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DEVELOPMENTS IN AIRCRAFT JET NOISE TECHNOLOGY

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SUMMARY

This paper briefly describes significant developments in two areas of jet noise technology: the development of jet noise technology relative to coannular nozzles of all types, and a recent approach to the analysis of flight effects that appears to allow simulated flight effects results to be transformed to actual flight conditions with a high degree of confidence. The coannular nozzle section presents results applicable to high-bypass-ratio turbofan engines, as well as current work on inverted-profile coannular nozzles applicable to low-bypass-ratio turbofan engines suitable for use in future supersonic cruise aircraft.

INTRODUCTION

This paper reviews some of the progress made in jet noise technology since the Aircraft Engine Noise Reduction Conference held at the NASA Lewis Research Center 4 years ago and reported in reference 1. During this time span, Lewis in-house and contracted technology programs have been concerned with noise problems typical of a variety of aircraft, as illustrated in figure 1. These aircraft include conventional aircraft (CTOL) and powered-lift aircraft using engines located over the wing (OTW) and under the wing (UTW), all of which use medium- to high-bypass-ratio turbofan engines, as well as supersonic cruise aircraft, which use low-bypass-ratio turbofan engines. Common to all these aircraft is the use of some type of turbofan engine. This has been reflected in the emphasis placed on the study of coannular jet noise, as is described in this paper. In addition, a recent approach to the understanding of the effects of flight on jet engine exhaust noise is discussed.

Other significant jet noise work being carried out at Lewis in such fields as jet noise suppressor technology and jet-surface interaction noise have not been covered in this paper because of time limitations.

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COANNULAR JET NOISE

Because turbofan engines are the primary candidates for all these types of aircraft, the study of coannular jet noise has been of cardinal importance. Figure 2 is a generalized sketch of a coannular nozzle showing the inner, or core, nozzle surrounded by the outer, or fan, nozzle. The two exhaust streams form three regions of turbulence that are important in the generation of jet noise: the region where the core flow and fan flow mix (region I); the region where the fan flow mixes with the ambient air (region II); and the region where the merged jets mix with the ambient air (region III). Each of these regions generates noise, and 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.

Conventional Coannular Nozzles

Over the past few years a large amount of research has been done on the jet noise characteristics of "conventional" coannular nozzles (e.g., refs. 2 and 3). Figure 3 shows the characteristics of the conventional coannular nozzles. These nozzles have large fan area to core area ratios and fan velocity to core velocity ratios less than 1.0. In this type of coannular nozzle the core-flow/fan-flow and merged-jet/ambient-air mixing regions are the significant noise-producing parts of the jet. These nozzles are applicable to high-bypass-ratio turbofan engines suitable for conventional and STOL aircraft applications, as well as to such research facilities as free jets.

Experimental work has been conducted (refs. 1, 3, and 4) on scale-model nozzles of this type, covering sufficient variations in area ratio, velocity ratio, and exit-plane offsets to permit prediction curves to be generated for this type of coannular nozzle. The results are shown in figure 4 as a change in noise from a reference level as a function of velocity ratio for a series of area ratios. The reference level, referred to as synthesis, is the antilogarithmic sum of the noise levels expected from each stream considered as a convergent nozzle acting alone and thus represents the noise level that would be observed in the absence of interaction effects. (This reference level also corresponds to the results of early jet noise prediction methods such as ref. 5.) The maximum noise reduction obtained for fan-to-core velocities ratios less than 1 increases with an increase in area ratio from an insignificant amount at an area ratio of 0.5 to 11 dB at an area ratio of 10. The velocity ratio at which the maximum reduction occurs varies between 0.5 and 0.4, depending on the area ratio. As a practical application the velocity ratios used in conventional and STOL high-bypass-ratio engines are above a value of approximately 0.7 for performance reasons, which limits the coannular reductions for practical use to between 3 and 4 dB. The reductions in noise such as shown in this figure (developed from the data of ref. 3) have been incorporated into design procedures such as the NASA Aircraft Noise Prediction Program (ANOPP) (ref. 6) and the current proposed Society of Automotive Engineers (SAE) prediction procedures. These design procedures are not applicable to coannular nozzles with fan-to-core velocity ratios greater than 1.0.

Inverted-Velocity-Profile Coannular Nozzles

Coannular nozzles that produce inverted velocity profiles (fan velocity higher than velocity core) have become interesting candidates for application to low-bypass-ratio turbofan engines. These engines are being considered for use in future supersonic cruise aircraft. This type of nozzle, shown schematically in figure 5, is characterized by a small fan-to-core area ratio (of the order of 1.0) and a fan-to-core velocity ratio in the range of 1.5 to 2.0. With this type of nozzle, the fan-flow/ambient-air and merged-jet/ambient-air mixing regions are the dominant sources of jet noise. Therefore, the prediction methods based on conventional coannular jet data, where the core-flow/fan-flow and merged-jet/ambient-air mixing regions are dominant, do not apply. To fill this gap in jet noise technology, Lewis has been sponsoring 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 basic models tested in these contractor studies are shown in figure 6. A coannular nozzle without plug and with an area ratio of 0.75 and a fan-stream radius ratio of 0.76 is shown in figure 6(a). (This radius ratio is defined as the ratio of the fan-stream inner radius to the fan-stream outer radius.) The model shown in figure 6(b) is a coannular nozzle with a central plug and with an area ratio of 0.67 and a fan stream radius ratio of 0.90. These test models had equivalent total diameters of 13 and 15 centimeters, respectively.

Typical results. - Results from the experimental programs are plotted in figure 7 as peak perceived noise level (normalized for jet density effects)[1] as a function of fan jet velocity for cases where the fan jet velocity was at least 1.5 times the core jet velocity. The jet noise levels for the coannular nozzles are 6 to 10 perceived noise decibels (PNdB) lower than if no favorable interaction occurred between the two sets (both jets exhausting through separate conical nozzles). Between the two coannular nozzles, the configuration with the central plug, which had a higher fan-stream radius ratio showed a 2-PNdB-greater noise reduction. The thrust losses are about 1.5 to 2.0 percent (referred to an ideal nozzle).

In addition to the base coannular configurations shown, configurations with mechanical suppressors were also tested by adding chutes, convolutions, or tubes to the fan stream, and, in some cases, including ejectors. These suppressed configurations

[1]The exponent at 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.

reduced the noise an additional 3 to 7 PNdB, but at the expense of relatively large thrust losses (as much as 8 percent greater than with the unsuppressed coannular nozzles).

Mission analyses (e.g., ref. 7) have shown that the noise reductions observed for the unsuppressed configurations relative to early predictions, which did not account for jet interaction effects, coupled with the low thrust losses involved (~1.5 to 2 percent) are sufficient to meet present FAR-36 noise standards. As a consequence, the technology studies have been concentrated on unsuppressed inverted-velocity-profile coannular nozzles in preference to suppressed configurations and extended to study the effects on noise and thrust characteristics of geometric variables such as radius ratio and area ratio.

Parametric trends. - The effects of velocity ratio on the noise reduction for two different-area-ratio coannular plug nozzles with constant fan radius ratio are shown in figure 8. The noise level relative to the synthesized level predicted for noninteracting jets is plotted as a function of core-to-fan velocity ratio for constant fan operating conditions. (The core velocity was changed by varying both temperature and pressure.) It can be seen that, over this range, the fan-to-core area ratio has very little effect on the noise. Maximum noise reduction occurs between core-to-fan velocity ratios of 0.3 and 0.5. As the core 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 fan stream. When the core flow is increased above a velocity ratio of 0.5, less noise reduction is again obtained, in this case because the core stream affects the jet noise generated in the merged-jet/ambient-air mixing region.

The effects of radius ratio on aeroacoustic performance for two velocity ratios are shown in figure 9. The noise reduction is shown in figure 9(a) as a function of fan-stream radius ratio. As the radius ratio is increased, the noise reduction is also increased, indicating the desirability, from an acoustic point of view, of designing engine nozzles with a high fan radius ratio. The noise reduction obtained with a core-to-fan velocity ratio of 0.5 was larger than for the no-core-flow case, as was previously discussed.

The effect of velocity ratio and fan radius ratio on the thrust characteristics both statically and when exposed to an external flow Mach number of 0.36 (takeoff conditions) is shown in figure 9(b). It is obvious that the thrust losses obtained with no core flow are quite severe (up to 10 percent relative to a convergent nozzle). For a velocity ratio of 0.5, losses are much lower (between 1 and 2 percent additional losses relative to a convergent nozzle). An increase in the radius ratio causes an increase in thrust losses, indicating the need, from a designer's point of view, to trade off the thrust losses with the amount of noise reduction in order to select the optimum nozzle radius ratio for an engine exhaust system.

Simulated flight effects. - The acoustic information presented in the preceding sections 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 these models under simulated flight conditions in an acoustic wind tunnel. Typical results obtained with a coannular nozzle without a plug with subsonic velocities in both streams (fan-to-core velocity ratio, ~1.5) are shown in figure 10. 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 8. The highest curve represents the static conditions, and the lower two 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 60° to 150° from the inlet axis. Peak noise reduction varied from 5 to 7 dB 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 under static conditions is maintained in flight.

Similar results are shown in figure 11 for a case where the fan stream was supersonic (pressure ratio, 2.5). The subsonic core conditions are the same as for figure 10, producing a 1.9 fan-to-core velocity ratio here. The results are very similar except that the peak reductions are somewhat smaller in magnitude (by about $1\frac{1}{2}$ 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 reduction in flight relative to a convergent nozzle, as the convergent nozzle is similarly affected.

DETERMINATION OF JET NOISE IN FLIGHT

The presentation of the preceding simulated flight directivity data for the coannular nozzles introduces another area of study where analytical and experimental efforts have been concentrated: the effects of flight on jet noise and the correlation of jet engine exhaust noise flight data with simulated flight model test information. It is imperative to be able to predict flight jet noise characteristics from analytical models and/or scale-model data because actual flight testing for research and development purposes is prohibitive in cost. Flight noise data from jet engines do not appear to agree with predictions based on classical jet noise theories, such as discussed in reference 9. However, these differences seem to be reconciled if the flight effects are applied to the jet mixing noise and to the internal noise of the engines as well, as suggested in reference 10. These effects of flight on jet engine exhaust noise directivity are illustrated in figure 12. In figure 12(a), flight effects on the jet mixing noise are presented for a typical turbojet engine. The solid curve represents the jet noise produced statically in terms of noise level as a function of radiation angle. The difference between the solid and the dashed lines represents the reduction in jet noise due to the source strength reduction introduced by the reduction of the relative velocity between the jet and the surrounding medium during flight. This effect is constant at all angles. The dash-dot curve represents the predicted flight noise directivity, incorporating the dynamic effect on noise as well. This dynamic effect tends to decrease the noise in the aft quadrant and increase it in the forward quadrant.

The flight effects on internal noise sources are shown in figure 12(b). Because these sources are not subjected to the relative flow field, there is no source strength reduction, but only motion or dynamic effects. These sources have no relative motion with respect to the nozzle; therefore, the velocity change has a greater effect when applied to the internally generated noise, resulting in larger increases of noise in the forward quadrant than that shown in figure 12(a) for jet noise. As with jet noise, a reduction in noise occurs in the aft quadrant.

The application of the preceding principles to the prediction of jet engine exhaust noise directivity for a hypothetical turbojet engine are shown in figure 13. The static case is illustrated in figure 13(a). The shock-free jet noise, shown by the dashed curve, is greater than the internally generated noise (dash-dot curve). The total exhaust noise (solid curve) is the antilogarithmic sum of the jet noise and internal noise levels and is dominated by the jet mixing noise for all angles. When the flight effects are included, as shown in figure 13(b), the reduction of jet noise at all angles is counteracted by the increased contribution of the internal noise in the forward quadrant. The total exhaust noise is now dominated by internal noise in the forward quadrant; jet noise continues to dominate in the aft quadrant. Total noise statically and in flight is compared in figure 13(c). For this case the flight effect has increased the jet exhaust total noise in the forward quadrant and reduced it in the rear quadrant.

Application of this method of flight analysis of jet mixing and internal noise to the exhaust noise of two actual engines is shown in figure 14. The engines selected had dissimilar levels of internal noise, and in the figure the actual flight data are compared with calculated values. The results for a "high"-internal-noise engine, the Viper 610 in an HS-125 airplane are shown in figure 14(a). Both the calculated OASPL values (shown by the curves) and the data (shown by the symbols (ref. 11)) show the increase of noise level in flight in the forward quac ,nt discussed previously (figs. 12 and 13). Also shown, both calculated and measured, are the noise reductions in the aft quadrant. The results from a similar evaluation for a "low"-internal-noise engine, the NASA Lewis-sponsored refanned JT8D engine on a DC-9 airplane, are shown in figure 14(b).

In this case, both data and calculations indicate a reduction of exhaust noise in flight throughout all angles. A very significant conclusion to be drawn from these results is that engine exhaust noise in flight can be predicted if the internal noise of the engines is properly accounted for.

CONCLUDING REMARKS

This paper has very briefly described signit. nt developments in two areas of jet noise technology that have great impact: jet noise reduction and the prediction of flight effects. Coannular nozzles including those with inverted velocity profiles, have been shown to offer significant noise reductions with little thrust loss. These results are particularly applicable to supersonic cruise aircraft. It was also shown that flight effects on jet engine exhaust noise can be predicted if the internal engine noise is properly accounted for.

APPENDIX - SYMBOLS

A_{CORE}	core jet area, m^2
A_{FAN}	fan jet area, m^2
A_j	jet (single stream) area, m^2
C_V	thrust coefficient, dimensionless
c_a	ambient sonic velocity, m/sec
L	sideline distance, m
M_0	free-st eam Mach number, dimensionless
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
$OASPL_{COANN}$	OASPL for coannular nozzle, dB re 20 $\mu N/m^2$
$OASPL_{CORE+FAN}$	OASPL for synthesized coannular nozzle (antilogarithmic sum of of core jet and fan jet OASPL's), dB re 20 $\mu N/m^2$
PNL_{pk}	peak perceived noise level, PNdB
R_i	inner radius of fan stream, m
R_o	outer radius of fan stream, m
T_{CORE}	core jet total temperature, K
T_{FAN}	fan jet total temperature, K
V_{CORE}	core jet velocity, m/sec
V_{FAN}	fan jet velocity, m/sec
V_j	jet (single stream) velocity, m/sec
θ	angle from nozzle inlet axis, deg
ρ_{FAN}	fan jet density, kg/m^3
ρ_{isa}	ambient density at standard conditions, kg/m^3
ω	density correction exponent

REFERENCES

1. Aircraft Engine Noise Reduction. NASA SP-311, 1972.
2. Williams, T. J.; Ali, M. R. M. H.; and Anderson, J. S.: Noise and Flow Characteristics of Coaxial Jets. J. Mech. Eng. Sci., vol. 11, no. 2, April 1969, pp. 133-142.
3. Olsen, W.; and Friedman, R.: Jet Noise from Co-axial Nozzles over a Wide Range of Geometric and Flow Parameters. NASA TM X-71503, 1974.
4. Olsen, W. A.; Gutierrez, O. A.; and Dorsch, R. G.: The Effect of Nozzle Inlet Shape, Lip Thickness, and Exit Shape and Size on Subsonic Jet Noise. AIAA Paper 73-187, Jan. 1973.
5. Jet Noise Prediction. Aerospace Information Report 876, SAE, 1965.
6. Stone, James R.: Interim Prediction Method for Jet Noise. NASA TM X-71618, 1974.
7. Whitlow, John B., Jr.: Effect of Airplane Characteristics and Takeoff Noise and Field Length Constraints on Engine Cycle Selection for a Mach 2.32 Cruise Application. NASA TM X-71865, 1976.
8. Amiet, Roy K.: Correction of Open Jet Wind Tunnel Measurements for Shear Layer Refractions. AIAA Paper 75-532, Mar. 1975.
9. Ffowcs Williams, J. E.: The Noise from Turbulence Convected at High Speed. Philos. Trans. R. Soc. London, Ser. A, vol. 255, no. 1061, Apr. 1963, pp. 469-503.
10. Stone, James R.: On the Effects of Flight on Jet Engine Exhaust Noise. NASA TM X-71819, 1975.
11. Brooks, J. R.; and Woodrow, R. J.: The Effects of Forward Speed on a Number of Turbojet Exhaust Silencers. AIAA Paper 75-506, Mar. 1975.

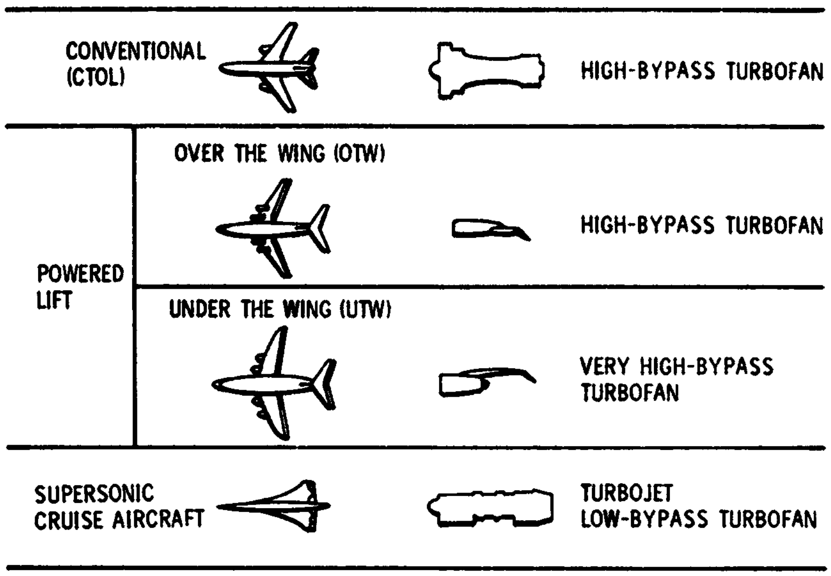
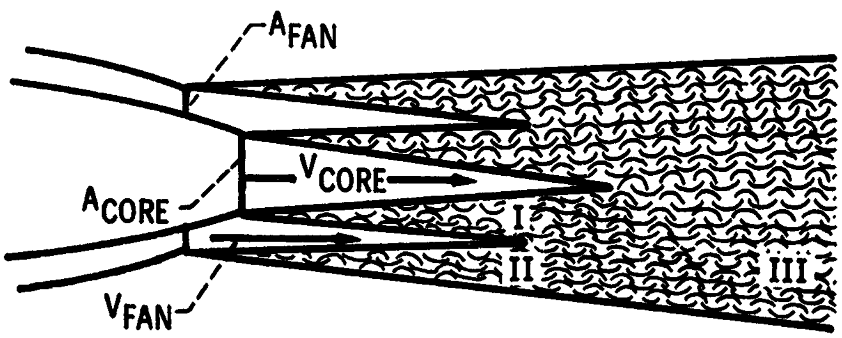


Figure 1.- Types of aircraft and engines affected by developments in jet noise reduction technology.



THREE NOISE-PRODUCING REGIONS:

I. CORE-FAN MIXING

II. FAN-AMBIENT MIXING

III. MERGED-JETS - AMBIENT MIXING

Figure 2.- Noise-producing regions in coannular jets.

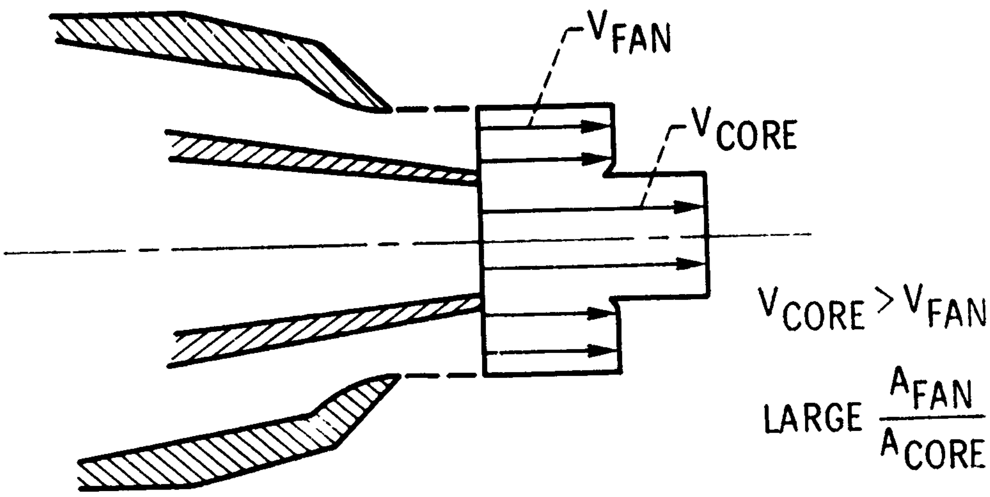


Figure 3.- Conventional coannular nozzles typical of high-bypass-ratio turbofans applicable to CTOL and STOL aircraft.

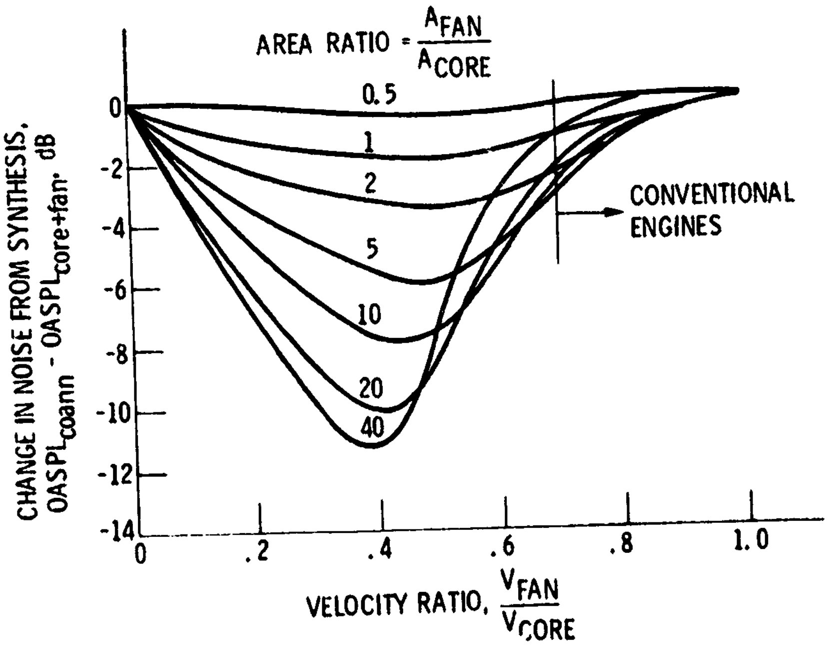


Figure 4.- Coannular noise reduction for conventional coannular nozzles.

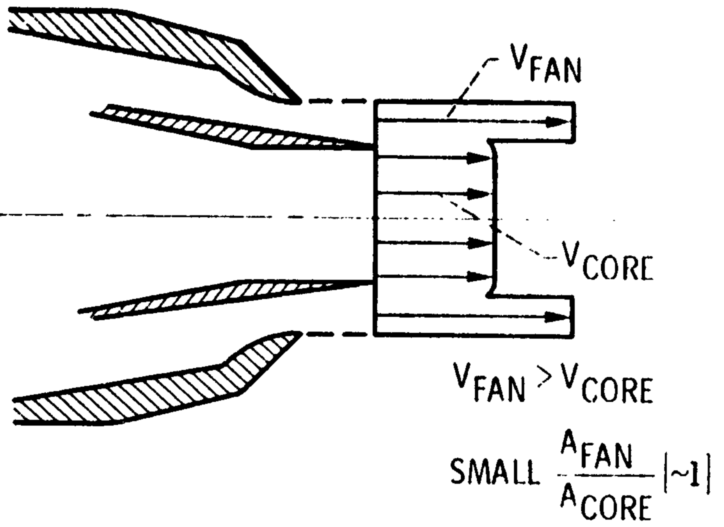
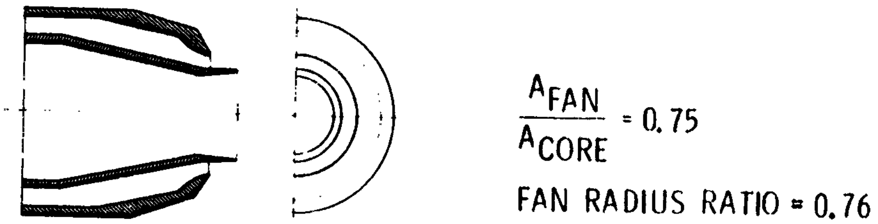
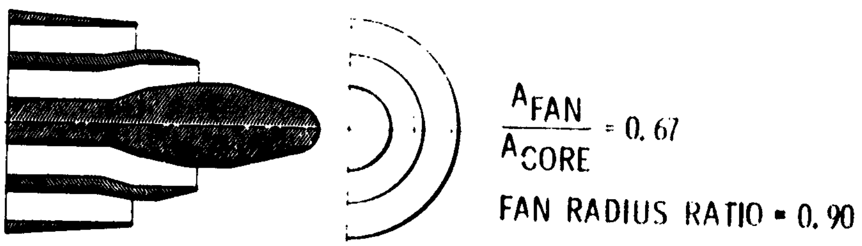


Figure 5.- Inverted-velocity-profile coannular nozzles typical of low-bypass-ratio turbofans applicable to supersonic cruise aircraft.



(a) Without plug.



(b) With plug.

Figure 6.- Typical test models of inverted-velocity-profile coannular nozzles.

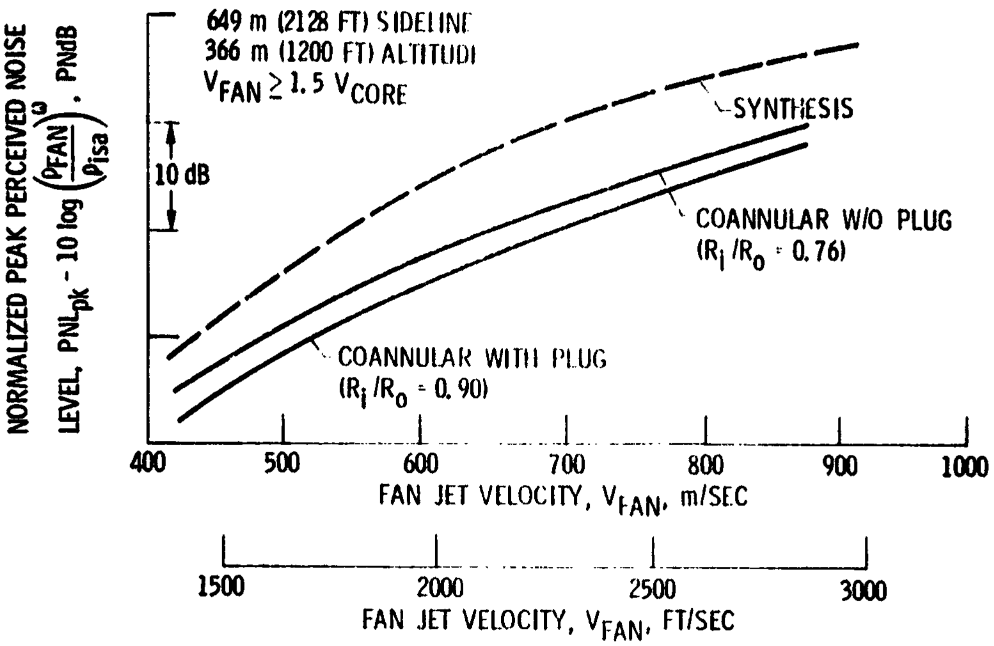


Figure 7.- Peak noise as function of jet velocity for typical inverted-velocity-profile coannular nozzles.

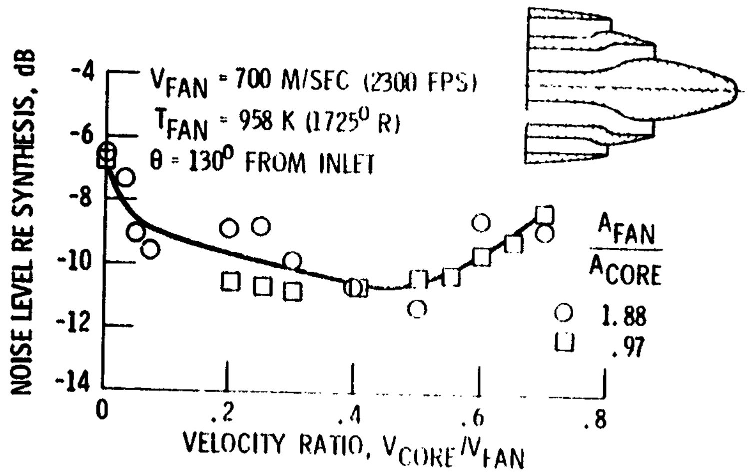
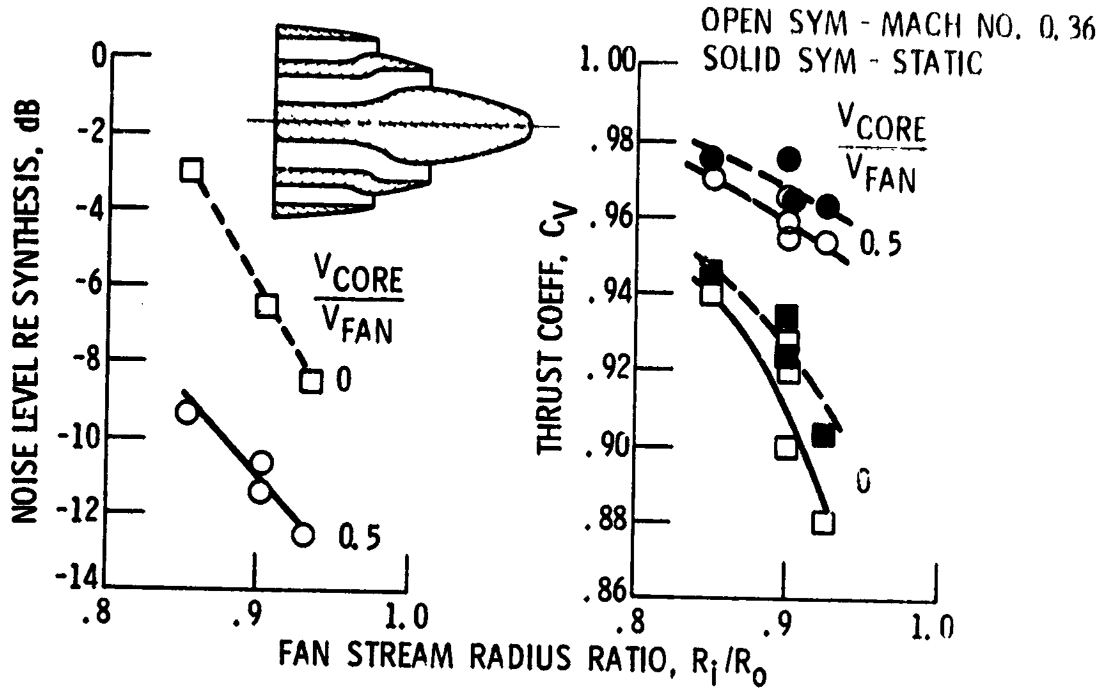


Figure 8.- Effect of velocity ratio on noise reduction of inverted-velocity-profile coannular nozzles. Ratio of inner to outer fan-stream radius, R_i/R_o, 0.90.



(a) Acoustic. (b) Aerodynamic.

Figure 9.- Effect of radius ratio on aeroacoustic performance of inverted-velocity-profile coannular nozzles.

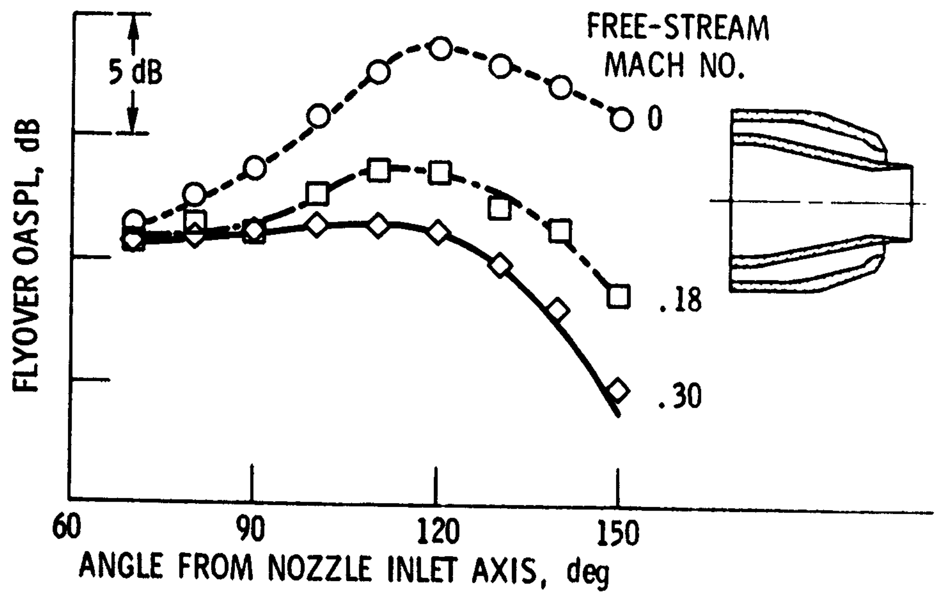


Figure 10.- Static and simulated flight directivities for inverted-velocity-profile coannular nozzles with subsonic fan stream (fan pressure ratio, 1.8).

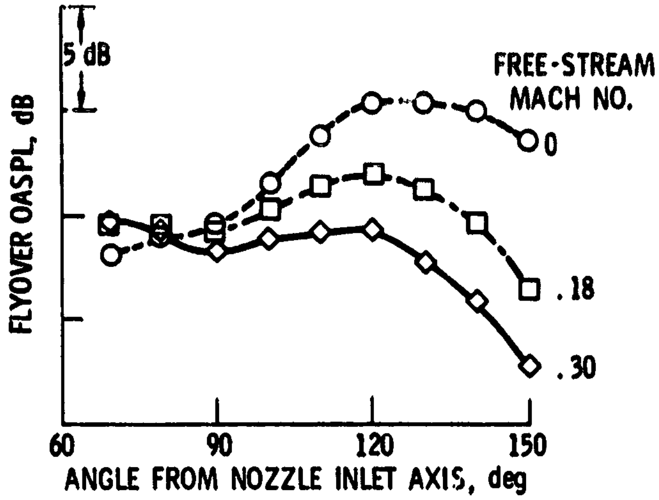
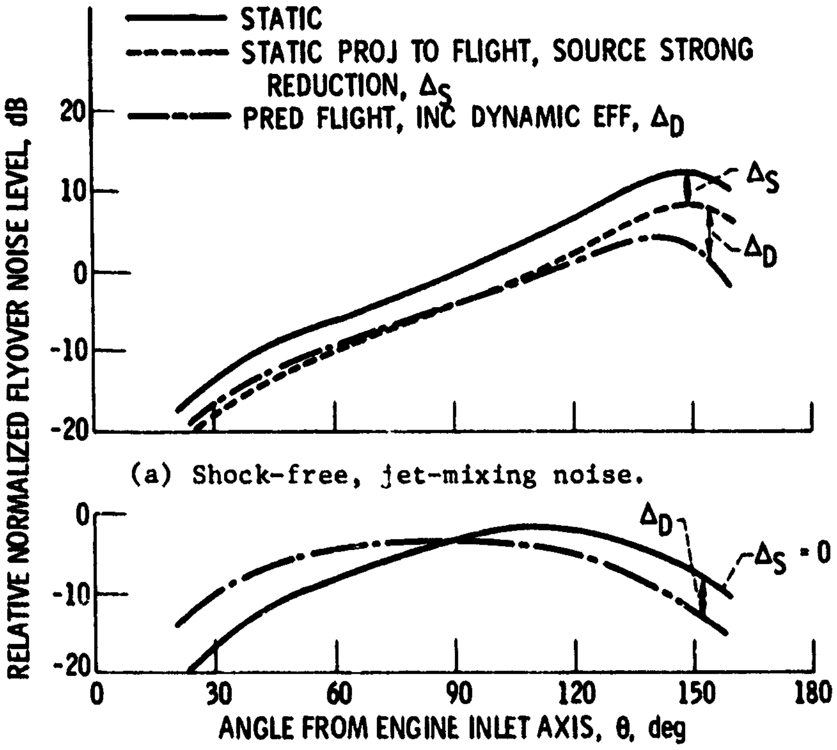
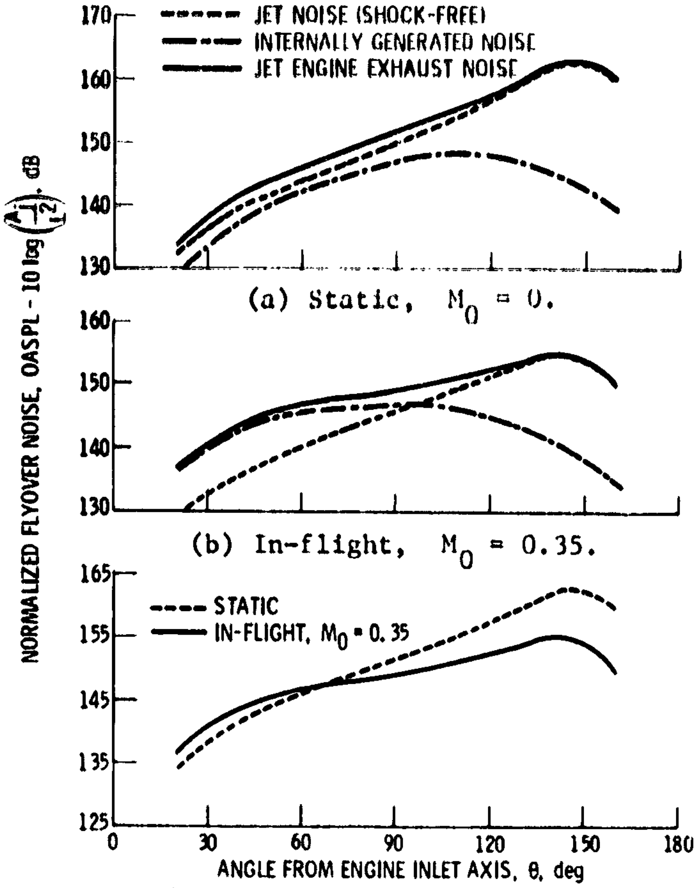


Figure 11.- Static and simulated flight directivities for inverted-velocity-profile coannular nozzles with supersonic fan stream (fan pressure ratio, 2.5).



(b) Internally generated noise.

Figure 12.- Typical effects of flight on jet engine exhaust noise.

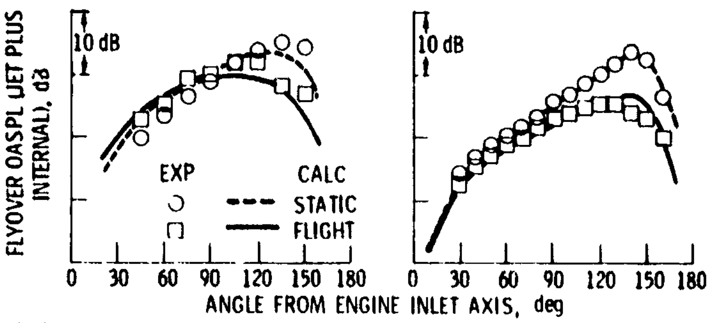


(a) Static, $M_0 = 0$.

(b) In-flight, $M_0 = 0.35$.

(c) Flight effect on total noise.

Figure 13.- Synthesis of jet engine exhaust noise directivity for hypothetical jet engine with ratio of jet velocity to ambient sonic velocity V_j/c_a of 1.80.



(a) High internal noise (Viper 610 engine in HS-125 airplane).

(b) Low internal noise (refanned JT8D engine on DC-9 airplane).

Figure 14.- Comparison of calculated and measured static and flight directivities for engines with different levels of internal noise relative to jet noise.