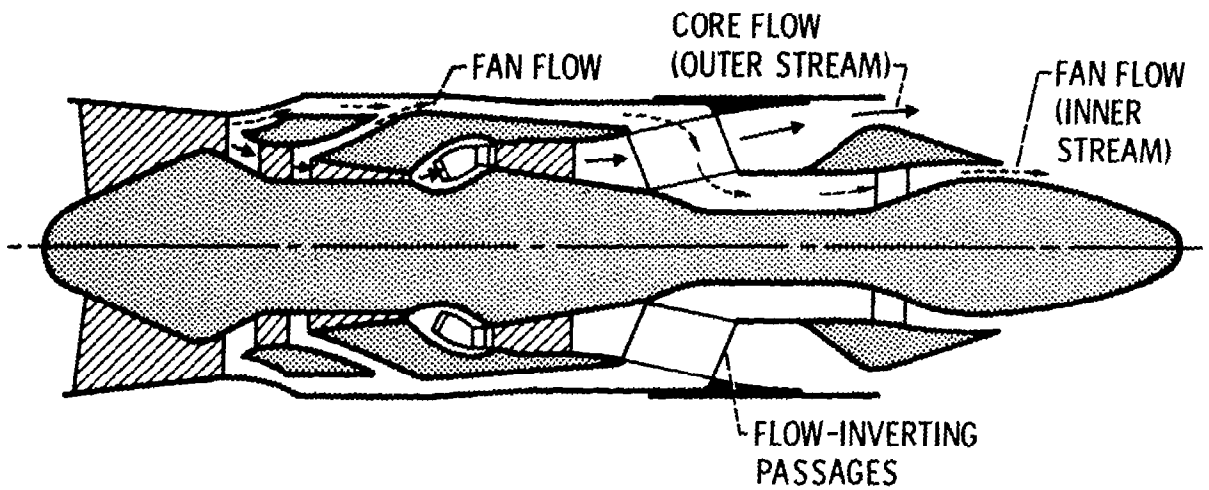
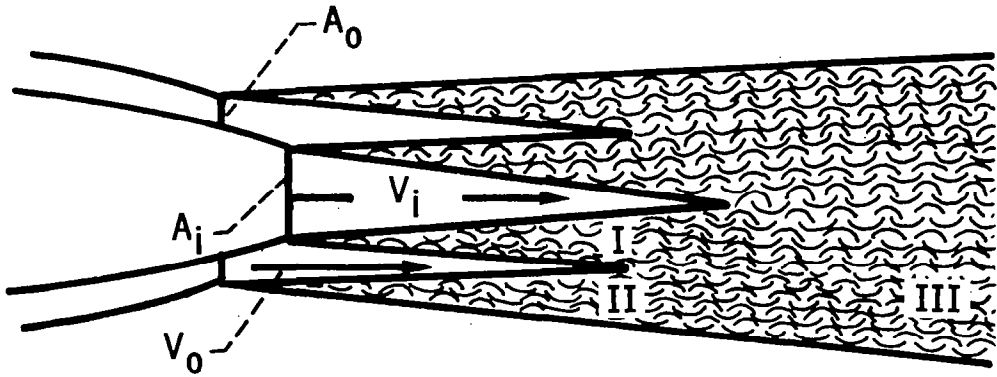


Figure 2.- Low-bypass turbofan concept - double-bypass, variable-cycle engine (VCE).



THREE NOISE-PRODUCING REGIONS:

- I. INNER-STREAM/OUTER-STREAM MIXING
- II. OUTER-STREAM/AMBIENT-AIR MIXING
- III. MERGED-JETS/AMBIENT-AIR MIXING

Figure 3.- Noise-producing regions in coannular jets.

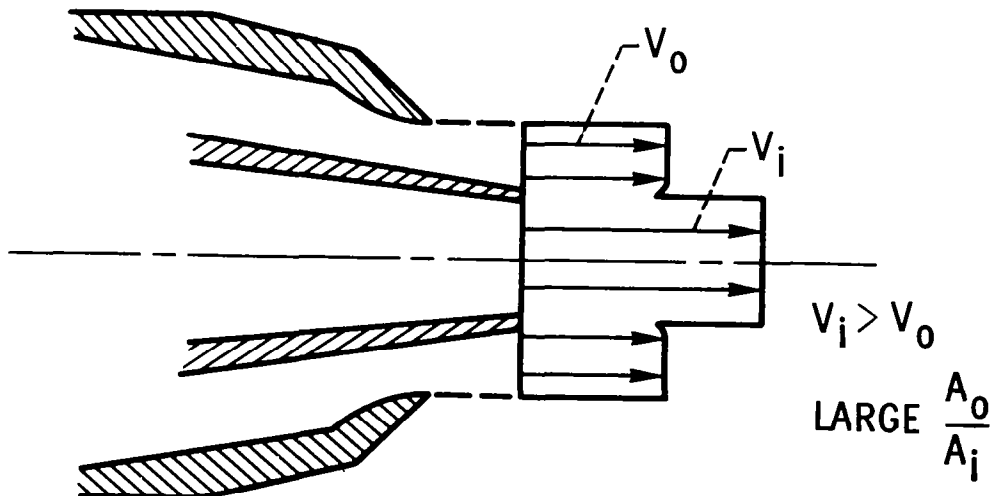


Figure 4.- Conventional coannular nozzles typical of high-bypass-ratio turbofans applicable to CTOL and STOL aircraft.

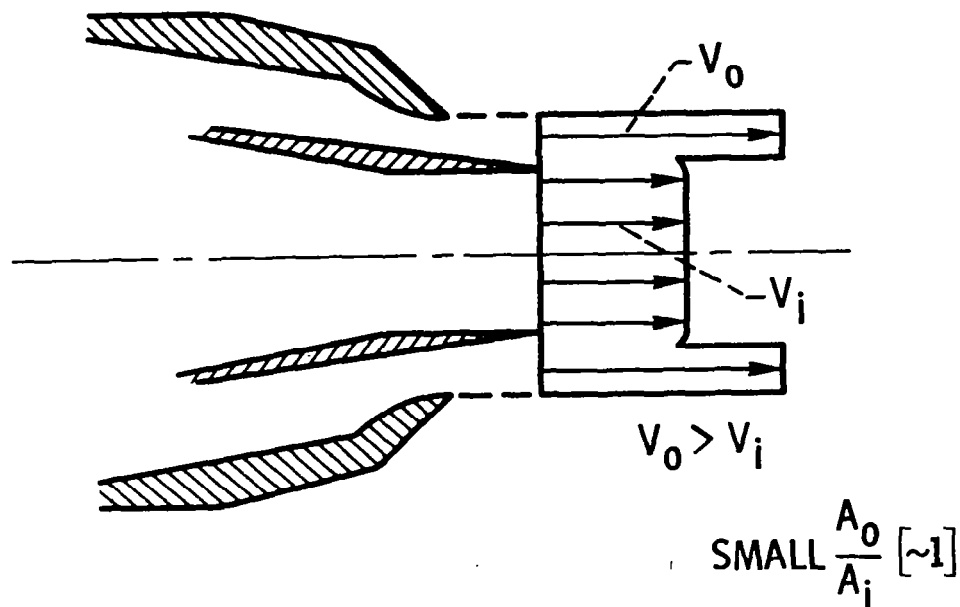
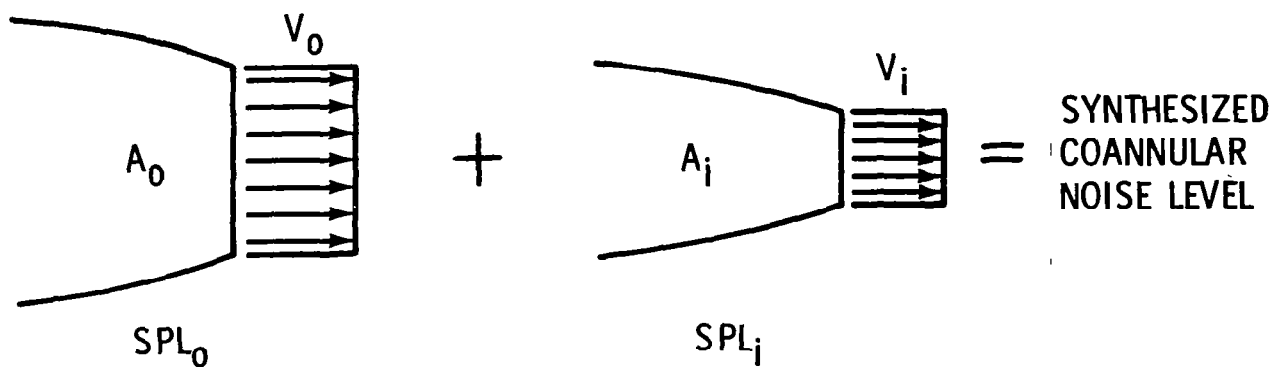


Figure 5.- Inverted-velocity-profile coannular nozzles typical of low-bypass-ratio turbofans applicable to supersonic cruise aircraft.



$$10 \log \left[\log^{-1} \left(\frac{SPL_o}{10} \right) + \log^{-1} \left(\frac{SPL_i}{10} \right) \right] = SPL_{syn}$$

Figure 6.- Synthesis of coannular noise level (identical to recommended prediction procedure SAE AIR876, July 10, 1965).

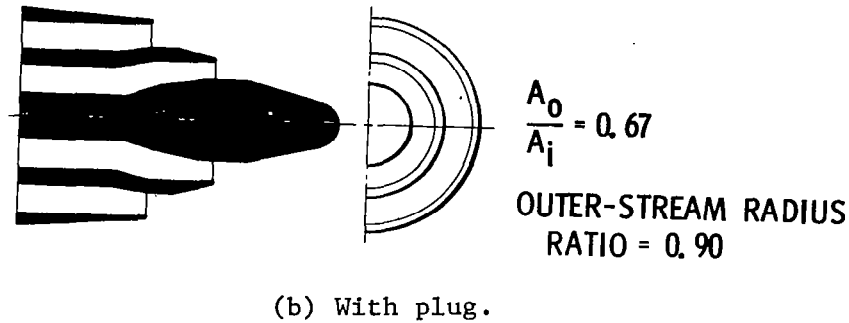
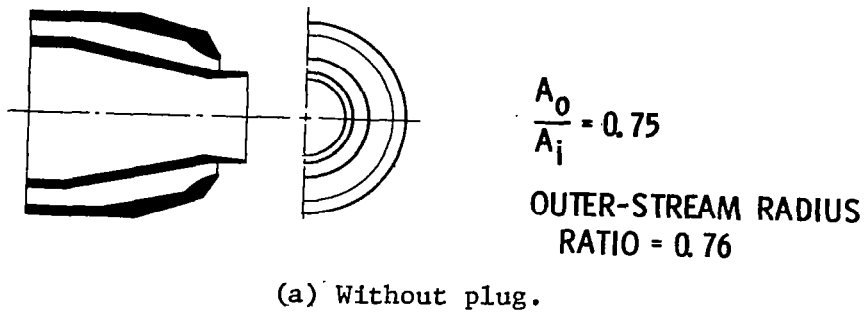


Figure 7.- Representative test configurations of inverted-velocity-profile unsuppressed coannular nozzles.

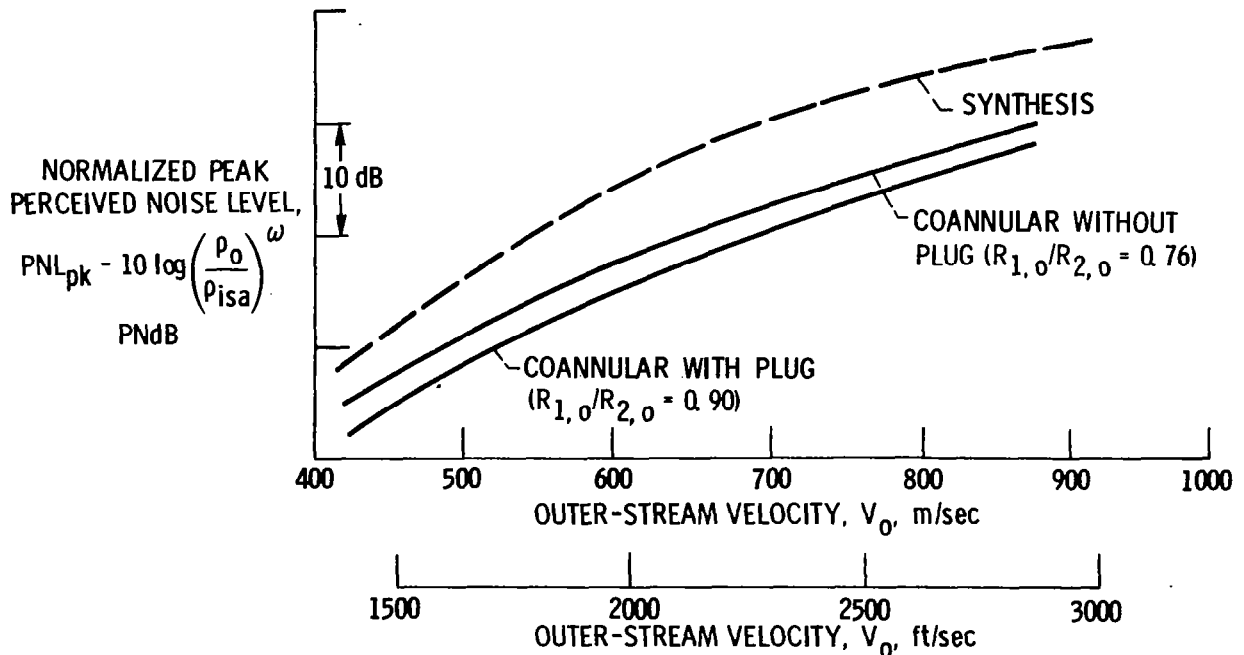


Figure 8.- Peak noise level as function of outer-stream velocity for typical inverted-velocity-profile unsuppressed coannular nozzles. Sideline distance, 649 m (2128 ft); altitude, 366 m (1200 ft); $V_o \geq 1.5 V_i$.

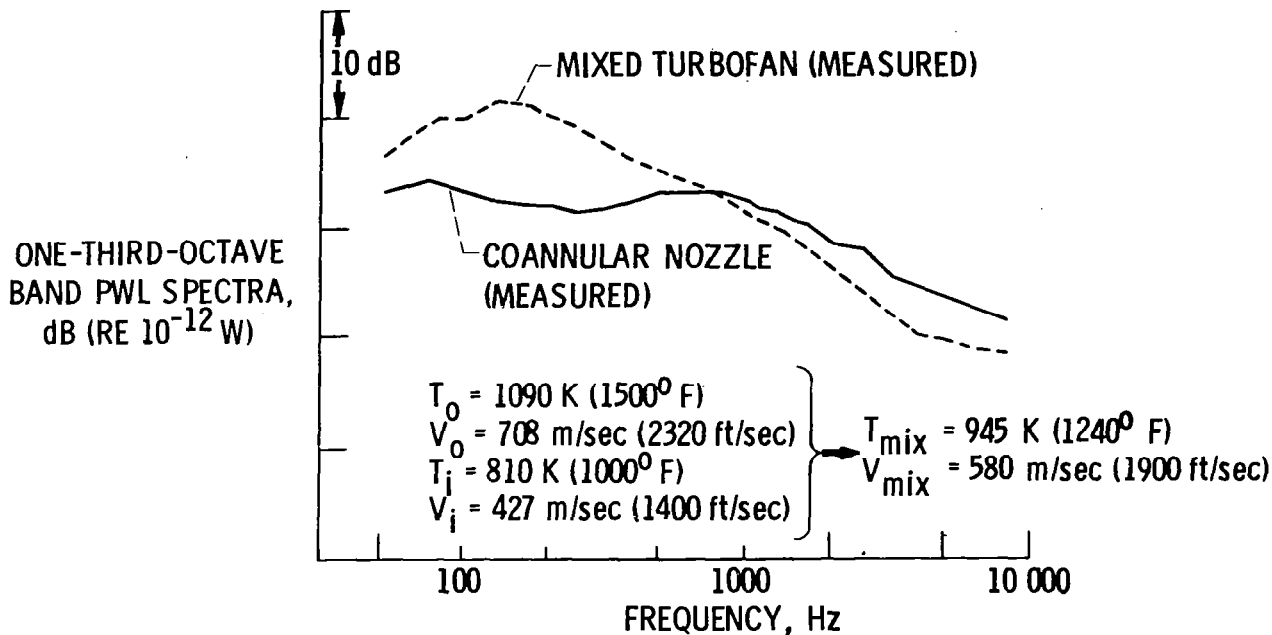


Figure 9.- Acoustic power spectra of unsuppressed inverted-velocity-profile coannular nozzle compared with equivalent mixed-turbofan single nozzle at equal flow and thrust conditions.

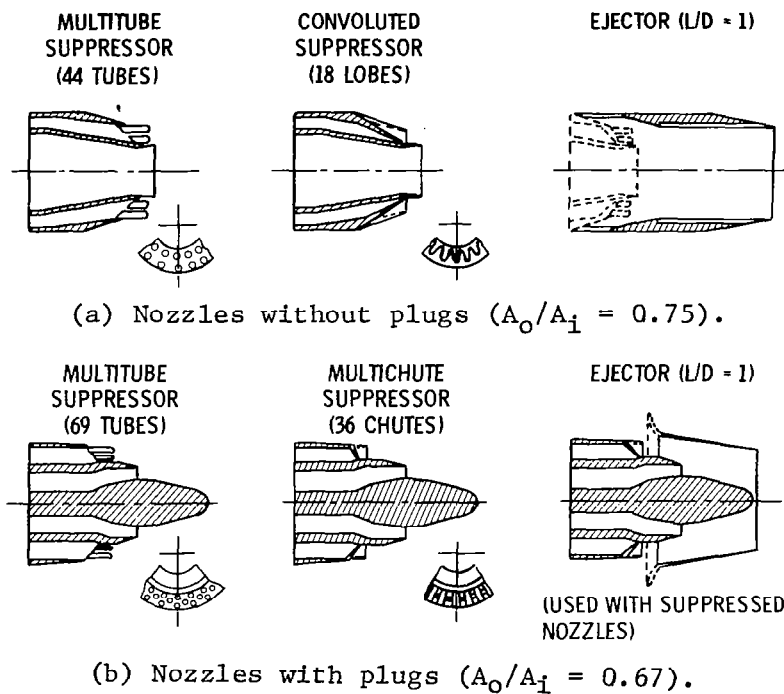


Figure 10.- Test configurations of inverted-velocity-profile coannular nozzles with outer-stream suppressors.

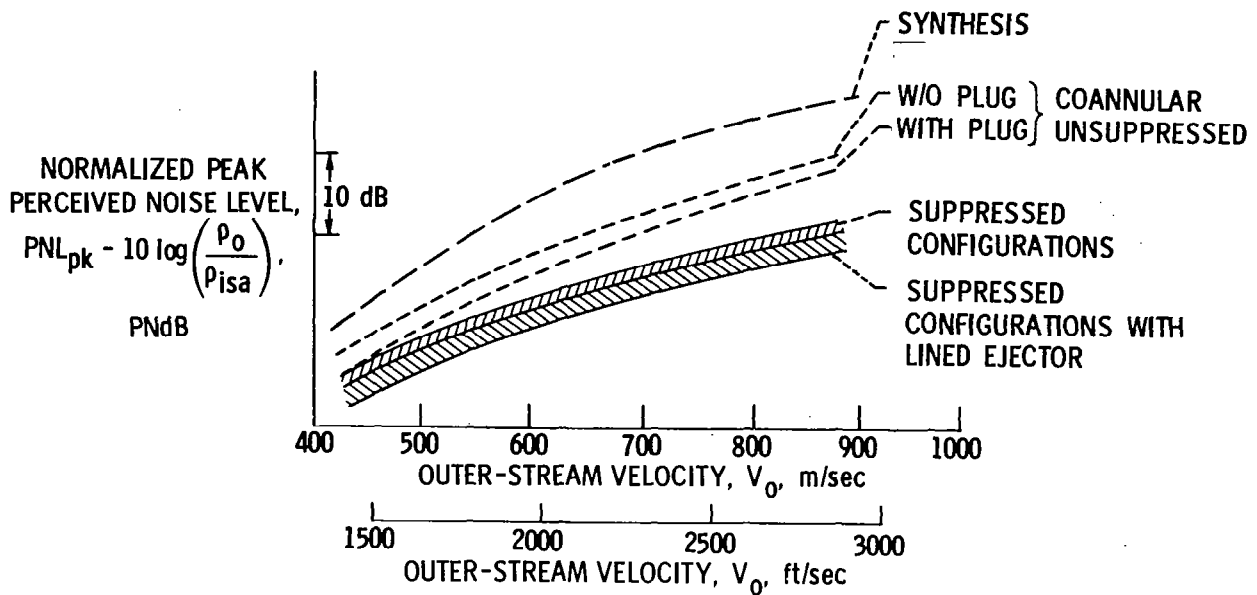


Figure 11.- Peak noise level as function of outer-stream velocity for typical inverted-velocity-profile coannular nozzles. Sideline distance, 649 m (2128 ft); altitude, 366 m (1200 ft); $V_o \geq 1.5 V_i$.

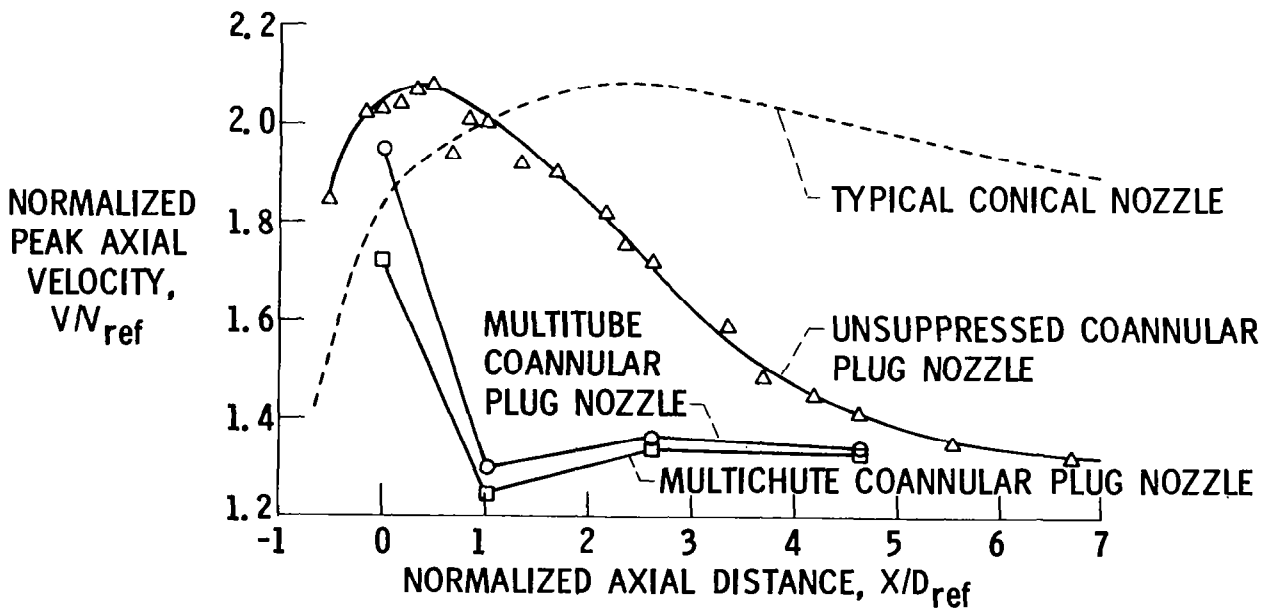


Figure 12.- Variation of peak axial velocity for suppressed and unsuppressed coannular plug nozzles. Total pressure ratio: inner stream, 1.5; outer stream, 2.86. Total temperature: inner stream, 812 K; outer stream, 784 K. Reference velocity, 304.8 m/sec (1000 ft/sec); reference diameter, 15.23 cm (6 in.).

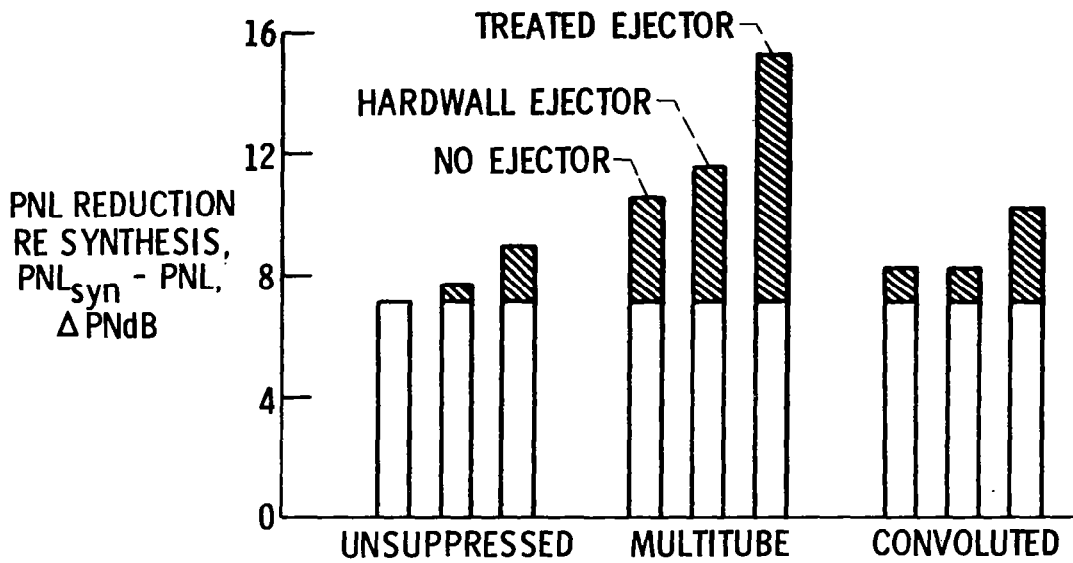


Figure 13.- Jet noise reductions relative to synthesized values for suppressed and unsuppressed coannular nozzles without plugs. Outer-stream velocity V_o , 714 m/sec (2340 ft/sec); inner-stream velocity V_i , 503 m/sec (1650 ft/sec).

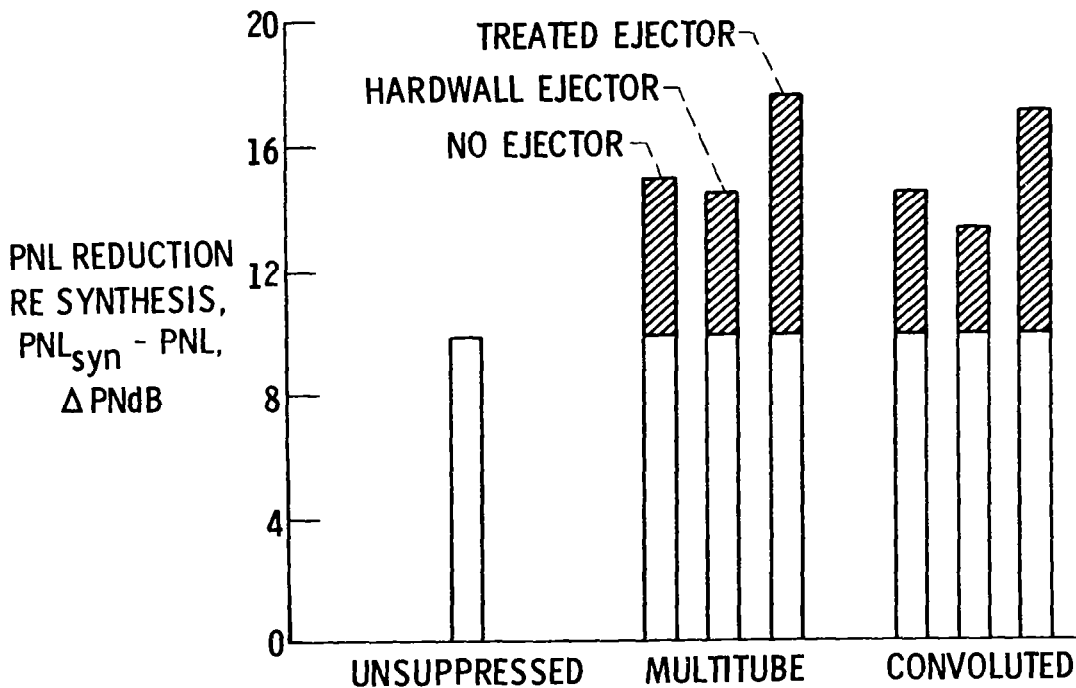


Figure 14.- Jet noise reductions relative to synthesized values for suppressed and unsuppressed coannular nozzles with plugs. Outer-stream velocity V_o , 732 m/sec (2400 ft/sec); inner-stream velocity V_i , 366 m/sec (1200 ft/sec).

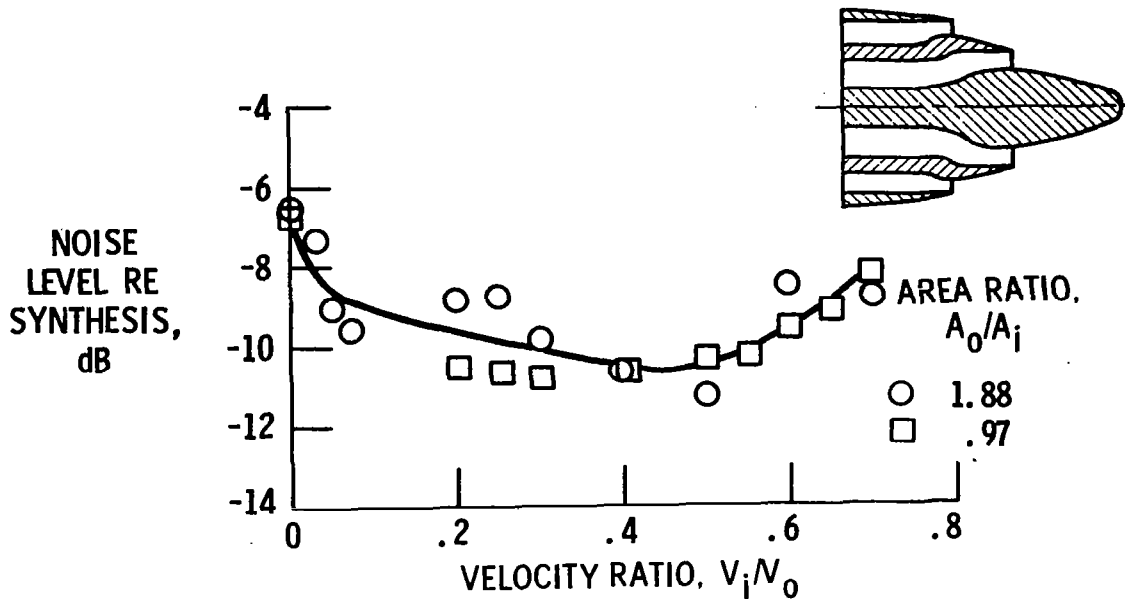


Figure 15.- Noise reduction of inverted-velocity-profile coannular nozzles as function of velocity ratio. Outer-stream radius ratio $R_{1,o}/R_{2,o}$, 0.90; outer-stream velocity V_o , 700 m/sec (2300 ft/sec); outer-stream temperature T_o , 958 K (1725° R); angle from nozzle inlet axis θ , 130°.

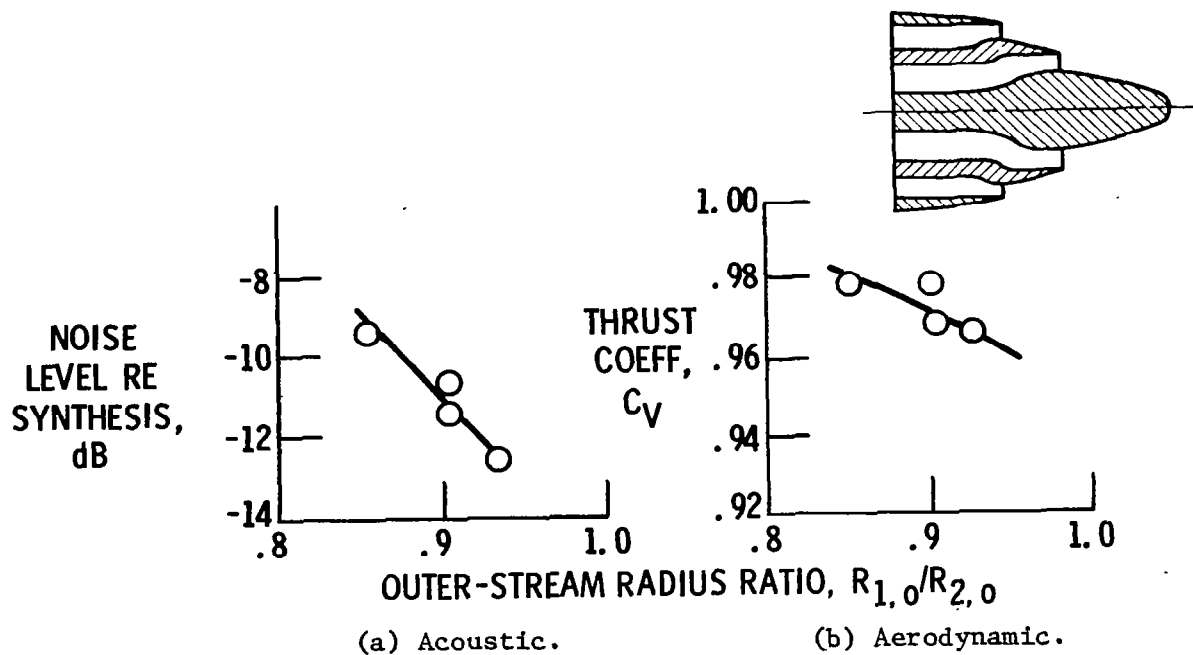


Figure 16.- Aeroacoustic performance of inverted-velocity-profile coannular nozzles as function of outer-stream radius ratio. $V_i/V_o = 0.5$.

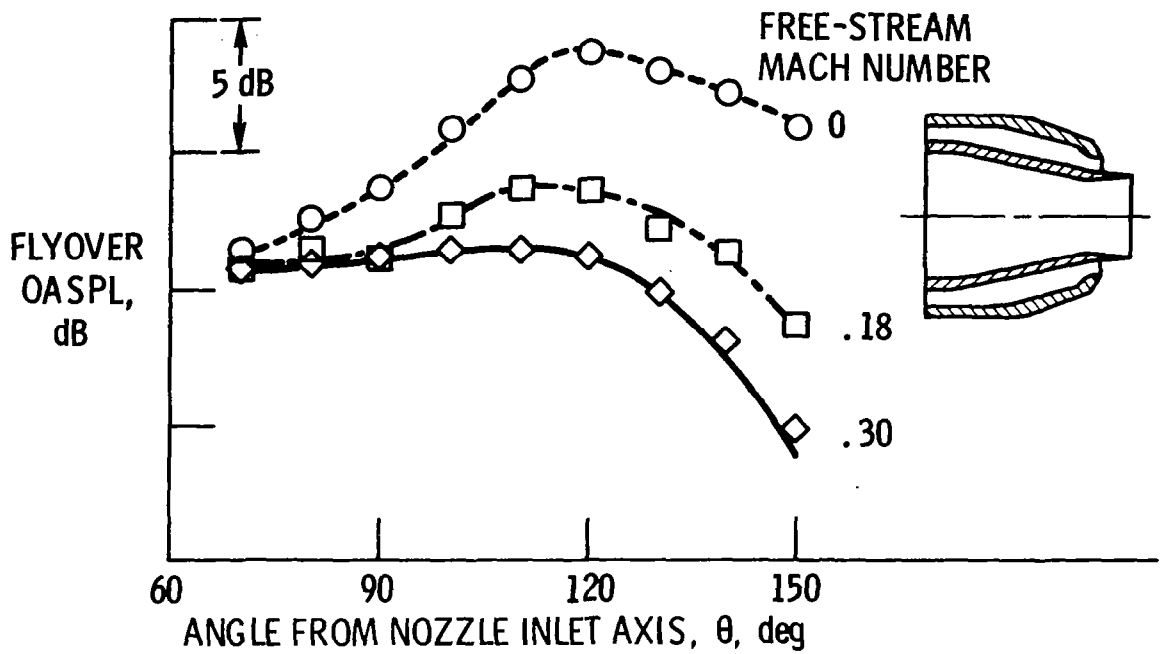


Figure 17.- Static and simulated flight directivities for inverted-velocity-profile coannular nozzles with subsonic outer streams (outer-stream pressure ratio, 1.8). $V_o/V_i \sim 1.5$.

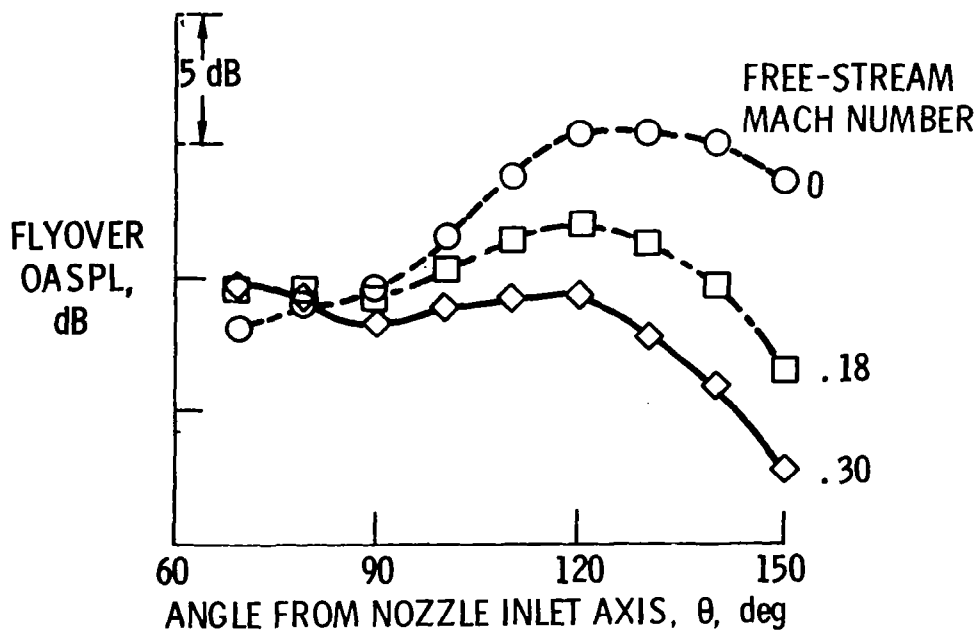


Figure 18.- Static and simulated flight directivities for inverted-velocity-profile coannular nozzles with supersonic outer streams (outer-stream pressure ratio, 2.5). $V_o/V_i = 1.9$.