STATUS OF NOISE TECHNOLOGY FOR ADVANCED SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

During the past several years, progress has been made in several areas of acoustic technology applicable to advanced supersonic cruise aircraft. This paper reviews some of the more important developments, which relate primarily to jet noise and its suppression. The noise-reducing potential of high-radius-ratio, inverted-velocity-profile coannular jets is demonstrated by model-scale results from a wide range of nozzle geometries, including some simulated flight cases.

These results have been verified statically at large scale on a variable-cycle-engine (VCE) testbed. A preliminary assessment of potential VCE noise sources such as fan and core noise is made, based on the testbed data. Recent advances in the understanding of flight effects are reviewed. The status of component noise prediction methods is assessed on the basis of recent test data, and the remaining problem areas are outlined.

INTRODUCTION

An environmentally and economically acceptable advanced supersonic cruise aircraft will require substantial advances in noise suppression technology over current, first-generation supersonic aircraft. This paper summarizes the present state of the art in noise technology applicable to supersonic cruise aircraft. Inverted-velocity-profile (IVP) coannular nozzles and mechanical suppressors, both of which show promise for jet noise reduction, receive primary emphasis. The discussion also includes the effects of flight and the influence of other (non-jet-mixing) noise sources. Throughout these discussions the status of prediction methods for the various noise sources is considered.

Inverted-velocity-profile (IVP) coannular nozzles have been identified as a major breakthrough in jet noise suppression applicable to supersonic cruise aircraft engines (e.g., ref. 1). The aeroacoustic benefits associated with IVP jets were first identified in a series of tests under NASA Lewis Research Center sponsorship (refs. 2 and 3). The results of these model-scale programs were reviewed at the 1976 SCAR Conference (refs. 4 to 6). These programs included unsuppressed configurations with and without center plugs as well as suppressed configurations. The unsuppressed IVP configurations were shown to provide noise levels near the Federal Aviation Administration guidelines, FAR-36 (1969), with good aerodynamic performance. Further noise reductions were shown for the suppressed IVP configurations but were accompanied by significantly poorer aerodynamic performance. Thus, the emphasis of NASA-sponsored IVP noise studies for the next several years was primarily on the unsuppressed configurations, and some of the highlights of those studies are included in this paper. During this time, however, a major Department of Transportation (DOT)/FAA study (with technical support from NASA) of jet noise suppressors placed considerable emphasis on suppressors, including those for IVP configurations.

Mechanical jet noise suppressor studies during the same time period considered both dual-stream (including IVP) and single-stream concepts. Results for one promising single-stream suppressor-ejector concept are discussed in reference 7; results for a promising single-stream chute-plug design are presented in reference 8. A brief discussion of these results is included in the present paper.

The subject of flight effects on jet noise has received considerable interest and effort in recent years. According to classical jet noise theory (e.g., ref. 9), jet mixing noise should be reduced in flight because of the reduced shear on the jet. However, some experimental results for jet engines in flight have indicated apparent discrepancies; specifically, the noise in the forward quadrant was found to increase rather than decrease in flight (e.g., refs. 10 and 11). Subsequent studies conducted or sponsored by NASA have shown that these apparent anomalies can be largely resolved when the engine internal noise is accounted for (refs. 12 to 19). These studies are briefly reviewed in the present paper, and an improved flight effects procedure (ref. 20) is shown to be reasonably accurate in the high-jet-velocity range of interest for supersonic cruise aircraft. The effects of flight on IVP coannular nozzles and mechanical suppressors are also discussed.

SYMBOLS

A	exhaust area, m^2
c_a	ambient sonic velocity, m/sec
F	thrust, kN
F_{Ref}	reference thrust (arbitrary), kN
L	source-to-observer distance, m
M_0	aircraft Mach number, V_0/c_a, dimensionless
m	flight velocity exponent (eq. (1)), dimensionless
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
PNL_N	normalized perceived noise level, $PNL - 10 \log\left[\frac{A}{L}\, 2\left(\frac{F}{F_{ref}}\right)\left(\frac{\rho_S}{\rho_0}\right)^{w-1}\right]$, PNdB

PNL_T tone-corrected perceived noise level, PNdB

R_I inner radius of outer stream nozzle, m

R_O outer radius of outer stream nozzle, m

w density exponent, dimensionless

V velocity, m/sec

β angle from jet axis to flightpath, deg

Δ OASPL difference, flight minus static, dB

θ angle referred to inlet axis, deg

ρ density, kg/m^3

Subscripts:

a ambient

calc calculated

exp experimental

F flight

j fully expanded isentropic jet (primary)

m mixed

S static

0 aircraft

1 inner stream (fully expanded)

2 outer stream (fully expanded)

JET NOISE SUPPRESSION

Jet noise is expected to be the most important noise source for advanced supersonic cruise aircraft, particularly at takeoff and cutback power. Therefore, the suppression of this noise source is of great importance to the development of an environmentally acceptable advanced supersonic cruise aircraft. Jet noise can be reduced by lowering the specific thrust at takeoff through engine-cycle modifications, by employing jet noise suppressor nozzles, or by a combination of these approaches. For example, the variable-cycle engines (VCE's) produce a relatively low specific thrust, and thereby relatively low noise, at takeoff and provide further noise reduction when IVP coannular nozzles are incorporated. For some other engine cycles, multielement mechanical jet noise suppressors are needed and will have to provide even greater noise reductions at a given specific thrust than the IVP coannular nozzle. So that the jet noise suppression characteristics of various approaches can be compared, it has been suggested (e.g., refs. 21 and 22) that noise levels be compared with those of a mixed-flow conical nozzle at the same total mass flow and at the same specific thrust. Such comparisons are made for the various suppressor concepts discussed herein.

Inverted-Velocity-Profile Coannular Nozzles

As mentioned previously, IVP coannular nozzles have been identified as a breakthrough in jet noise suppression applicable to advanced supersonic cruise aircraft. As illustrated schematically in figure 1, this approach consists of exhausting the higher velocity stream through a high-radius-ratio annulus and the lower velocity stream through an inner nozzle. Such velocity profiles can be obtained by crossducting the fan and core streams (e.g., ref. 23) or by burning in the fan duct (e.g., ref. 24). Advances in engines incorporating these approaches were discussed at a recent NASA conference on aeronautical propulsion (ref. 25).

The noise benefits of the IVP coannular nozzle concept are shown in figure 2. Normalized peak perceived noise level is plotted against the mass-averaged jet velocity (ideal specific thrust) for several of the many configurations tested (refs. 26 and 27). A reference curve is also shown for a hypothetical, perfectly mixed conical nozzle (ref. 28). For all these coannular nozzle data, the outer-stream velocity is 1.5 to 2 times the inner-stream velocity. Noise reductions for the coannular nozzles, relative to the conical nozzle, generally improve as the ratio of the inner radius to the outer radius of the outer stream R_I/R_O increases. The bulk of the IVP data fall in a band about 6 PNdB below the conical reference, but even lower levels can be seen for some high-radius-ratio cases.

The radius ratio and velocity ratio between the two streams strongly influence the noise level at a given mass-averaged jet velocity, as illustrated in figure 3, taken from reference 27. The noise of the coannular nozzle relative to that of the perfectly mixed conical nozzle is plotted against the outer-stream to inner-stream velocity ratio V_2/V_1 over a range of mass-averaged jet velocities for radius ratios of 0.52 to 0.95. These results are in terms of the overall sound pressure level at the peak sideline noise angle, $\theta = 135^{\circ}$. The data include both conventional and inverted velocity profiles. For all four configurations a minimum noise (maximum suppression) exists for the IVP conditions. For the 0.52- and 0.62-radius-ratio nozzles, the minimum noise is only about 3 decibels below the conical nozzle prediction. As the radius ratio is increased, the minimum noise is still further reduced, to 4 decibels below the conical nozzle prediction at a 0.68 radius ratio and to over 9 decibels below the conical prediction at noncoplanar 0.95 radius ratio. The velocity ratio at which this minimum noise occurs decreases somewhat with increasing radius ratio.

IVP noise prediction. - Since the noise is a complicated function of flowfield and geometric variables, it is necessary to go beyond simple plots such as figure 2 to correlate the data. The complexity of the IVP jet noise generation processes is shown in figure 4. As many as four noise-generating regions must be considered. It is the differing trends of these different noise sources with operating conditions that leads to the existence of a minimum noise as velocity ratio increases, such as illustrated in figure 3. The low-frequency noise is generated well downstream of the nozzle where the two flows have mixed and can no longer be distinguished; this is termed the merged region. The higher frequency jet mixing noise is generated in the region near the nozzle exit where the individual jets can still be identified; this is termed the premerged region. When either or both streams are supersonic, noise can be generated by turbulent eddies passing through shock waves; thus, we must in general consider inner-stream shock noise and outer-stream shock noise.

Empirical models relating these noise-generating processes to those of a conical nozzle have been developed (refs. 21, 29, and 30). Small-scale, plugless, coannular nozzle experimental spectra (ref. 2) are compared with predictions based on the empirical models of reference 30 in figure 5. Sound pressure level is plotted against frequency for an angle of 120°, in the rear quadrant, in figure 5(a). For this case both streams are supersonic, so all four noise sources must be considered; but it is the jet mixing noises that dominate at this angle. The shock noise levels, predicted by an empirical modification to the theory of Harper-Bourne and Fisher (ref. 31), contribute somewhat in the high-frequency range but not as much as the premerged mixing noise. Results for the same conditions, but in the forward quadrant at $\theta = 75^{\circ}$, are shown in figure 5(b). It is apparent that shock noise is much more important in the forward quadrant than in the rear quadrant. The inner-stream shock noise dominates the midfrequency range and determines the peak sound pressure level. The outer-stream shock noise controls the high-frequency range. Although the relative contributions of the various sources are different in the forward and rear quadrants, the spectra at both angles are predicted with good accuracy.

Large-scale verification of IVP concept. - The acoustic characteristics of IVP coannular nozzles, originally determined from a series of model-scale tests, have now been verified on an engine, as discussed in more detail in reference 32.

Typical results are shown in figures 6 and 7 for the NASA - General Electric VCE testbed coannular plug nozzle as well as for a similar model nozzle at essentially the same conditions, with a mixed jet velocity of about 590 meters per second. For both the engine and the model, the experimental results are scaled up to a typical product-engine size (total exhaust area, 0.903 m^2) at a typical sideline distance (slant range, 731.5 m). The results are also compared with the prediction procedure of reference 30. Perceived noise is plotted as a function of angle in figure 6. The model results are verified by the engine results. The engine results are an average of 0.8 PNdB below the model results, and the standard deviation between the two data sets is 1.5 PNdB. The overall accuracy of the prediction method is also confirmed by the testbed data. The average bias of the prediction with respect to the testbed data is less than 0.1 decibel, and the standard deviation is 1.0 decibel. The predicted contributions of the combined jet mixing noises (merged plus premerged) and the shock noises (from both streams) are also shown. Although the jet mixing noise is most important in this case, the shock noises do contribute somewhat in the forward quadrant. Although not shown here, at higher power settings and in flight, the shock noise becomes even more important and can contribute significantly to the effective perceived noise level.

Further evidence of the overall accuracy of the scaling procedure and of the prediction can be seen in more detail in figure 7, along with some indications of areas requiring improvements to the prediction procedures. Experimental data for both testbed and model scaled up to typical product-engine size are compared with the prediction on a spectral basis. The prediction procedure is accurate at low frequencies (the merged jet region) and thus gives a good estimate of the perceived noise level (PNL). It appears that improved prediction procedures are needed for premerged mixing noise and shock noise, which control the high frequencies. These sources may contribute more significantly in flight and also become more important for the shorter distances involved at the flyover noise measurement point.

Mechanical Jet Noise Suppressors

Various system studies of propulsion systems for future supersonic cruise aircraft (e.g., refs. 23 to 25) have indicated that FAR-36 (1969) noise levels can be approached with variable-cycle engines with unsuppressed IVP coannular nozzles. Other studies (e.g., ref. 33) have indicated slightly higher noise levels for such engines. In any case, FAR-36 (1969) noise levels cannot at present be predicted for such engines with any reasonable allowance for design margins without resorting to advanced operating procedures or shielding schemes. To obtain such design margins, and also to have any possibility of approaching the FAR-36 (1977) subsonic aircraft requirements, some means of suppressing jet noise will probably be needed. Therefore, although NASA's resources have been focused primarily on unsuppressed IVP coannular nozzles over the past few years, mechanical jet noise suppressor technology has continued to be advanced by the industry with some support from DOT (FAA) and more limited support from NASA. The DOT (FAA) study included a large number of single-stream and IVP-coannular suppressors; some of the most promising concepts of both types were tested in simulated flight.

Single-stream suppressors. - In addition to the variable-cycle engines, low-bypass engines with single-stream suppressors may be feasible supersonic cruise propulsion systems. Results for a promising single-stream suppressor concept developed by General Electric with support from DOT (FAA) and NASA have been reported recently in reference 8. Similarly promising results are also presented in reference 7 for a single-stream suppressor-ejector developed by McDonnell Douglas and tested with limited NASA support.

Typical results for a single-stream suppressor-ejector, in this case the McDonnell Douglas design, are shown in figure 8. Model-scale static experimental data (ref. 34) are scaled up to a typical product-engine size (exhaust area, 0.713 m^2) at a typical flyover altitude (381 m). As was done for the IVP coannular nozzles, the experimental suppressor results are compared with a predicted baseline (ref. 28) for a conical nozzle at the same ideal specific thrust. At a relatively high jet velocity (~715 m/sec, fig. 8(a)) the peak PNL of the suppressor is 8.7 PNdB below the peak PNL of the conical nozzle according to the Rolls-Royce spin rig data, or 10.4 PNdB below the peak PNL according to the NASA Ames 40- by 80-Foot Wind Tunnel data. Thus, comparing these results with those of figure 2 shows that the suppressed low-bypass-ratio engine may be slightly quieter than a variable-cycle engine with an unsuppressed IVP coannular nozzle at the same specific thrust. However, engine weight, nozzle thrust loss, and many other factors must also be considered in choosing the best engine type for a specific application. At lower jet velocity (~490 m/sec, fig. 8(b)), the peak PNL suppression is reduced to 4.5 PNdB (spin rig) or to 6.3 PNdB (40- by 80-Ft Wind Tunnel). This reduction of suppression with decreasing jet velocity is typical of most single-stream suppressors. NASA Langley made a detailed system-noise - cost-sensitivity study of the McDonnell Douglas suppressor concept as part of an international study on the feasibility of developing noise rules for civil supersonic cruise aircraft (ref. 33). This study, based on the limited (spin rig) data available at that time, indicated that the FAR-36 (1969) noise levels might be achieved without undue cost penalties.

IVP coannular nozzles with suppressors. - Quieter variable-cycle engines may be achieveable with a suppressed IVP coannular nozzle. It was the possibility of relatively small outer-stream suppressors (small in comparison with mixed-flow, single-stream suppressors) that caused the initial interest in the IVP concept. The initial IVP model tests (refs. 2 and 3) emphasized outer-stream suppressors. With these suppressors, static peak PNL was reduced as much as 6 PNdB below that of an unsuppressed IVP coannular nozzle at the same ideal specific thrust. Because of the promise of this approach, NASA Lewis is sponsoring model-scale static and simulated flight tests (contract NAS3-21608) and large-scale VCE testbed static tests (contract NAS3-20582, exhibit C) of an outer-stream-suppressed coannular plug nozzle.

IMPORTANCE OF NON-JET-MIXING NOISES

Although it is fairly well established that jet-mixing noise is the most critical noise problem for supersonic cruise aircraft, it is necessary to develop an understanding of the other potential noise sources. For example, fan noise may well become dominant at approach, and shock-cell noise may have a significant effect on the effective perceived noise level at takeoff. Core noise contributes only slightly at low power, according to the VCE testbed results. Duct-burner combustion noise is a potential problem for which no data base yet exists. This section discusses the current status of the fan, shock-cell, and duct-burner combustion noises.

Fan Noise

Although the VCE early acoustic test was not structured to provide a definitive answer to the fan noise problem, some useful data were obtained. Tests were conducted on the testbed with a conical nozzle and two different inlets, one hardwall and one suppressed. Typical results, in terms of tone-corrected PNL directivity, are shown in figure 9 for approach and cutback power settings.

The results are scaled up to a typical product-engine size (exhaust area, 0.903 m^2) at a typical sideline distance (slant range, 731.5 m). In each case, the unsuppressed-inlet results are shown by the solid line and the suppressed-inlet results are shown by the dashed line. The fan noise can then be estimated by antilogarithmic subtraction of the suppressed, tone-corrected perceived noise level (PNL_T) from the unsuppressed value. Coannular plug nozzle data at the same power setting are shown by the circular symbols. The square symbols denote the implied total noise for an unsuppressed-inlet coannular configuration obtained by the antilogarithmic sum of the suppressed-inlet coannular plug nozzle noise and the estimated fan noise from the conical nozzle test.

At approach power (fig. 9(a)) the fan noise would apparently contribute substantially to the EPNL if it were not suppressed. In flight, with the jet-mixing noise reduced and the forward-quadrant fan noise increased, as expected, the unsuppressed fan noise might become the controlling source. It is clear that if the jet noise limit is to be achieved at approach power, an inlet suppression of approximately 15 PNdB might be required. Of course, detailed trade-off studies will be needed to determine the optimum suppression requirements. At cutback power (fig. 9(b)) the unsuppressed fan noise would still be discernible, although not as prominently as at approach power. Thus, the level of suppression required would be less than at approach power. At takeoff power, shock-cell noise makes it difficult to determine the effect of fan noise on the PNL.

The inferred fan noise from the VCE testbed is compared with predicted values from reference 35 in figure 10. Although this prediction does not apparently model the noise-generating mechanisms for this high-tip-speed split fan, such comparisons are appropriate since this method has already been used to estimate the relative importance of fan noise for such engines. Some indication of agreement between the inferred and predicted values is obtained at a typical approach power (fig. 10(a)). The agreement is not so good at cutback power (fig. 10(b)). Clearly, development of fan noise prediction procedures for high-tip-speed fans should continue in order to provide more realistic and accurate estimates. However, at typical approach power settings, the current prediction (ref. 35) does give a reasonable enough estimate of fan noise to indicate its importance relative to other noise sources.

Shock-Cell Noise

As was pointed out earlier in the discussion of the IVP coannular jet noise prediction, shock-cell noise can be a significant contributor to the take-off flyover EPNL. In reference 36, shock noise and methods of controlling it are discussed in some detail.

Although the prediction procedure of reference 30 does include shock-cell noise calculated from a method based on modification of the Harper-Bourne and Fisher theory (ref. 31) for conical nozzles, further development is required to obtain more accurate predictions (e.g., fig. 7). Even the theoretical basis for this prediction procedure may need improvement, as indicated in reference 37.

Since shock-cell noise is of potential importance, it may be necessary to employ convergent-divergent nozzles in order to reduce or eliminate it. Noise reductions obtained by applying such an approach to single-stream circular nozzles are reported in references 36 and 37. However, for IVP coannular nozzles, the VCE testbed results and related model tests showed no benefit for a convergent-divergent, outer-stream nozzle. Because of complications involved with interacting coaxial supersonic jets (e.g., ref. 38), further research on coannular shock noise and its control is clearly needed. Incorporating a porous center plug in the nozzle exhaust also appears to offer a means of reducing shock noise (ref. 39).

Duct-Burner Combustion Noise

One variable-cycle engine concept of interest features burning in the fan duct, a method that can then produce an inverted velocity profile. Thus, the combustion noise generated in such a duct burner should be considered. However, no data base exists for such configurations. Various methods have been developed to predict combustion noise (e.g., refs. 40 to 42); however, these are based on data for core-engine combustors. In terms of the correlation parameters developed in these predictions and in more recent studies (e.g., ref. 43), the conditions expected for a duct burner fall well beyond the range of available data, and extrapolation is uncertain. Exercising these predictions for duct-burner conditions indicates that, if such extrapolation is valid, duct-burner combustion noise could be significant at takeoff. Resolution of this problem must await the development of a suitable data base.

FLIGHT EFFECTS

To assess the effect of jet noise on the environment of the airport vicinity, it is necessary to predict the effect of flight on jet engine exhaust noise. For new or proposed aircraft particularly, such predictions will be based at least in part on model and large-scale static and simulated flight experiments. Because of costs, to rely solely on full-scale flight tests would severely limit the number of configurations and concepts that could be tested. Therefore, it is of great importance to be able to predict in-flight noise from static or simulated-flight data.

The flight geometry is illustrated, and some of the key parameters are defined, in figure 11. According to classical jet noise theory (Ffowcs Williams, ref. 9), in-flight subsonic jet noise should vary with flight velocity and a flight velocity exponent m as $10 \log\left[V_j^{8-m}(V_j - V_0)^m\right]$. For the static case ($V_0 = 0$) this reduces to the well-known V_j^8 expression of Lighthill (ref. 44). Thus, by this reasoning, the difference between static and flight levels, $(OASPL)_F - (OASPL)_S$, corrected for motion effects by adding $10 \log\left[1 - M_0 \cos(\theta + \beta)\right]$, should be given by $10 \log\left[(V_j - V_0)/V_j\right]^m$.

Based on such considerations, several investigators (e.g., refs. 10, 11, and 45) have expressed their results in terms of a flight velocity exponent m defined as follows:

$$m \equiv \frac{(OASPL)_F - (OASPL)_S + 10 \log\left[1 - M_0 \cos (\theta + \beta)\right]}{10 \log\left[1 - \left(\frac{V_0}{V_j}\right)\right]} \qquad (1)$$

Such data have typically been presented as plots of m versus θ, the angle from the inlet axis. Also, prediction methods for jet noise flight effects (e.g., Bushell (ref. 11)) have been proposed on the basis that m can be defined as a unique function of θ. However, it has been pointed out (ref. 17) that m is not a physical quantity but an expression based on assumed relations and that such relations do not accurately and uniquely represent the physical processes. Furthermore, it was shown in reference 17 that the exponent m is sufficiently sensitive to the measured OASPL's that the presence of even small amounts of non-jet-mixing noise can result in negative values of m. (Positive m values indicate noise reduction in flight, while negative m values indicate noise amplification in flight.) Therefore, it was indicated that prediction methods should not be formulated on the basis of m as a function of θ, as has been proposed (e.g., refs. 11 and 45).

A composite plot of typical experimental values of m available from the literature as a function of θ is shown in figure 12; the proposed prediction curves of Bushell (ref. 11) and Hoch (as given in ref. 45) are also shown. The flight data (refs. 10 and 45 to 49) show a wide range of results, including negative m values in some cases. The prediction of Bushell (ref. 11) also indicates an angular range of negative m values, primarily in the forward quadrant, as is consistent with some of the engine data (refs. 10, 11, and 45). On the other hand the simulated-flight data exhibit positive m values at all angles for shock-free jets (e.g., refs. 50 and 51, which are typical of such data), with the exception of some of the data of reference 46. The reference 46 data have a correction applied for an assumed sound absorption by the free-jet turbulent shear layer; without this correction the m values would be higher and closer to the other model data. Thus, it is apparent that improvements over the prediction of Bushell (ref. 11) are needed, and such predictions have been proposed by NASA Lewis (ref. 16) and the Société Nationale d'Etude et de Construction de Moteurs d'Aviation (SNECMA).[1] At jet velocities below approximately 520 meters per second, the earlier NASA Lewis method (ref. 16) fits the data somewhat better than does the SNECMA prediction, but the earlier NASA method is inadequate at high jet velocities. Therefore, a modified method has been developed (ref. 20) that shows better agreement with the data base than does reference 16 or SNECMA. Furthermore, the new method is more closely related to fundamental theories (refs. 9 and 52) than the earlier methods.

Plots of flight velocity exponents versus angle for the J85 turbojet engine on the Bertin Aerotrain (ref. 46) and comparisons with the prediction

[1]Method proposed to Society of Automotive Engineers A-21 Committee on Aircraft Noise by SNECMA.

method of reference 20 are shown in figure 13. The results have been corrected for Aerotrain background noise (ref. 46), for internal noise (ref. 16), and (where appropriate) for shock-cell noise (ref. 30). The results cover a range of jet velocity from 445 to 680 meters per second. The agreement is good in the rear quadrant, but the m values are consistently overpredicted for angles from 50^o to 120^o. The decrease in m with increasing θ at large angles and high jet velocities, a decrease that can produce negative m values (noise increase in flight), is due to supersonic convection effects and becomes more pronounced as jet velocity increases.

A statistical comparison is made in figure 14, where the distribution of the number of samples is plotted versus the experimental minus the calculated flight increment (in groupings of 0.5-dB width). The data base for this figure includes the low-bypass-ratio refanned JT8D engines on the DC-9 airplane and the higher-bypass-ratio JT9D engines on the DC-10 airplane (ref. 15). The error distribution is narrower for the present method than for the SNECMA method. The SNECMA method also has a significant peak at $\Delta_{exp} - \Delta_{calc} = -4.0$, indication of a significant problem with the SNECMA method. It is shown in reference 20 that the new method agrees better with the data base than a recently proposed SAE method. Over the data base range of jet velocity (primary) from 280 to 680 meters per second, the new method has a standard deviation of 1.5 decibels, and the proposed SAE (SNECMA) method has a standard deviation of 2.5 decibels.

IVP Coannular Nozzles

As was reported at the 1976 SCAR Conference (ref. 4), the aeroacoustic advantages of the IVP coannular nozzle concept have also been obtained under simulated flight conditions at model scale. The results of these tests are reported in detail in reference 51. Further analysis (ref. 29) of these results has shown that when the merged region and the premerged region are considered separately, the flight effects are quite similar to those of a conical nozzle at the appropriate (merged or premerged) conditions. Relative velocity exponents (eq. (1)) resulting from the analysis of reference 29 for the merged and premerged regions are shown as a function of angle in figure 15. Also shown is the range of conical nozzle mixing-noise results (ref. 51) from the same facility and over the same range of jet velocities and temperatures. The merged-region exponents are essentially in the middle of the conical nozzle range, but the premerged-region exponents tend to be on the high side (larger noise reduction in flight).

From the results discussed in the preceding paragraph it appears that the aeroacoustic advantages expected for IVP coannular nozzles should be retained in flight. However, some caution may be warranted since the tests of reference 51 were limited to two plugless coannular nozzles and were also limited to jet velocities and temperatures below those of interest for supersonic cruise application. More recent simulated flight tests conducted under contract NAS3-20619 generally confirm the trends cited in this discussion, but the final reduction of these data was not completed in time to incorporate the results in this paper.

Single-Stream Suppressors

It has been acknowledged that flight effects can be quite critical to jet noise suppressors. Therefore, recent suppressor tests (e.g., refs. 7 and 8) have emphasized flight effects. The results of reference 8 for a single-stream suppressor-ejector model are shown in figure 16 to illustrate typical trends. These results are for the same jet conditions as figure 8 but for simulated flight. The model-scale experimental data (ref. 34) are scaled up to a typical product-engine size (exhaust area, 0.713 m^2) at a typical flyover altitude (381 m), and the results are compared with those predicted (ref. 28) for a conical nozzle at the same ideal specific thrust. By comparing these results with figure 8, it can be seen that the peak noise suppression is less in simulated flight than under static conditions. The spin-rig data, particularly at low jet velocity (fig. 16(b)), appear to be contaminated by extraneous noise sources. The 40- by 80-Foot Wind Tunnel data indicate that although the flight results tend to be less favorable than the static results, peak noise suppressions of 7 PNdB at low jet velocity to 8 PNdB at high jet velocity may still be attainable in flight.

CONCLUDING REMARKS

This paper has reviewed some of the recent advances in acoustic technology applicable to advanced supersonic cruise aircraft, with emphasis on jet noise suppression and flight effects.

The noise-reducing characteristics of high-radius-ratio, inverted-velocity-profile coannular jets has been demonstrated by model-scale results from a wide range of geometries, including some simulated-flight cases. These results have now been verified statically at large scale on the variable-cycle-engine (VCE) testbed. The testbed results agree with scaled model data and with a prediction procedure based on model data.

A preliminary assessment of other potential VCE noise sources, based on the testbed data, has been presented. Unsuppressed fan noise appears to be significant and could be the controlling noise source at approach. Duct-burner combustion noise has been identified as a potentially significant problem for which no data base or acceptable prediction method is available.

An improved jet noise flight effects prediction has been developed and compared with experimental data obtained from the Bertin Aerotrain with a J85 engine, the DC-10 airplane with JT9D engines, and the DC-9 airplane with refanned JT8D engines. It has been shown that, over the data base range of jet velocity (primary) from 280 to 680 meters per second, the new method has a standard deviation of only 1.5 decibels.

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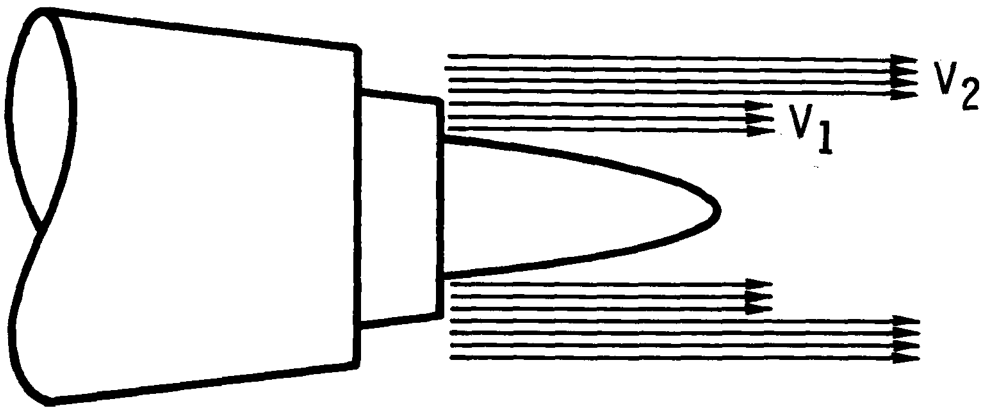

Figure 1.- Flow schematic of inverted-velocity-profile coannular jets.

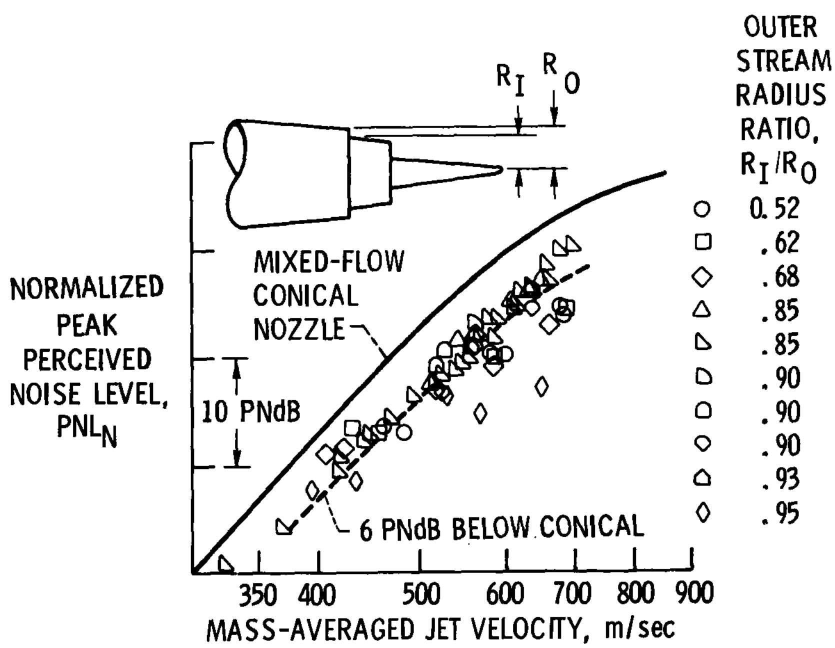

Figure 2.- Normalized peak perceived noise level for inverted-velocity-profile coannular nozzles as function of mass-averaged jet velocity.

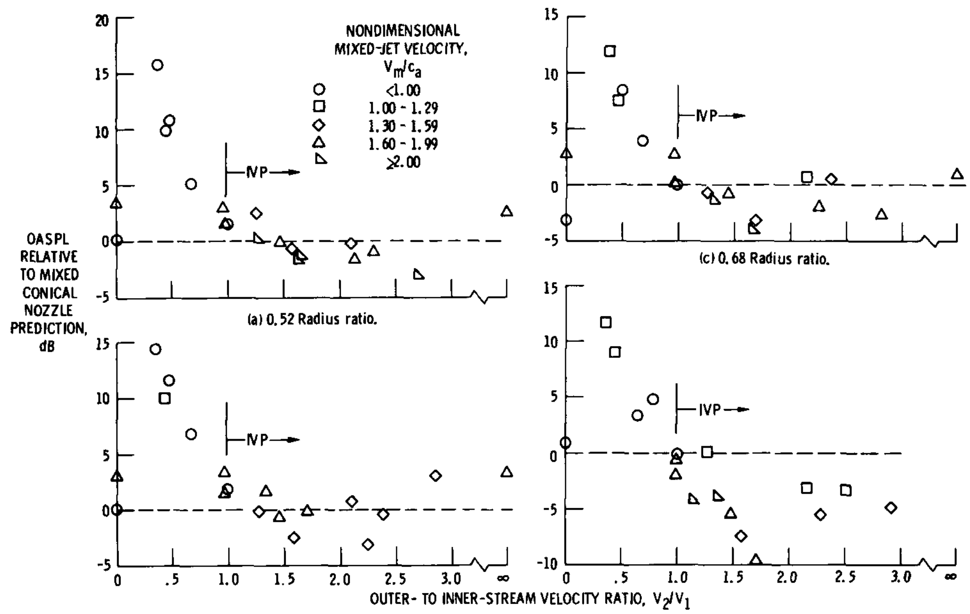

Figure 3.- Effect of velocity ratio on noise, relative to mixed-flow conical nozzle prediction, for different outer-stream radius ratio coannular nozzles. Angle referred to inlet axis, θ, 135°.

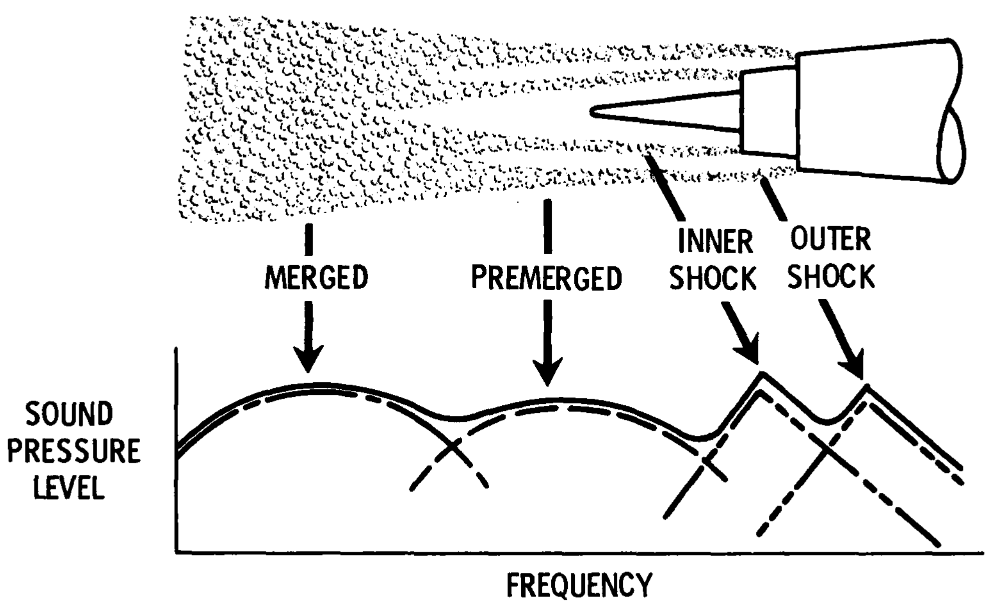

Figure 4.- Inverted-velocity-profile coannular nozzle jet noise sources.

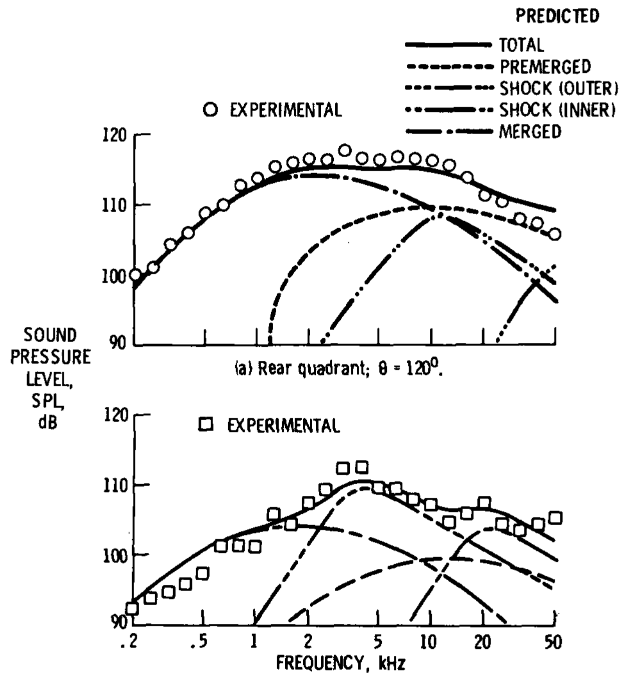

Figure 5.- Comparison of inverted-velocity-profile jet noise prediction with static model experimental data. Plugless coannular nozzle; mixed-jet velocity, $V_{j,m}$, 652 m/sec; mixed-jet temperature, 922 K; both streams supersonic.

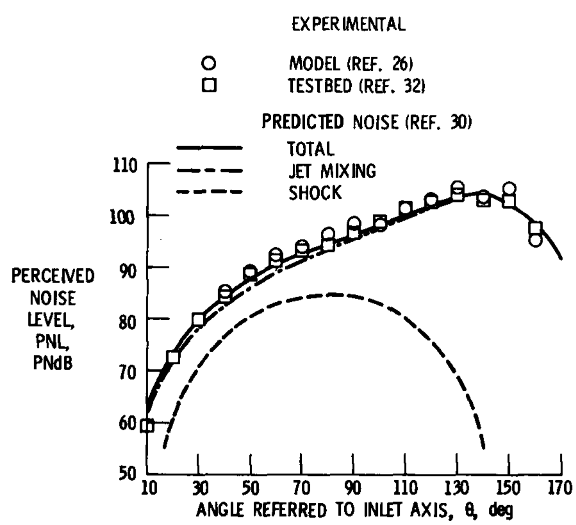

Figure 6.- Comparison of model and variable-cycle-engine-testbed experimental perceived-noise-level directivity with prediction at typical product-engine size (0.903-m^2 exhaust area) and at 731.5-m slant range. Mixed jet velocity, $V_{j,m}$, 590 m/sec; outer-stream radius ratio, R_I/R_O, 0.85.

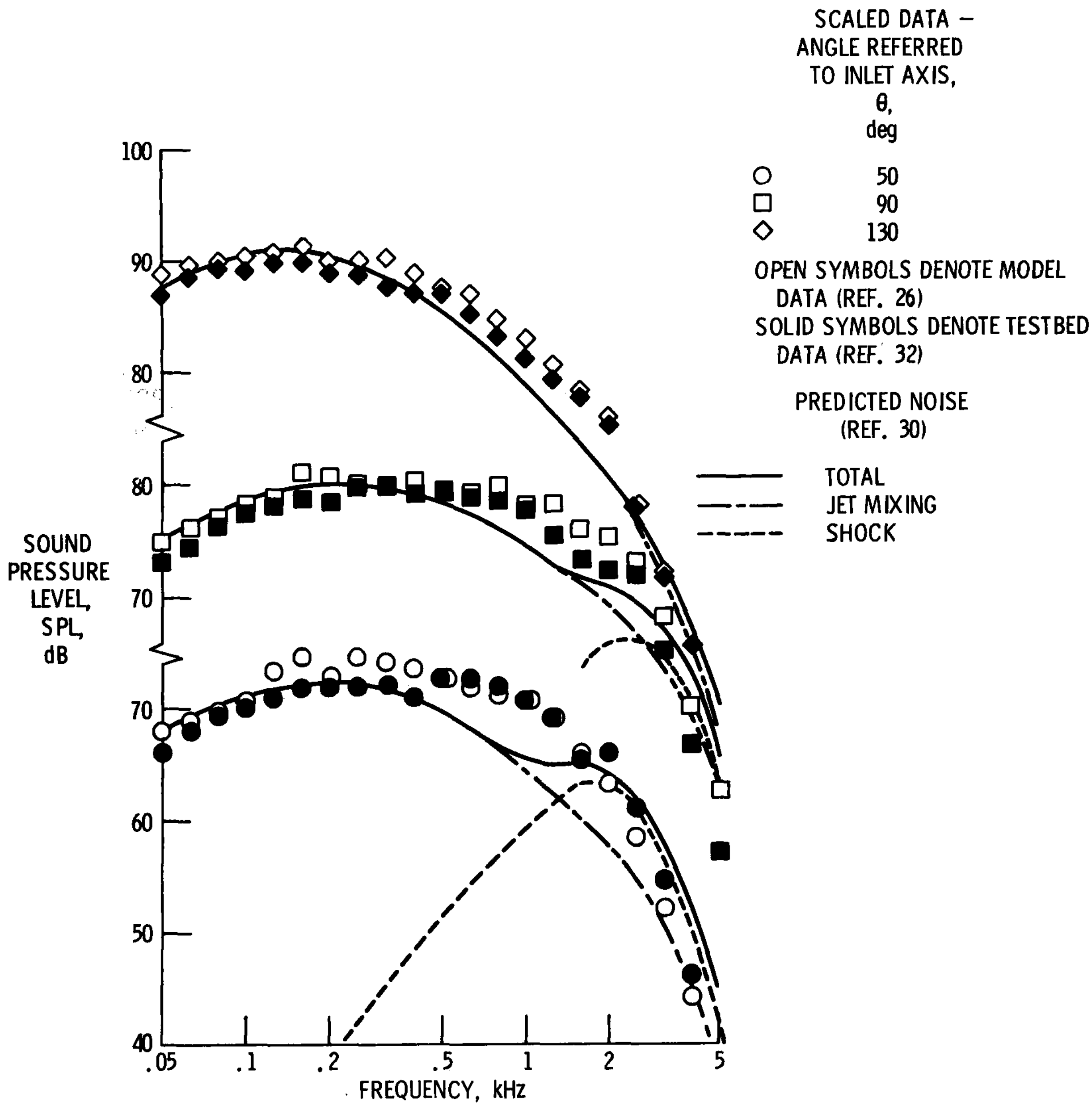

Figure 7.- Comparison of model and variable-cycle-engine-testbed experimental sound-pressure level spectra with prediction at typical product-engine size (0.903-m^2 exhaust area) and at 731.5-m slant range. Mixed-jet velocity, $V_{j,m}$, ~590 m/sec; outer-stream radius ratio, R_I/R_O, 0.85.

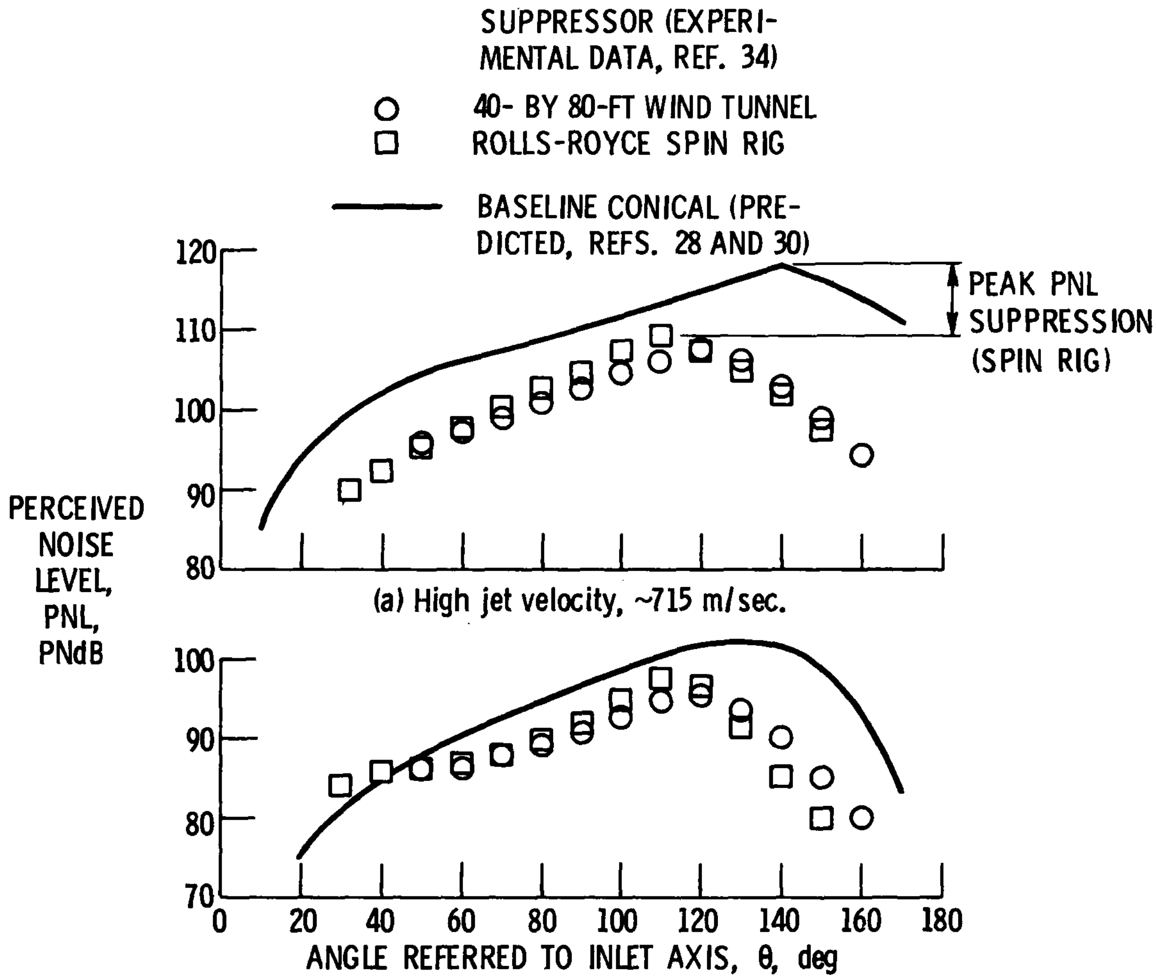

Figure 8.- Comparison of experimental, static perceived-noise-level directivity for McDonnell Douglas suppressor with lined ejector and prediction for a conical nozzle. Engine size (exhaust area), 0.713 m^2; flyover altitude, 381 m.

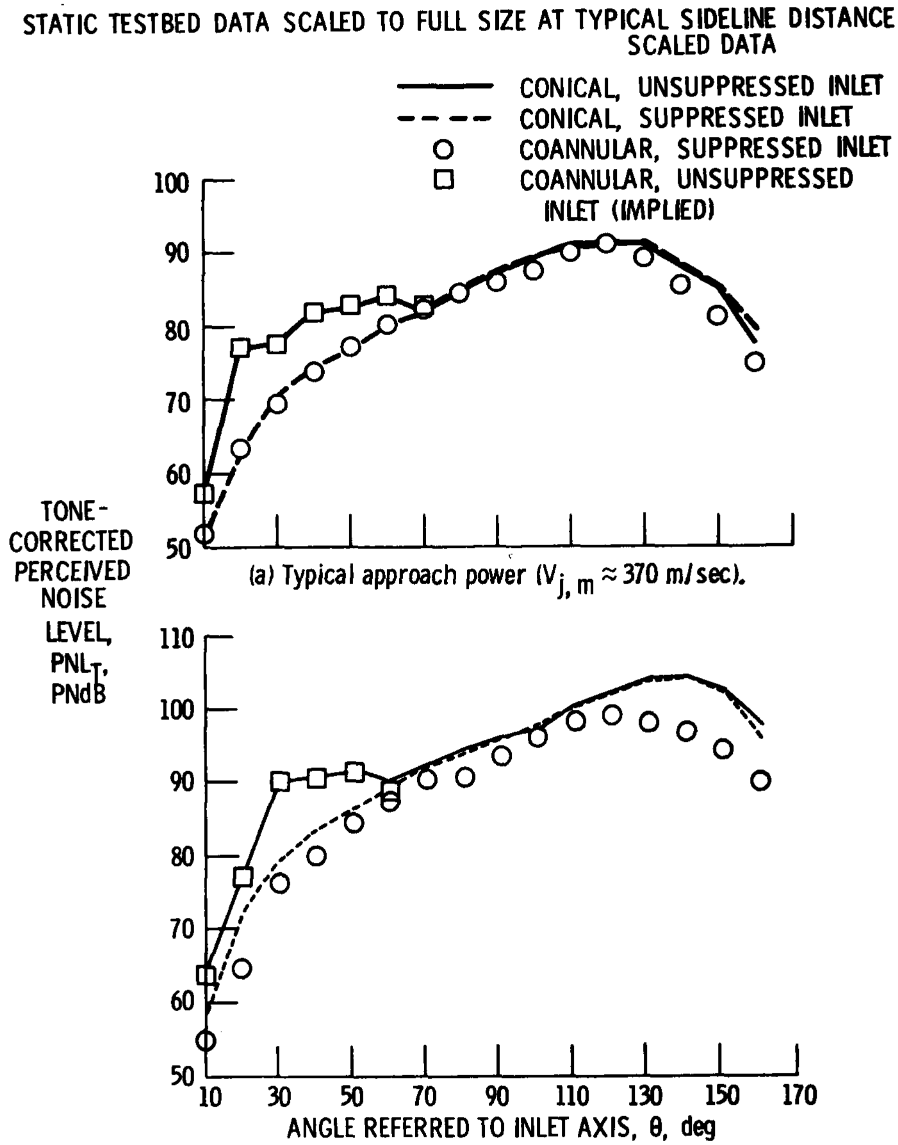

Figure 9.- Effect of fan noise on variable-cycle-engine-testbed, tone-corrected, perceived-noise-level directivity at different mission conditions. Typical product-engine size (0.903-m^2 exhaust area) at 731.5-m slant range.

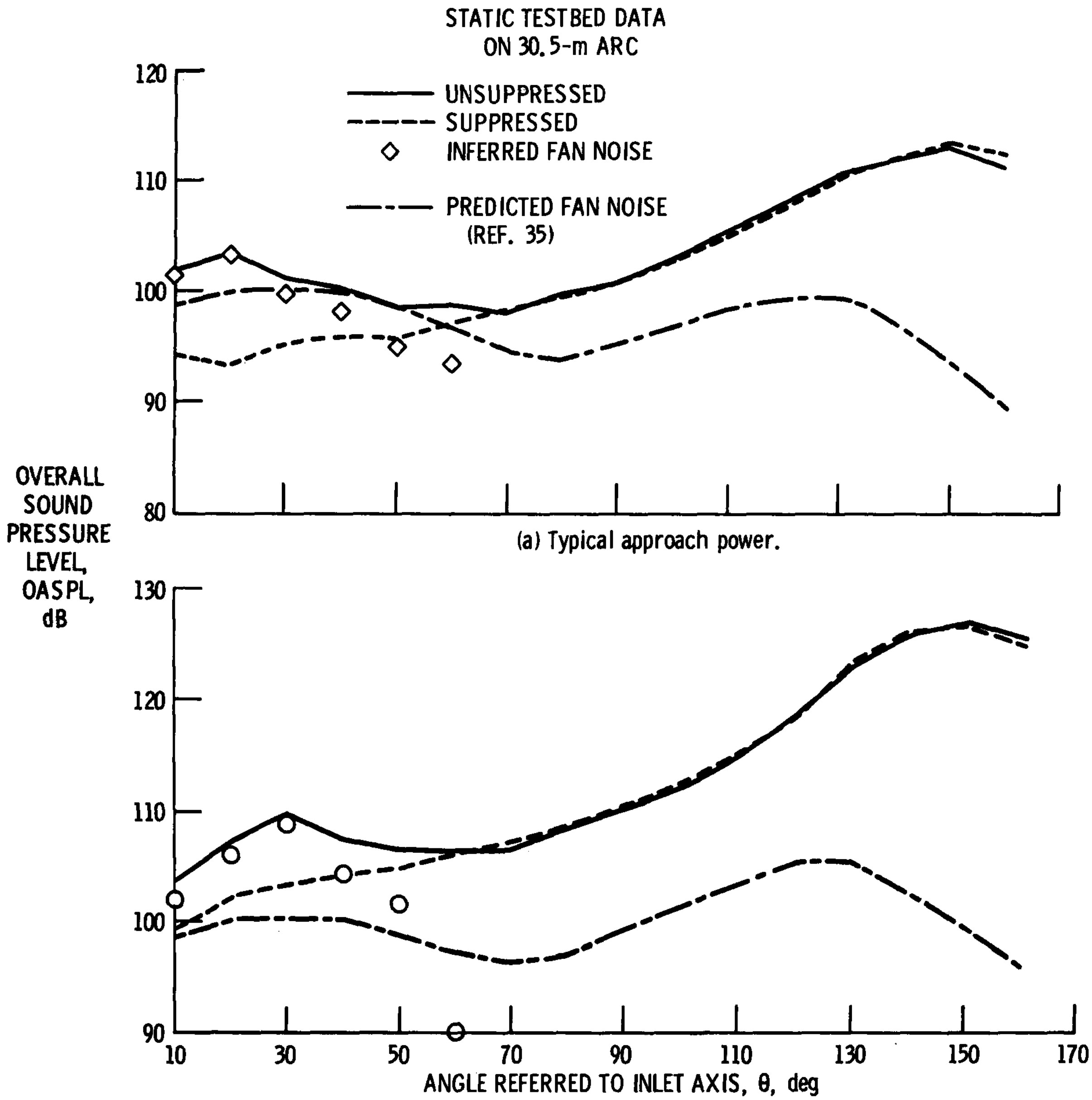

Figure 10.- Comparison of variable-cycle-engine-testbed, fan-noise overall sound-pressure-level directivity with prediction.

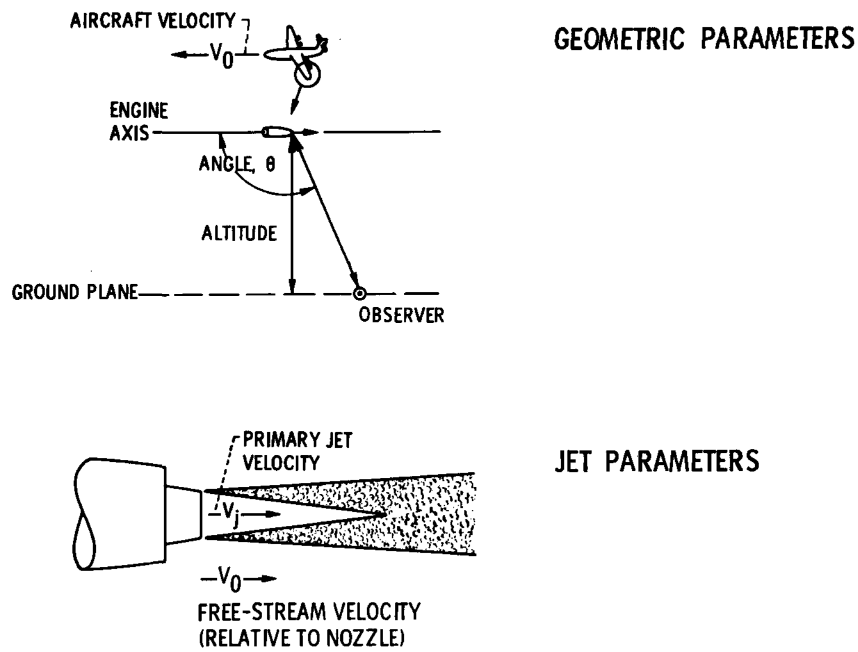

Figure 11.- Flight effects on exhaust noise (terminology for level flyover at aircraft Mach number M_0).

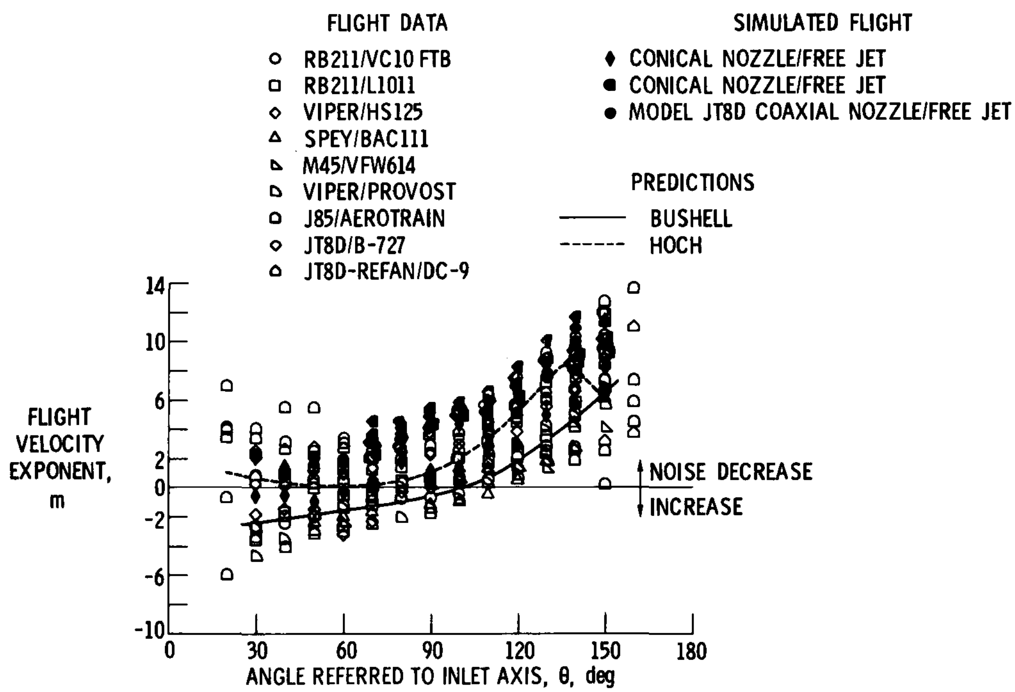

Figure 12.- Typical values of flight velocity exponents for a series of flight and simulated flight tests.

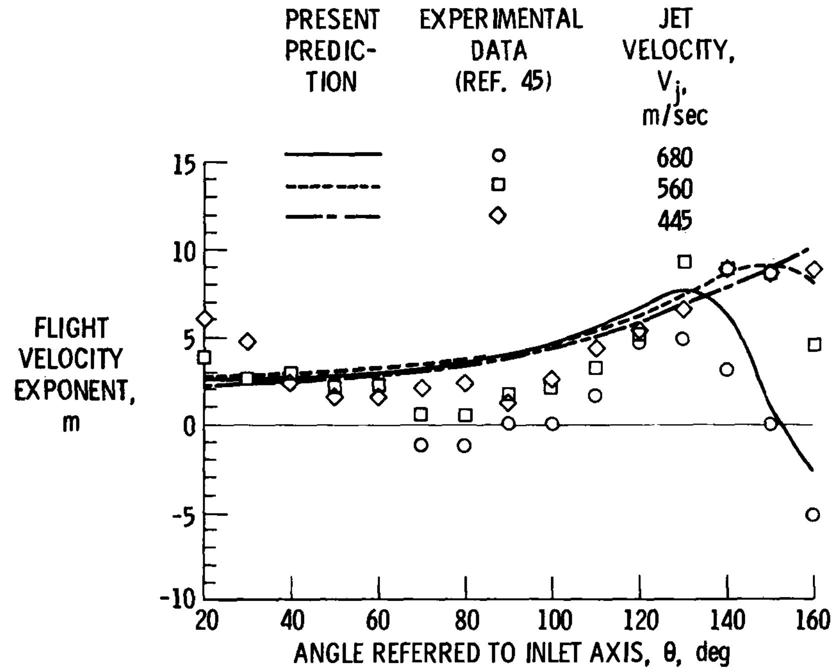

Figure 13.- Comparison of experimental and predicted flight velocity exponents for jet mixing noise of a J85 turbojet engine on the Bertin Aerotrain. Flight Mach number, M_0, 0.24.

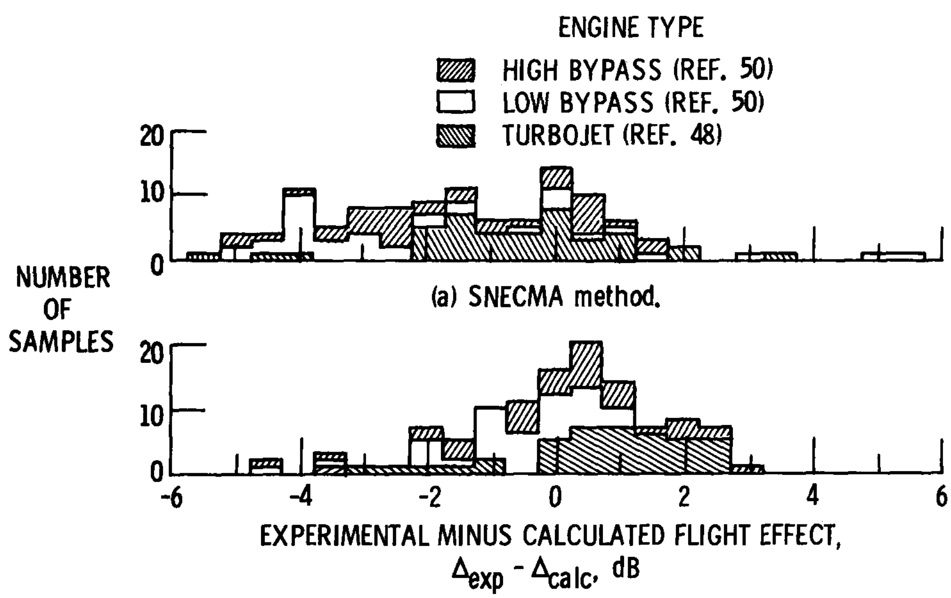

Figure 14.- Statistical comparison of prediction methods.

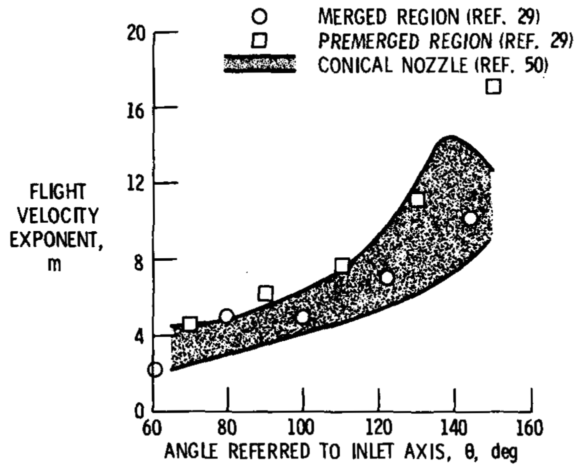

Figure 15.- Comparison of flight velocity exponents for inverted-velocity-profile coannular merged and premerged regions with conical nozzle data.

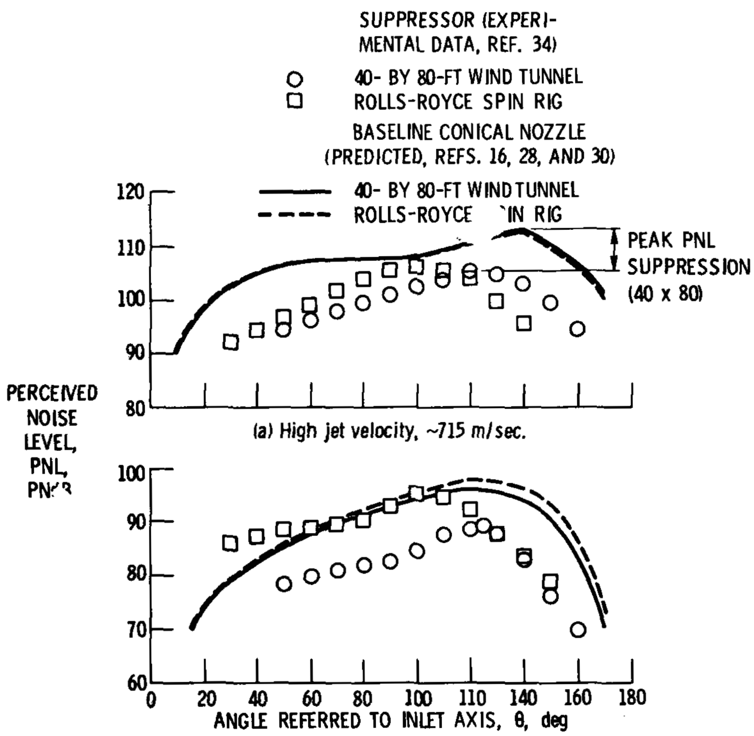

Figure 16.- Comparison of simulated flyover perceived-noise-level directivity for McDonnell Douglas suppressor with lined ejector and conical nozzle prediction. Engine size (exhaust area), 0.713 m^2; flyover altitude, 381 m.