Status of Some Current Research in Jet Noise

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Introduction

SINCE the introduction of the jet aircraft, jet exhaust noise has been a pressing problem and, except for the current high-bypass turbofans, constitutes the primary source of noise. Growth versions of both current high-bypass and future 10-ton turbofan engines with bypass ratio of 4-5 are expected to have difficulty meeting the FAR 36 (1977) levels. The 1990 generation CTOL aircraft powered by advanced technology engines with bypass ratio of 6-7 also will have difficulty in meeting goal levels below FAR 36 (1977). A relatively limited amount of technology exists on methods for high-bypass engines jet noise reduction, although some work has been done on multi-element suppressors for the core flow. The jet velocity of a high-bypass engine is relatively low, compared to low-bypass and straight jet engines, since more of the gas energy is removed by the turbine prior to expansion in the exhaust nozzle. Future noise reduction from high-bypass engines will require core noise removal before expansion, in addition to jet noise suppression. A goal of over 5 dB is a challenge because incorporation of most known jet noise suppression devices, which were developed for high-velocity jets, ends up making more noise.

The noise level of current narrow-body aircraft at takeoff is jet-noise-controlled. An internal mixer nozzle holds promise of reducing jet noise by 3-4 dB at the FAR 36 sideline measuring distance for the P&WJT8D powered aircraft, although other types of suppressors cannot be ruled out if more suppression is required.

Future SST's will have to be around 15 EPNdB quieter, even to meet FAR 36 (1969) levels, when compared to designs unconstrained by noise requirements. In order to achieve FAR levels, engine/airframe design tradeoffs will be required, and use will be made of advanced variable-cycle engines in addition to utilizing jet noise reduction techniques, such as the inverted velocity profile nozzle, the internal mixer nozzle of multielement suppressors, or combinations of these.

Usually, derivative aircraft, utilizing the advanced noise technology, are larger and hence are not able to demonstrate smaller ground noise contours than the older versions. In addition, future advanced new aircraft will be required to meet stiffer efficiency constraints; thus the manner in which the technology will be utilized on new or derivative aircraft will be governed by regulatory and economic factors.

The objective of this paper is to review the status of jet noise technology and suppression concepts being pursued. In-flight effects on jet noise suppressors remain a critical issue and in need of much more attention.

Jet Noise

Aerodynamic noise is generated by a freejet because of the turbulence created on mixing with the ambient air; the ratio of acoustic power output divided by jet power is around 10^{-4} for jet speeds equal to the atmospheric speed of sound. Noise produced by turbomachinery and combustion, called core noise, coming down the tailpipe adds to the jet noise. This source becomes more important as the jet velocity decreases below 425 m/s (1400 ft/s). Sound propagating (refracting) through a shear layer is not necessarily an acoustic energy-conserving process. It can be scattered or considered to be absorbed to explain certain observations in some cases; it also can modify and amplify the jet flow noise. For supersonic jets, shock noise is added to the preceding sources. Shock noise radiates primarily in the forward quadrant. Noise reputed to come from large-scale spiral-mode-flow instability has been observed in small-scale and J-58 engine tests with round convergent nozzles under supersonic flow conditions. This noise source may be related to the crackling noise often heard from high-velocity jets.

At jet velocities of twice the ambient speed of sound, the ratio of acoustic power to jet fluid power is approximately 3×10^{-3}. Acoustic energy from the jet, therefore, is a small by-product of the flow energy involved and at the present time cannot be measured within the jet itself. Thus, experimentally it is not possible to identify the acoustic source distribution separately from the effects of sound propagation within the jet. Even though we know that the generation and propagation of sound are inextricably coupled, conceptual separation of these mechanisms is done only to simplify visualization of the problem. The most recent improvement in our understanding of the subject arises in incorporating the effects of the acoustic/mean-flow interaction. The mean-flow shrouding, including transverse velocity and temperature gradients, affects the radiation of the turbulent mixing noise. The prediction and measurement of quantities defining turbulent flow is still in need of refinement; so at present a successful aeroacoustic theory must be formulated in such a way as to make only minimal demands on the flow specification.

Status of Our Ability to Predict

So where are we in our ability to predict noise from jets? A unified aerodynamic/acoustic prediction technique has been developed for assessing the noise characteristics of conical and suppressor nozzles, the details of which are described in Ref. 1. The fine-scale turbulence, produced in the mixing

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regions of the jet plume, is assumed to be the primary source of noise, as in the classical theories. The interaction between the generated noise and the jet plume (sound/flow interaction of fluid shielding) is modeled using an extension of the theory[2] for high-frequency multipole sources convecting in a parallel shear flow. The flowfield itself is modeled utilizing an extension of Reichardt's method[3] to provide predictions of jet plume velocity, temperature, and turbulence intensity distributions. References 1-3 are covered in greater detail in Ref. 4.

These basic modeling elements (flowfield prediction, turbulent mixing noise generation, and sound/flow interaction) have been coupled in a discrete volume element computation procedure. The jet plume is divided into elemental volumes, each roughly the size of a representative turbulence correlation volume appropriate to that particular location in the jet. This is illustrated in Fig. 1. Each volume element is assigned its own characteristic frequency, spectrum, and intensity directly related to the local flow properties (i.e., mean velocity, density, and turbulent structure quantities such as intensity, length scale, etc.). The sound/flow interaction effects for each volume element are evaluated from the flow environment of that element. The individual elements are assumed to be uncorrelated with each other, so that the total contribution to the far field is simply the sum of the individual volume element contributions added on a mean-square pressure basis in each frequency band.

An example of predicted far-field noise spectra and directivity for a conical nozzle is shown in Fig. 2, along with measured characteristics from scale-model tests. Figure 3 shows similar predictions for a multichute/plug suppressor nozzle and comparisons with measured scale-model data. These results indicate that the unified aeroacoustics model can be used successfully to predict most of the observed characteristics of static conical and multielement suppressor nozzles. Experience with many diagnostic computation studies indicates that the observed noise characteristics are a result of the competing influences of turbulent mixing, convective amplification, and acoustic shielding. These competing influences are in a delicate balance, and the type of volume-element calculation described herein, summing up all of the individual contributions, is required to predict the far-field noise properly.

Although what has just been described is impressive, the fact remains that there is not complete agreement on the procedures and results shown among research workers. For example, Fig. 4, from another source, shows that, utilizing essentially the same theoretical approach as just described, i.e., predictions based on the Lilley acoustic theory with rudimentary source modeling,[5,6] the sounds at low angles for a simple conical jet are considerably different from the experimental data. These differences in calculating methods, etc., should be resolved in time.

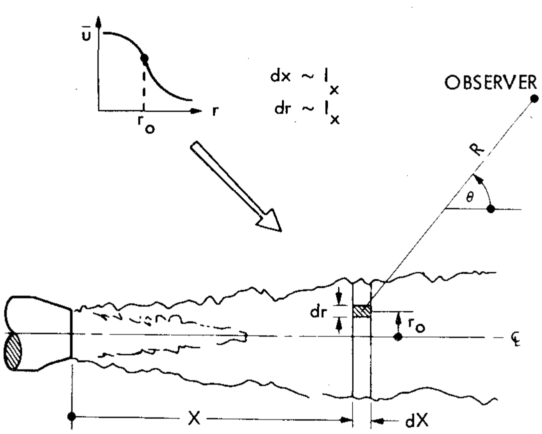

Fig. 1 Jet plume volume element subdivision.

What Are the Problems?

The preceding situation reveals a failure in the theory as well as differences in interpretation and calculating methods. The shrouding theory shows that the jet velocity and temperature profile expel the higher-frequency noise out the sides of the jet, leaving mostly the low frequency to go down the center of the jet, which results in a "zone of silence." The current theory correctly predicts that for subsonic jets the angle of maximum noise is outside the zone of silence [which is the cone within the angle, $\cos^{-1} a_0/(a_j+U_j)$, with respect to the jet axis]. For correctly expanded supersonic flows, however, the experimentally determined angle of the maximum noise lies inside the predicted zone of silence and is, in fact, given by the angle of eddy Mach wave radiation which is $\cos^{-1} a_0/0.7\, U_j$. Thus the concept of the zone of silence is not of universal validity, and consequently, sound can be

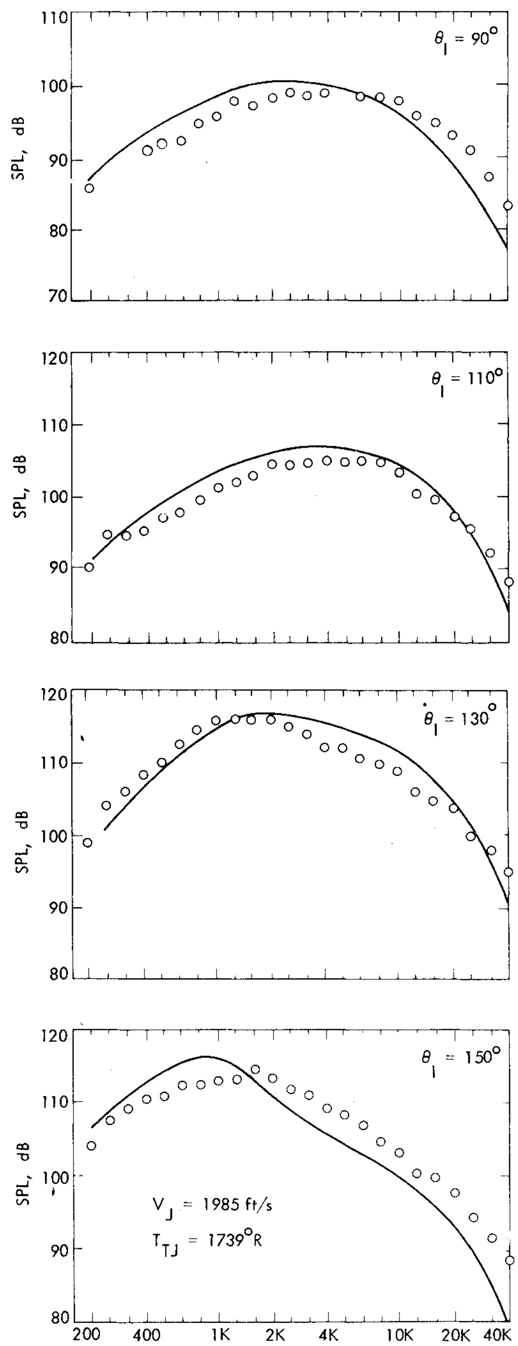

Fig. 2 Conical nozzle spectrum theory vs data comparison (4.24-in.-diam nozzle, 40-ft arc).

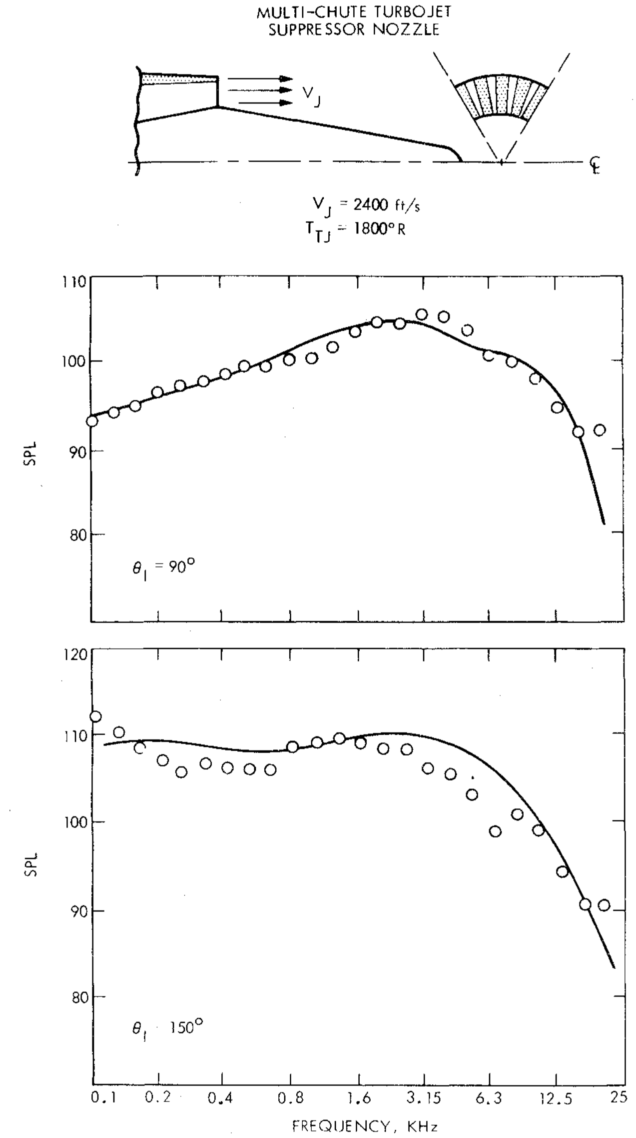

Fig. 3 Multichute suppressor nozzle theory vs data comparison [36-chute (area ratio = 2.0), $A_j = 336$ in.^{2}, 160-ft arc].

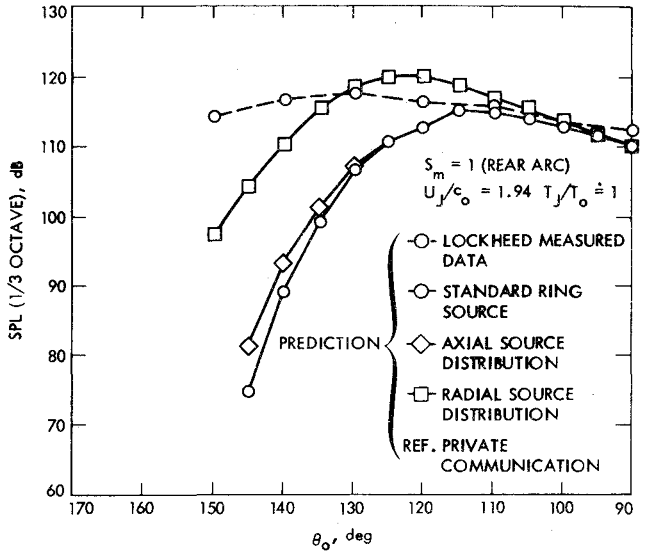

Fig. 4 Comparison of measured jet mixing noise and small-scale turbulence noise prediction.

radiated within this zone of silence which for supersonic jets is attributable to a mechanism of sound production different from that for subsonic jets[7-11] Shock noise adds another degree of complication, particularly for multielement nozzles.

Our inability to accurately predict the noise of a jet in motion, termed flight effects, remains the key stumbling block in our knowledge of the subject. This includes the confusion in the interpretation of the results of in-flight simulation techniques, such as the free jet (where the microphone is placed outside the flow) and the wind tunnel (where the microphone is inside the flow), where complicated analytical methods are used to reduce the data to actual flight conditions. In the free-jet case, an absorption correction is applied at the outer shear boundary to bring the results into agreement with the in-flight noise, a factor not yet fully substantiated. In the case of the wind tunnel, because of wind-tunnel size limitations, reverberation, and background noise level, the measurements are made in the near field and are corrected for source distribution and near-field effects in a complicated and semiempirical manner.

The Rolls Royce spin rig, on which the jet is mounted at the end of a rotating arm, also used to measure in-flight effects, was reported to possess a significant amount of internal noise, and the experimental results, although similar to engine results, require extensive data reduction. The French aerotrain has turned out to be an effective testing device, but the nozzles are mounted on an engine and hence do not yield pure jet noise, and consequently other sources of noise must be taken into account.

A lot of progress has been made recently nevertheless, and continuous probing into the troublesome areas surely will bear results; for example, the use of high-speed Schlieren motion pictures,[12] shadowgraphs etc., reveals motions of the jet which are considerably different from just a purely random turbulence model, i.e, consisting of relatively compact eddy sources. First of all we observe, in many cases, large-scale deviations of the motion from the mean and often observe that the deviations are somewhat orderly. One should bear in mind that the mean-flow conditions and the mean statistical properties of the fluctuations such as power spectra may not be adequate to describe the process of noise generation in a flow that is not totally random. Figures 5 and 6 show two kinds of large-scale motion. The first one for a subsonic jet appears to consist of vortices that come together (pairing) to form one larger vortex. Microphones located in close proximity to the vortex pairing process reveal large noise output, whereas the other globs of fluid going by do not produce as large a pressure signal. This type of motion, although appearing more orderly at an instant of time, does occur in a random fashion, so that the time and position of the pairing event cannot be predicted or (so far) controlled.

The second class of large-scale motion results from instabilities of a jet. Figure 6 shows large, more or less orderly structures. Whether or not there is some connection between the two types of large-scale motions or if they can coexist is not known. Computation shows that the noise output from large-scale motion for supersonic jets can account for some noise coming from angles that are inside the zone of silence, just as for the case of Mach wave radiation, as mentioned previously. A turbulent outer interface of a jet moving supersonically with respect to the ambient will generate highly directional Mach waves whatever the source of this motion may be, viz., small-scale or large wavelike motions. These Mach waves can radiate into the zone of silence when their velocity of convection is low supersonic, and the angle approaches 0 deg as the convection velocity reduces to the sonic value. The concept of the zone of silence is, from geometric acoustics, valid at very high frequencies and infinite wave fronts and refers only to sound propagation of a wave from within a jet.

Although all of these troubling features of the flow remain, and the acoustic output from large-scale motions or any other

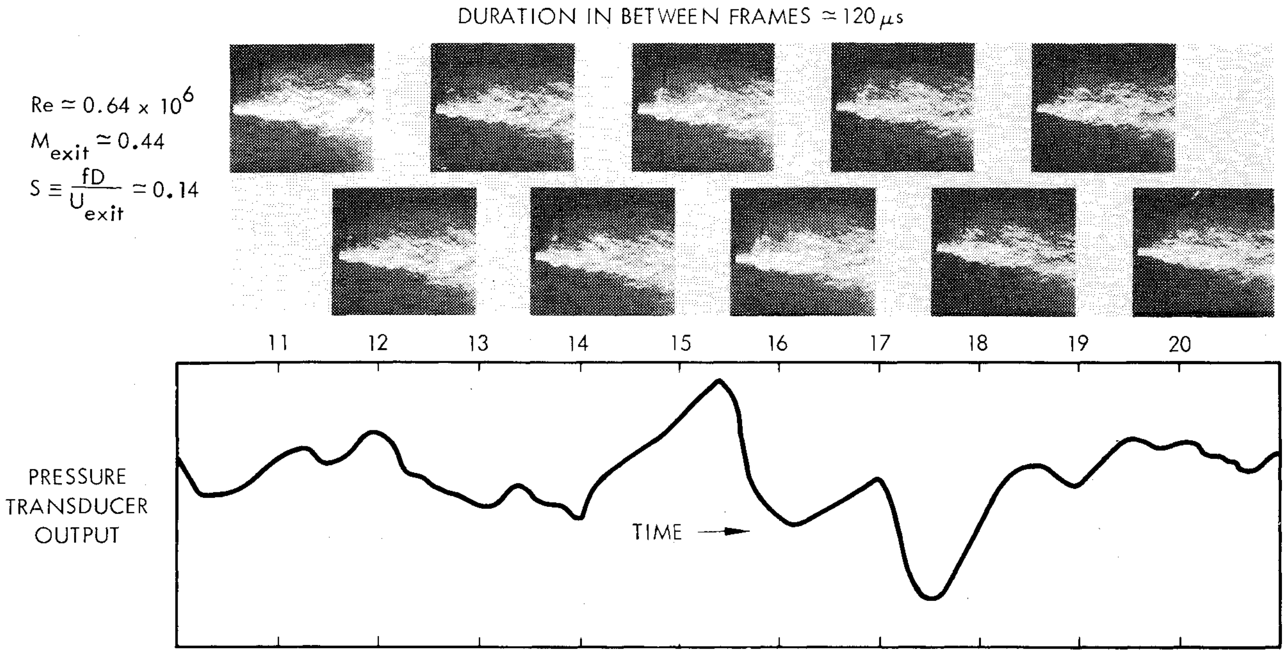

Fig. 5 High-speed motion pictures of large-scale jet structures with near field pressure.

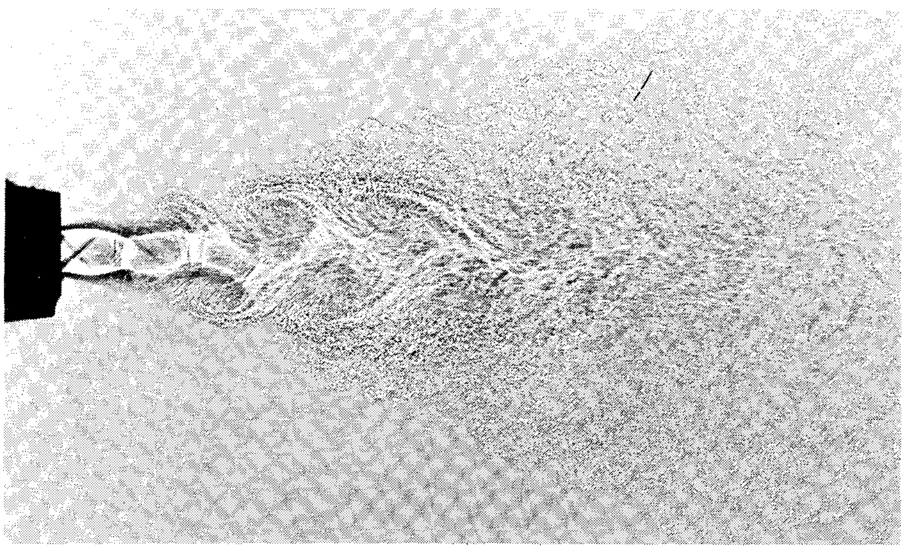

Fig. 6 Evidence of large structures in a supersonic jet.

aspects of noise generation, propagation, or flight effect is uncertain, our understanding of the subject cannot be considered adequate. The remainder of the paper will be concerned with data and specific aspects of the technology, the status of the technology, as well as pointing out areas of uncertainties and anomalies.

Some Aspects of Jet Noise Suppression

During the past few years, manufacturers and research organizations have actively undertaken a more systematic investigation of jet noise generation and suppression principles. The bulk of the early work was done under static conditions. We have learned through bad experience not to rely on static results alone to predict in-flight noise, an issue to be discussed later.

There are many kinds of exhaust nozzles, but they can be classed as follows: a single jet, usually a conical nozzle or annular with plug, or one that consists of more than one annulus with different velocities in each annulus, or a nozzle consisting of many elements. There are an infinite number of geometries, but the preference here is to deal with five basic velocity profiles that categorize the fundamental differences in nozzle types; these will be referred to in this paper as shown in Fig. 7. The velocity profile shapes for the straight conical and internal mixer nozzle are the same; the latter one has a lower velocity, resulting from first mixing the fan flow and core flow before expanding through the nozzle.

The addition of an ejector, also referred to as a secondary nozzle, on any of the nozzles can result in lower noise radiation. The ejector is a device that surrounds the primary nozzle and permits ambient air to enter and mix with the jet. The result is usually a lower-velocity jet emerging from the secondary nozzle, which generally produces less noise on further mixing with the outside air. The secondary nozzle often is acoustically lined to remove some of the high-frequency noise generated within the secondary nozzle.

It has been customary to consider internal mixer nozzles and inverted velocity profile nozzles as suppressors, although some debate this point and refer only to the multielement system as a real suppressor and the former two as flow schemes that are less noisy than the baseline unmixed case shown in Fig. 7. What is observed from each type will be discussed next.

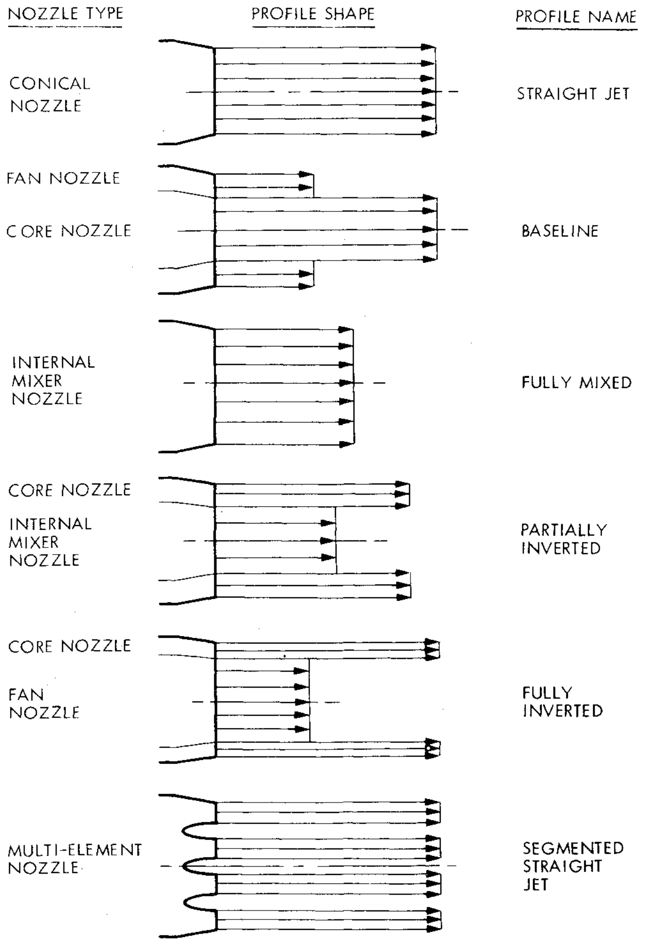

Fig. 7 Nozzle configurations and corresponding jet velocity profiles.

Conical Nozzle

This is a straight jet that has been studied extensively but still is not understood completely for reasons described previously.

Baseline Nozzle

The introduction of fan flow on the outside of the core flow, if the fan velocity is less than approximately 0.7 the velocity of the core flow, will reduce the net noise from the nozzle; this, in spite of the fact that the thrust of the coflow nozzle is greater if the core flow is not changed while the fan flow is increased. Introduction of the fan flow increases slightly the low-frequency noise and decreases the high-frequency noise when compared to the original core jet.[13]

Figure 8[14] shows that, while holding thrust, total nozzle area, and total mass flow rate constant (considered to be a more appropriate way to consider the problem), the OASPL decreases (top curve) when fan flow is increased up to approximately 0.7 V_{fan}/V_{core}, the minimum noise being at 0.5.

Mixer Nozzle

When the fan and core flow streams are first mixed prior to expansion out of a common nozzle, the net noise will be even lower than that which results from the previous case. In addition, mixing the hot core flow and cold fan flow prior to expansion can, if the mixer losses are not high, result in greater thrust than the sum of the two individually expanded streams by as much as a few percent, depending on flow ratio, temperature ratio, etc., of each stream.

An ideally mixed nozzle should have a noise output of a plain conical nozzle of the same mixed flow velocity, temperature, and area. If the mixing is not such as to produce a flat velocity profile or if the mixer introduces internal noise,

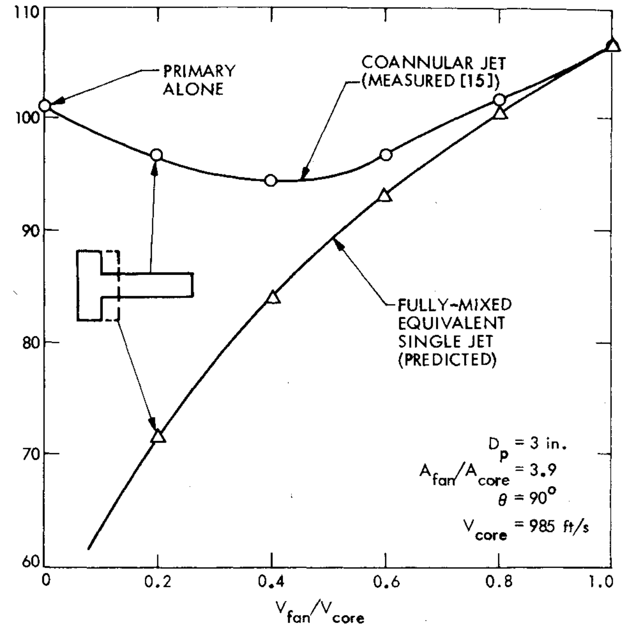

Fig. 8 Comparison of noise from coannular jet with noise from fully mixed equivalent single jet. (At each V_{fan}/V_{core}, the comparison is at constant thrust, area, and mass flow rate.)

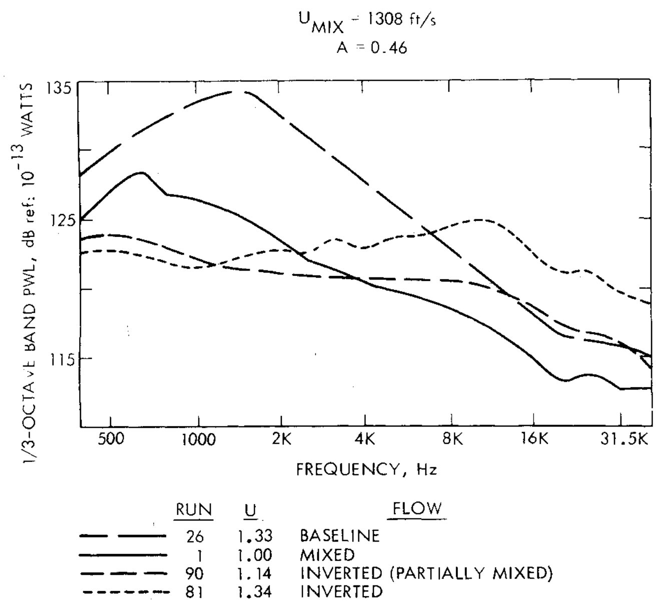

Fig. 9 Effect of inverted flow velocity on power spectra.

the net noise will be somewhat different from that of a pure conical nozzle.

The lower curve in Fig. 8 is the comparable noise output of the fully mixed jet. Clearly the fully mixed nozzle is less noisy than the coflow system. If, however, thrust, mass flow, and total enthalpy had been held constant, the results would have been essentially the same. These figures were for shock-free flows and for cases where the higher temperature is associated with the high-velocity stream. More work is required for the case of flows with shocks and the high temperature associated with the low-velocity stream.

Inverted Velocity Profile

If, on the other hand, the high-velocity flow is put on the outside and low-velocity flow on the inside, i.e., totally reverse the usual fan and core velocity situation, the net noise can be even lower than for the mixer flow case. For lowest noise, the velocity ratio and area ratio between the jets must

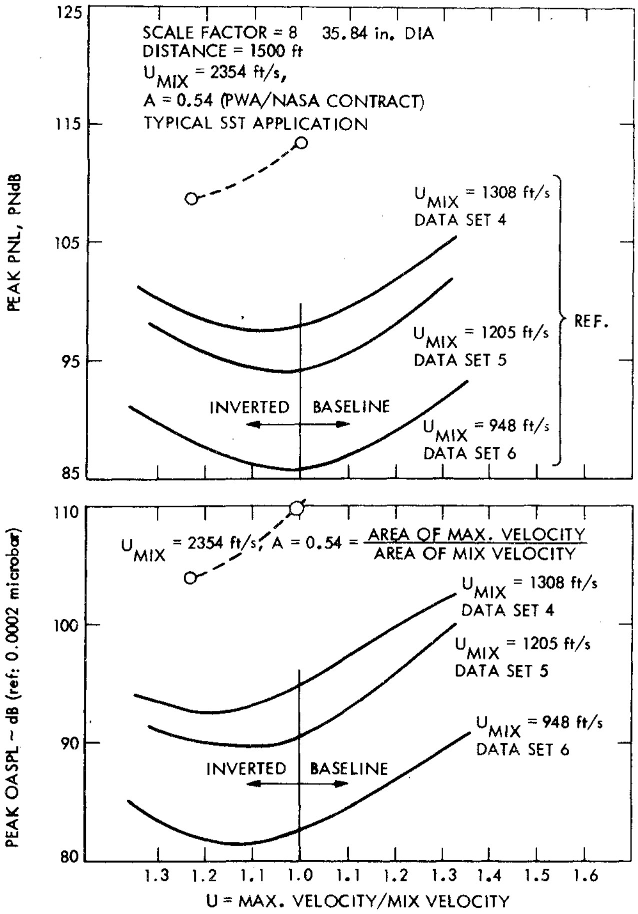

Fig. 10 OASPL and PNL as a function of velocity ratio and U_{mix}.

be optimized, and it may be necessary to do partial mixing (termed partially inverted) in order to achieve a more favorable velocity ratio for noise reduction. Figure 9[15] shows power spectra for the baseline (Fig. 7), fully mixed, partially inverted, and full inverted for the P&WJT8D size engine. Clearly the inverted profile produced substantially less low-frequency noise but more high-frequency noise. Also, it should be noted that the spectra of the inverted nozzles exhibit a double hump, characteristic of multielement nozzles.

Figure 10 shows the peak OASPL and PNL as a function of velocity ratio and average mix velocity for a P&WJT8D engine size nozzle. In all cases, the inverted velocity nozzle was less noisy than the mixed flow case for $U=1$ and also for the baseline case. It can be seen that, as U_{mix} increases, the optimum U increases, so that for high-velocity requirements such as an SST application the inverted velocity profile appears to have an advantage of several decibels over the mixed flow nozzle according to these static experimental results.

What can we say about the possible mechanisms involved which lead to the noise output characteristics observed? When the high-velocity jet is on the outside instead of being the inner flow, the high-velocity jet experiences greater shear stress, since the relative velocity between jet and ambient air on the outside is greater than in the base case, and also it is exposed to a larger shear area, since the perimeter is larger. The high-velocity jet is also in shear with the low-velocity flow, now on the inside. The total retarding force on the high-velocity jet has increased over the base case; thus the high-velocity jet emerging from the nozzle generates more high-frequency noise, which is highest at the beginning of the mixing region. The frequency output is a function of the velocity and mixing layer thickness, i.e., velocity gradient. The low-frequency noise comes from the region downstream of the nozzle, because the velocity and shear gradients are low. The rapid initial mixing and quick development of a large low-velocity

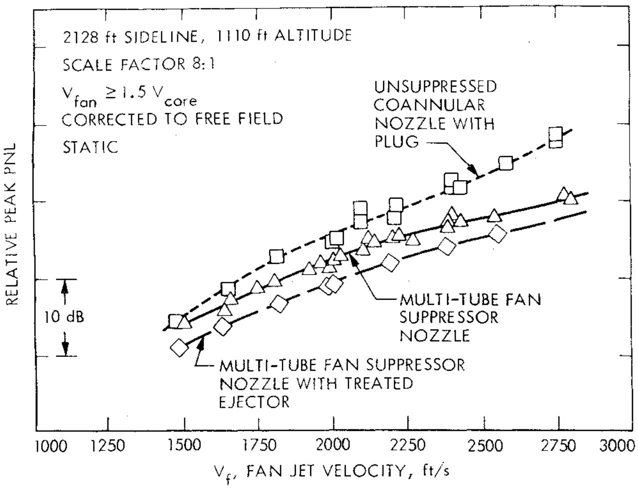

Fig. 11 Inverted velocity profile nozzle with multitube suppressor and treated ejector.

plume result in the double-humped spectrum. The high-frequency noise can be reduced more easily than the low-frequency output by acoustically lined ejectors and atmospheric attentuation

Interestingly enough, these same principles apply to the multielement nozzle, with one additional factor that will be mentioned later. Multielements can be combined with the inverted profile concept to achieve even greater suppression. Figure 11 shows that further reductions in noise over the inverted coannular plug can be achieved by placing a multitube suppressor for rapid mixing of the ambient air and high-velocity stream. Then even further noise reduction is possible by incorporating an acoustically lined ejector. It is important to remember that the far-field noise reduction can be achieved by both a total power reduction, which is not large for a plain inverted flow nozzle, and by atmospheric attenuation of the high-frequency noise to the far field. There is more high-frequency noise generated in the inverted profile jet than for a straight conical jet.

Multielement Nozzles

An extensive amount of work has been reported on multielement suppressors.[16,17] The elements of the nozzle can be tubes, lobes, spokes, chutes, etc. These can promote rapid mixing between the high-velocity jet and the ambient air.

Figure 12 shows the spectral output as a function of tube number and area ratio (total base area divided by high-velocity jet area). The double hump can be noted, as was shown with the plain inverted velocity coannular nozzle. The principle of operation is described in the following.

The jet, just after leaving the nozzles, experiences rapid deceleration due to the greater amount of jet shear area afforded by the presence of multielements as compared to a single round nozzle. The initial mixing region produces the high-frequency noise, and then the collection of the individually mixed jets merges and produces the low-frequency noise. The one important difference between the inverted and the multielement nozzles is that, fortunately, a large portion of high-frequency noise within the array appears to be effectively shielded by the outer row of jets, for reasons not fully understood, so that at velocities near or above critical you essentially hear what you see; i.e., the noise comes from the outer perimeter.[18] The primary function of the jet noise suppressor is to generate high-frequency sound in lieu of low-frequency sound, so that it can be removed by an acoustically lined ejector or, more readily, by the atmosphere. The low-frequency noise output is less than the original conical nozzle output because the merged velocity, i.e., the final mixing velocity of each element, is lower than that from a single large jet.

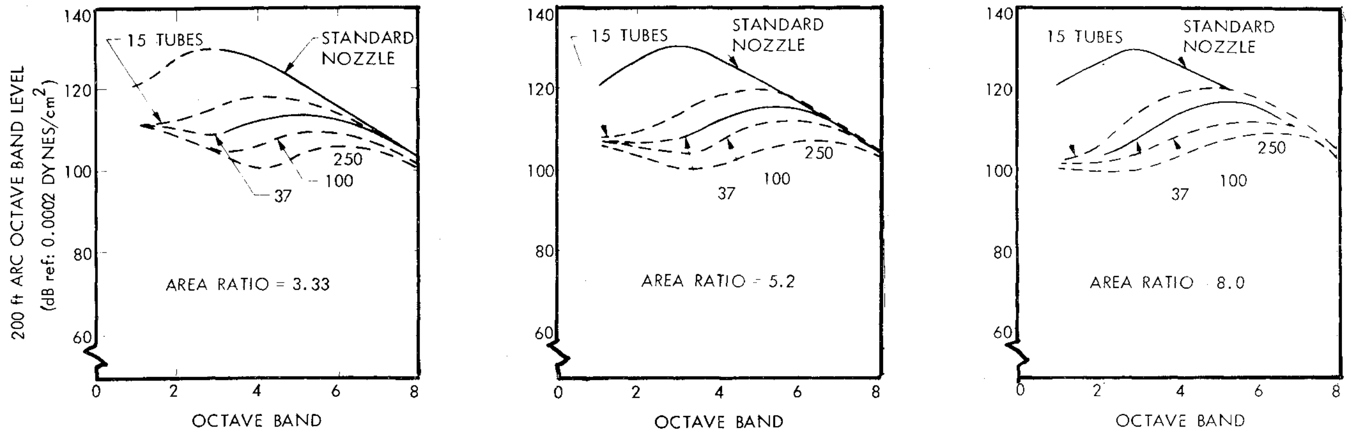

Fig. 12 Effect of tube number on spectra. PR = 3.0; T = 1500 °F; noise at maximum PNL angle.

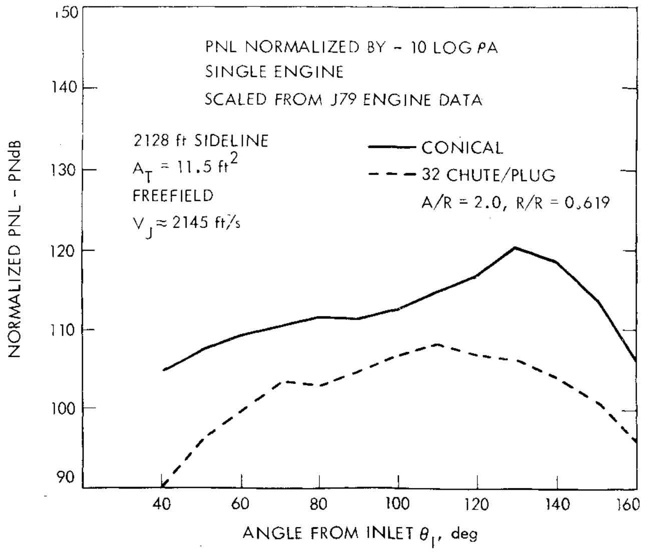

Fig. 13 PNL directivity of conical and mechanical suppressor from J79 engine tests.

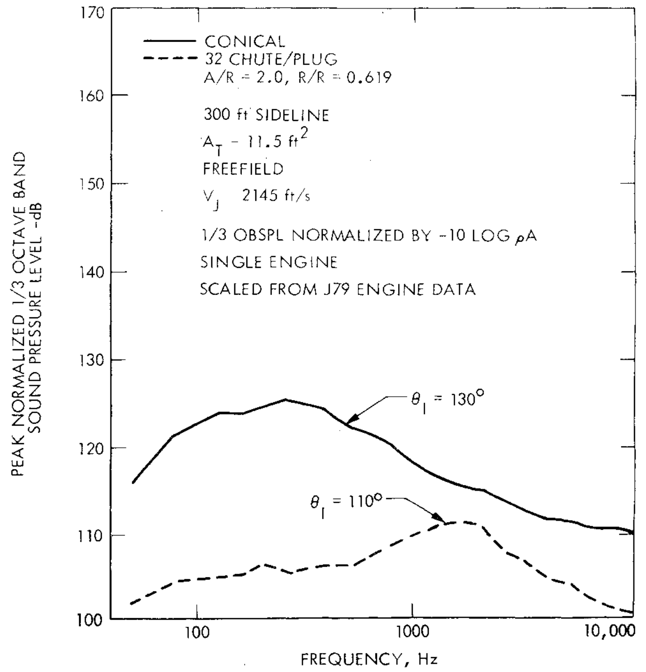

Fig. 14 J79 engine jet noise spectra comparisons of conical and mechanical suppressor.

Shock noise is added to the basic nozzle mixing noise, and this source can be very troublesome for high-pressure-ratio nozzle applications. More work is required in this area, particularly for flight conditions. Figure 13 shows the static PNL directivity for the conical and 32-chute/plug nozzle of area ratio 2, and Fig. 14 shows the spectrum of the conical and 32-chute nozzle at the peak noise angles for the static case. An important point to note is that, although a substantial reduction in total noise is achieved, the suppressor peak noise angle occurs at 110 deg, as compared to 130 to 140 deg for the conical. This characteristic is generally true of all mechanical suppressors and poses a problem that appears in the in-flight effects, to be discussed later. Figure 15 shows the peak PNL as a function of jet velocity for both a model- and full-scale conical and suppressor nozzle, attesting to known principles of scaling. Also, it should be noted that at lower velocities the suppressor effectiveness diminishes rapidly and can be more noisy at velocities below 1300 ft/s in this case. Figure 16 shows PNL static against static thrust loss for a family of suppressors designed for high-velocity jets. Suppression of 16.5 PNL compared to the straight conical has been achieved with a total thrust loss of only 0.75%.

In-Flight Effects: The Crucial Issue

At the onset, we should be aware of the fact that we do possess only limited data on clean, uncontaminated jet noise in flight. These limited and sometimes controversial data have led to a great deal of speculation as to what really happens to a clean jet in flight.

Figure 17 shows OASPL as a function of vehicle velocity for three nozzles. The data are jet noise reduced from the aerotrain. Clearly, in-flight conditions will, in general, tend to reduce the maximum noise generated by a jet in comparison to the static case; hence, this is considered to be a beneficial effect. Figure 18 shows PNL directivity for the three nozzles at 1800 ft/s. For the conical nozzle, the peak noise under static conditions is at 140 deg and at 119 dB, whereas in flight the maximum noise is at a slightly lower angle and at 112 dB, so that a peak-to-peak noise reduction of 7 dB has occurred. The noise reduction at 90 deg in this case is 0.5 dB.

In the case of the 104-tube suppressor nozzle, the peak noise is at 120 deg under static conditions, and under flight conditions the peak noise angle again shifted to a lower angle, and the peak-to-peak noise reduction is 3 dB. The noise decrease at 90 deg is 2 dB. All mechanical suppressors seem to have their peak noise closer to 90 deg, and they experience less peak-to-peak noise reduction due to flight.

The noise suppression between the 104-tube suppressor and the conical nozzle under static conditions is 10 dB, while the difference betweeen the two under flight conditions is around 5 dB, so that some of the static suppression advantage of the suppressor over the straight conical nozzle is lost in flight. This situation is clearly one of the major problems with

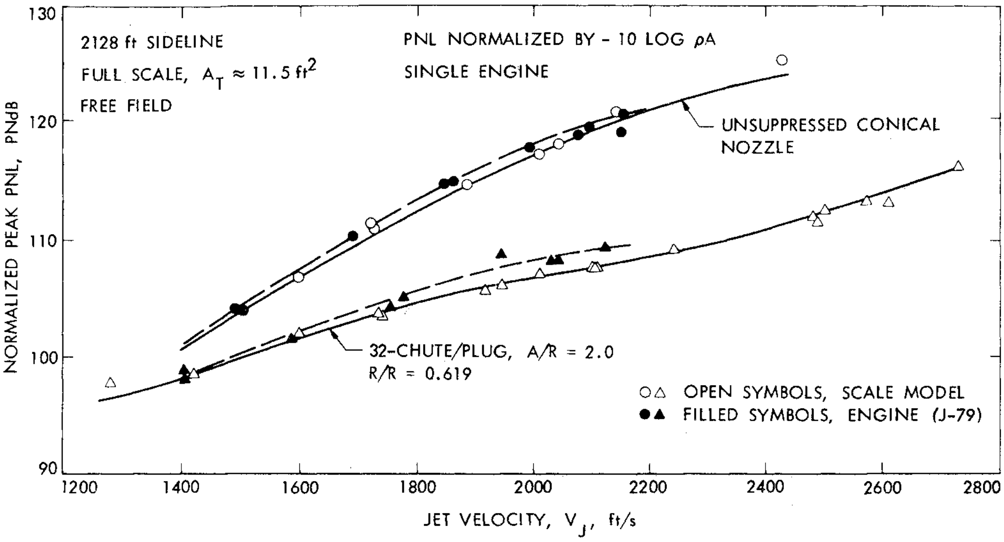

Fig. 15 Engine-scale model peak PNL comparisons with conical and mechanical suppressor nozzles.

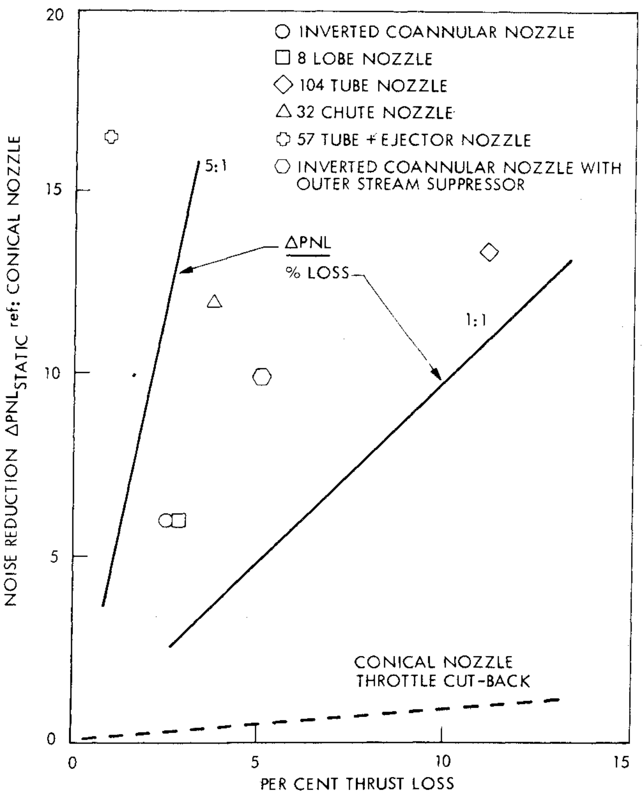

Fig. 16 Comparison of static noise and performance characteristics.

suppressors, and the other is that the thrust loss increases with flight speed, forcing the requirement that the mechanical suppressor be retracted for cruise conditions. Why is there a decrease in the peak-to-peak suppression with flight between the conical nozzle and mechanical suppressor? We do not entirely know, but even a more interesting question turns out to be, why is there so little decrease in the noise of any nozzle at around 90 deg due to flight? The 90-deg position is simple and interesting to study, since, at all other angles, a convective correction because of the noise sources being in motion is required; but the fluid shielding, convective effects, etc., are minimal at 90 deg. If we do not understand the sound output at 90 deg, the output at all other angles is even more guesswork. A convenient parameter to consider is the velocity exponent N', which is a measure of the nozzle sound source strength modification as a function of the jet and relative velocity, where

$$(N') = \frac{\mathrm{OASPL}_{\mathrm{static}} - \mathrm{OASPL}_{\mathrm{flight}} - 10\log(1 - M_a\cos\theta)}{10\log\left[V_j/(V_j - V_a)\right]}$$

where M_a is the aerotrain or freejet Mach number, and θ_a is the acoustic angle referenced to the inlet. The relative velocity between the jet and surrounding air decreases as flight velocity increases; hence, the noise will decrease but, unfortunately, not to the levels expected from theoretical considerations at all angles.

Consider the angle $\theta = 90$ deg where the factor $10\log(1 - M_a\cos\theta)$ is zero. The OASPL in flight is expected to be proportional to $10\log(V_j - V_a)^8$ and the corresponding static OASPL proportional to $10\log V_j^8$. Then the formula gives $N' = 8$. If the effect of jet stretching is accounted for, N' can be shown to be modified to 7 instead of 8. (Figure 22 shows much lower values of N', which means that the expected reduction due to dependence of OASPL on a high power of the relative velocity does not occur.) In fact N' is negative at some values of θ in the forward quadrant. It is known that the turbulence level decreases and the jet stretches due to flight, but it is evident that this is not the only criterion that appears to govern the total jet noise in these tests.

There is disagreement on the causes for that which has been observed. There are those who think and calculate the cause to be due to engine internal core noise that does not decrease as jet noise does due to flight and eventually will control the overall noise. However, the major propulsion firms in the U.S. and Europe, using current prediction methodology and limited test data, determine insufficient core noise levels for this to happen.

The boundary layer developed over the nacelle in flight has been considered to be another factor contributing to this situation.[19] The flow out the nozzle will mix with the boundary-layer air, which at the end of the nozzle is essentially at rest, so that the jet flow does not experience a relative velocity effect immediately on leaving the nozzle, but this should affect only the high-frequency output near the end of the nozzle, since the boundary layer gets mixed quickly, unless, of course, the jet mixing and pursuant motions are governed by the inital mixing conditions. Figure 19 shows the spectra of three different nozzles under static and flight conditions at 90 deg and at 550-m/s (1800-ft/s) jet velocity. The similarity of the static and flight spectra independent of vehicle velocity is most disconcerting and amazing. Core noise is known to be primarily a low-frequency phenomenon due to combustion. Therefore, one may expect that the static and flight spectra would be equivalent in the region where core

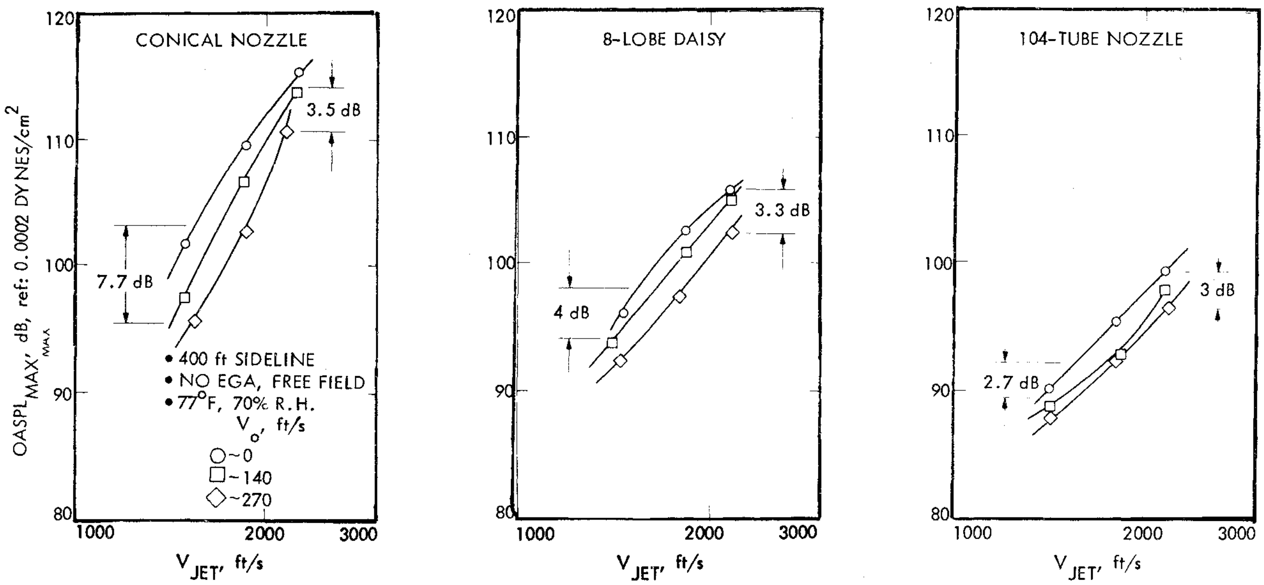

Fig. 17 Peak OASPL characteristics (aerotrain).

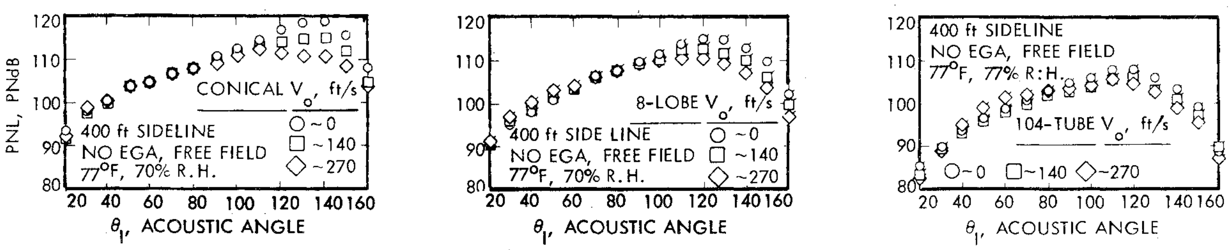

Fig. 18 Bertin aerotrain: PNL directivity patterns (V_j = 1830 ft/s).

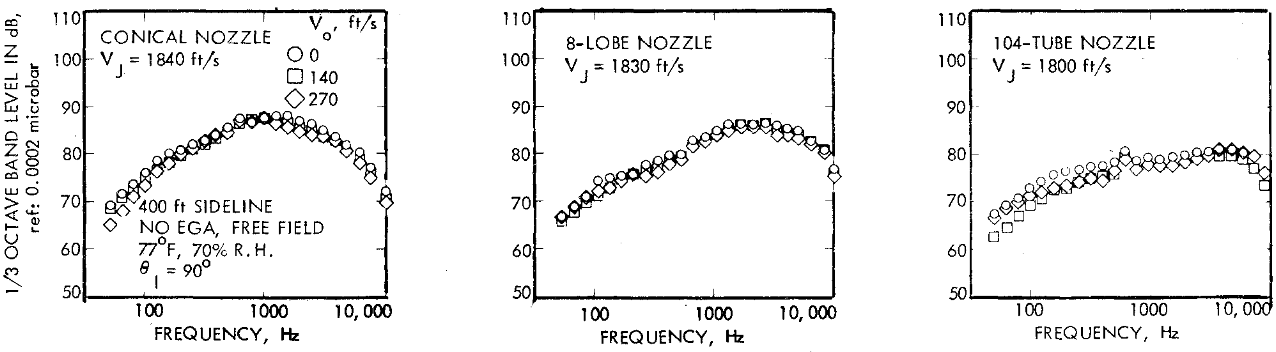

Fig. 19 Comparison of static and flight spectra (θ_I = 90 deg, V_j = 1800 ft/s).

noise is suggested to cause contamination of the jet noise. The fact that the 90-deg spectrum in flight is equivalent in level to the static spectra over the entire frequency range suggests that the core noise spectrum shape would be equivalent to that of the jet noise spectrum. This is contrary to current experience.

Although it has been shown and observed analytically that large-scale motions can occur in particular with supersonic jets, to my knowledge this never has been observed to occur when the coannular flow, to simulate flight, is introduced; Fig. 20[20] is recent evidence of this fact. The figure shows that, as the coannular flow velocity is increased, to simulate flight motion, the large-scale motion increased, and shock or crackling noise was observed to be generated from the wild whipping motion. One would expect the reduced stresses and turbulence level resulting from a coflow jet to smooth out the motion of the main jet. Perhaps the coflow is an exciter of the jet and of its internal disturbances under certain conditions. Although the effects of flight on shock noise have not been studied extensively, there is some information to indicate that shock noise can increase due to flight, particularly for multielement and inverted flow nozzles. One can visualize cross-wind conditions that will cause uneven stressing around the jet and cause asymmetric shock structures. My intent here is not to say that the large-scale motions are the cause of the anomalies observed but to show flow conditions that are nonlinear, hard to predict, and may be a contributing factor. Finally, one must consider the effects of the airframe flow and acoustic interactions that influence the noise under flight conditions.

Figure 21 shows ΔPNL as a function of thrust loss. Clearly, when comparing Fig. 21 for the flight case with Fig. 16 for the static case, we see that the amount of sound suppression has decreased due to flight, whereas the thrust loss has increased. For comparison purposes, the PNL decrease of throttling back a conventional conical nozzle is shown; we see that there is, however, still a significant noise benefit derived from suppressors. It is believed that, for applications where the jet velocity is over 700 m/s (2300 ft/s), a ΔEPNL/Δpercent gross

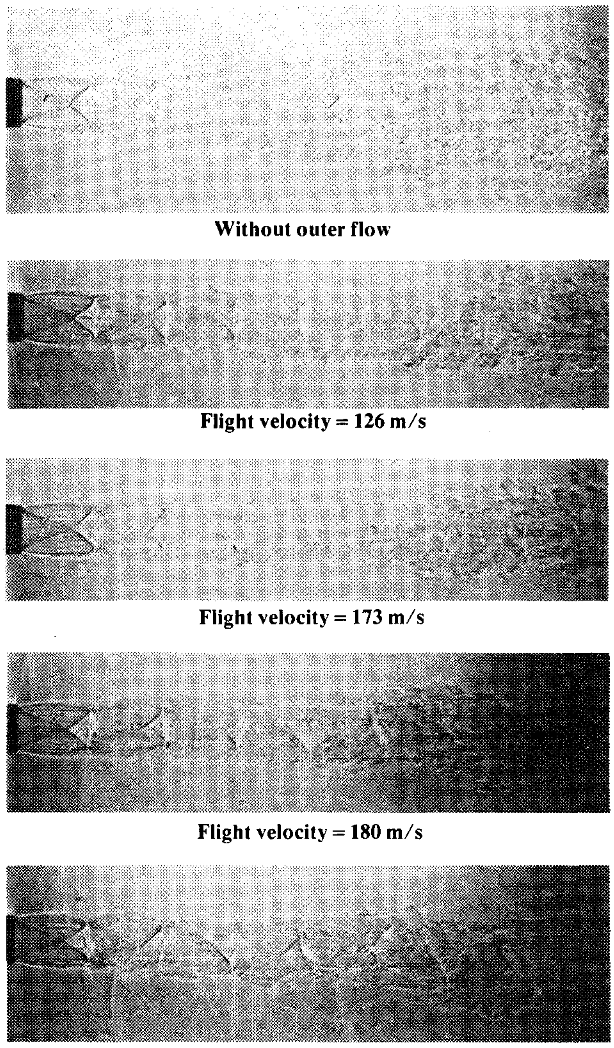

Fig. 20. Effects of forward flight on shock-associated noise at a nozzle pressure ratio of 3.70.

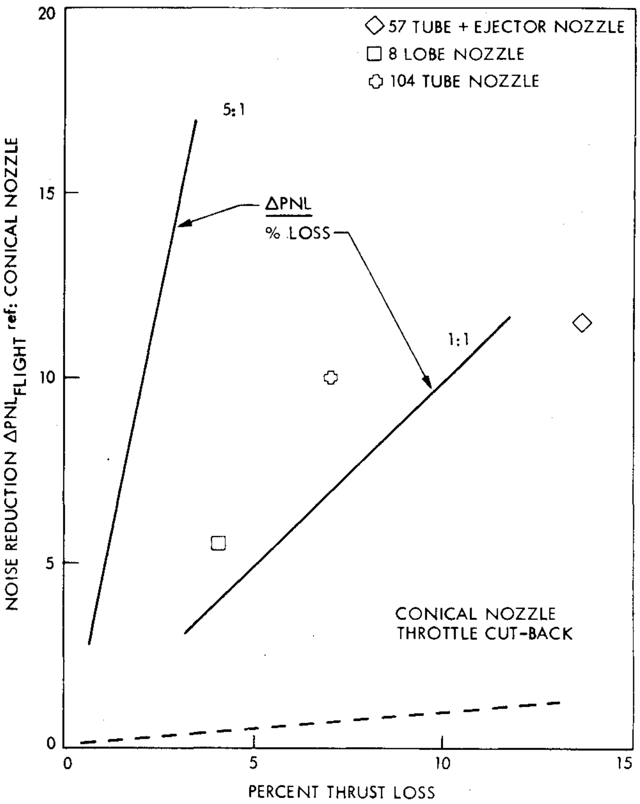

Fig. 21 Comparison of flight noise and performance characteristics.

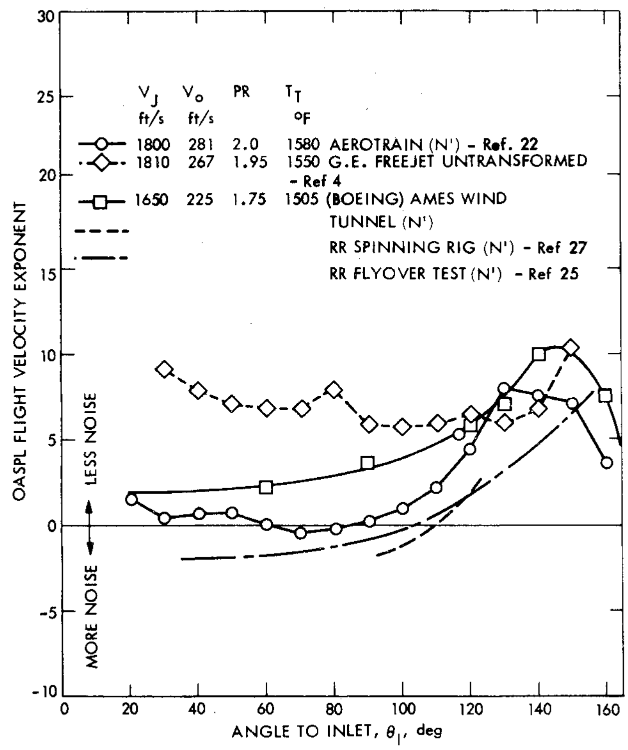

Fig. 22 Comparison of conical nozzle data at 400-ft sideline for aerotrain, freejet, wind tunnel, spinning rig, and aircraft flyover.

thrust loss of near 2 may be achieveable under flight conditions, with a weight penalty of 5 to 10% of the basic engine weight.

Flight Simulation

As pointed out earlier, the three most promising types of flight simulation facilities are 1) stationary jet in a large-scale wind tunnel,[16,18] 2) stationary jet immersed in a larger surrounding jet (a free-jet facility), and 3) jet mounted at the end of a rotating arm (a spinning rig). In addition, a ground-based moving vehicle (e.g., the Bertin aerotrain) also is used to study flight effects.

One of the major problems facing the aeroacoustics community is that the effects of aircraft forward motion as observed from the stationary simulation experiments do not correspond fully with the flight effects derived from full-scale aircraft flyover or aerotrain or even spin rig tests. The problem is illustrated quantitatively in Fig. 22, where the flight effects on jet noise from a conical nozzle are expressed in terms of the "relative velocity exponent." Typical results from all the systems mentioned are compared. The aerotrain, aircraft, wind tunnel, and spin rig have to be corrected for convection of the source in order to compare with the freejet data. The correction for convection used in this case was $(1 - M_a \cos\theta)$. The comparison shows that, although there is more or less agreement at large angles in the rear arc, the flight simulation results at 90 deg and in the forward arc differ significantly. The freejet and wind-tunnel results show a significant noise reduction with forward velocity at 90 deg and in the forward arc, whereas the aerotrain, flight tests, and spin rig (which are all moving nozzles) show either no change or an increase in noise at these angles. The wind tunnel data in Fig. 22 are similar to those given in Ref. 21.

Figure 23 shows the freejet spectra at 90 deg for the same three types of nozzles which are shown for the aerotrain on

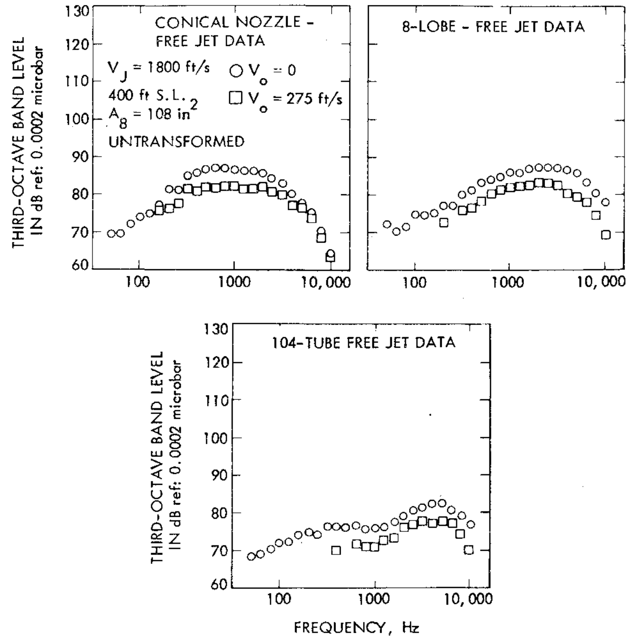

Fig. 23 Freejet spectra at 90 deg for three nozzles.

Fig. 19. Figure 24 shows a different set of three nozzles, including, however, a conical one taken in the Ames wind tunnel at 90 deg. Aircraft flyover spectra are not shown, but the data available appear to be similar to the aerotrain results.

Clearly the results for a nozzle in motion do not agree with the stationary nozzle simulation data. Reference 22 describes a method that brings the freejet data into close agreement with the flight data. This is termed "transformed freejet" data. The method entails the determination of the types of sources (monopoles, dipoles, etc.) within the jet contributing to the observed sound in order to apply the appropriate convection factor for each pole and not just $(1-M_a\cos\theta)$. In addition, refraction and absorption corrections are performed to account for the presence of the freejet shear layer. These corrections are functions of frequency, shear layer thickness, and angle of observation. Unfortunately, this type of correction[22,23] has met with considerable skepticism by the noise community, since scientific evidence for this absorption phenomenon has not been substantiated fully. Finally, Figs. 25 and 26[24] show the results of testing of the P&WJT8D engine, statically and in the Ames wind tunnel, with four different nozzles: the baseline, internal mixer, 20-lobe ejector-suppressor, and inverted velocity profile. The data in Fig. 25 are at a sideline distance of 122 m and in Fig. 26 at 649 m, where the reduction in perceived noise levels due to atmospheric absorption of high frequencies can be seen. Although the 20-lobe nozzle gave by far the best suppression statically, it lost much of it at a tunnel velocity of 90 m/s (300 ft/s). The inverted profile nozzle tests, just completed, show that the in-flight suppression has been maintained. At the time of the writing of this paper, the test results for the inverted velocity profile with a 20-lobe suppressor on the outside high-velocity stream were not available. The Ames 40-×80-ft wind tunnel has turned out to be a most effective acoustic test facility.

In the final analysis, the type of nozzle, i.e., internally mix or inverted profile alone or in combination with the mechanical multielement type, will be governed by the engine cycle, type of aircraft, and mechanical considerations. Needless to say, it is a matter of urgency to reconcile the differences that are observed in the simulation methods if cost-effective development of nozzle concepts is to take place, since flight testing of each concept would be prohibitively costly and time-consuming.

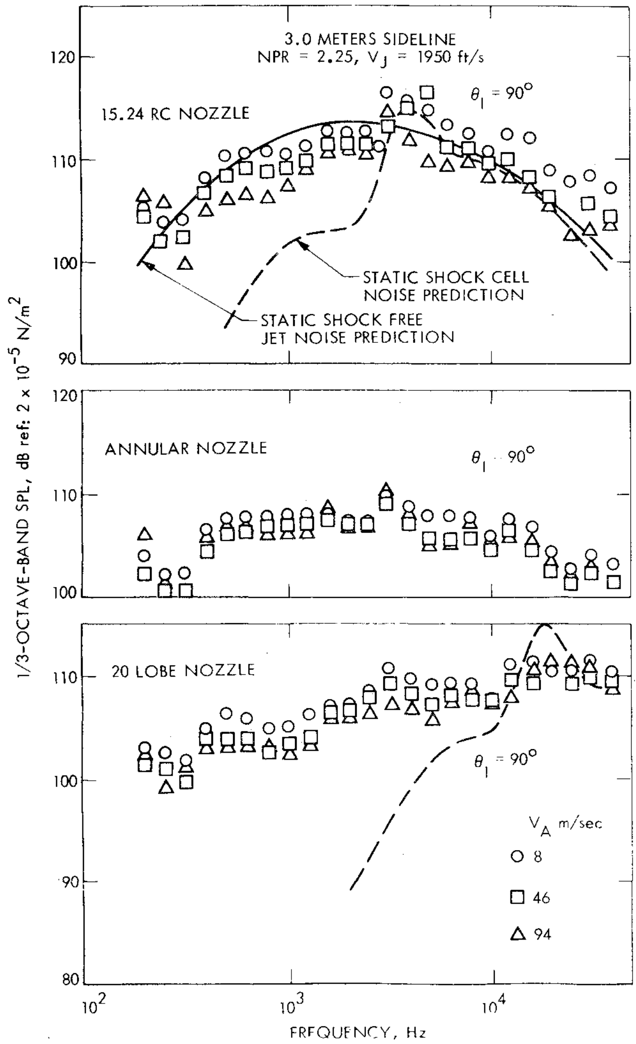

Fig. 24 Wind-tunnel spectra at 90 deg for three nozzles. Effect of ambient velocity on 1/3-octave spectra.[26]

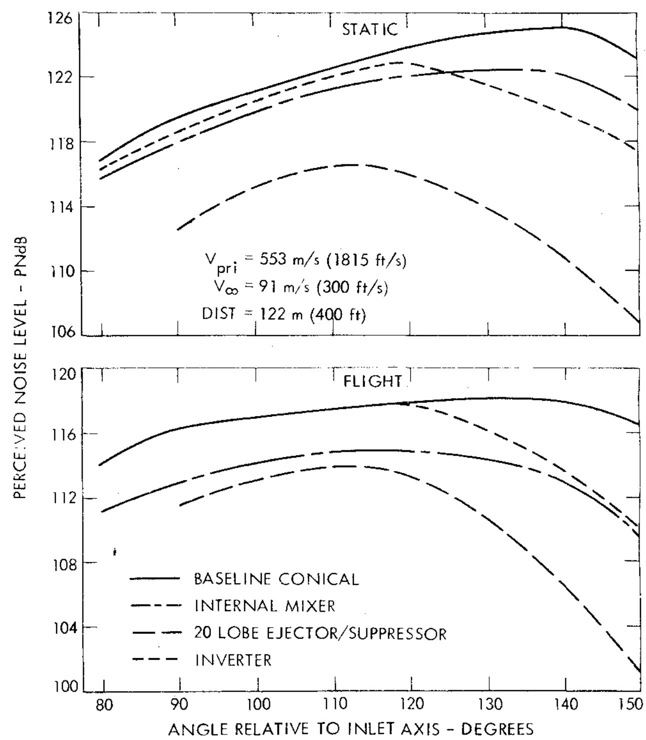

Fig. 25 Flight effect on noise for various nozzles at a measurement distance = 122 m.

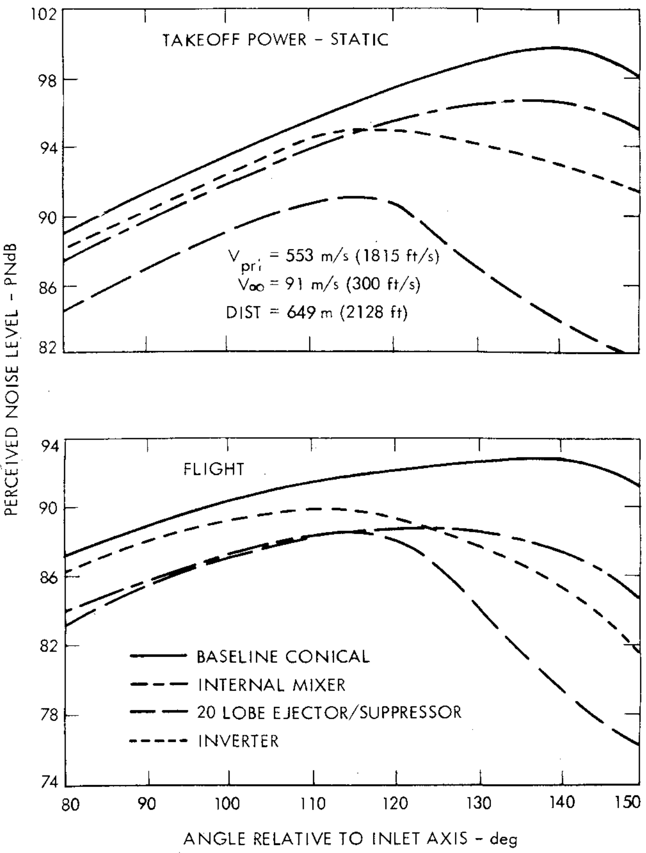

Fig. 26 Flight effect on noise for various nozzles at a measurement distance = 694 m.

Mechanical Design Considerations

All types of noise suppression nozzles increase system weight and complexity. These devices must operate in the high-temperature exhaust environment of the engine.

For subsonic aircraft of low bypass ratio, the internal mixer appears to be the current favorite. For high-bypass engines, the type of suppression concept is not clearly evident. The losses involved for internal mixers could be too high, and so some kind of inverted velocity profile or mechanical suppressor on the core flow will have to be considered.

In general, large pressure or airflow differences between the fan and primary streams will not lend themselves to internal mixer systems, so that the cycle and engine design will have a great deal to do with the final noise suppressor concept utilized.

For future SST designs, a nozzle consisting of a combination of retractable multielements, variable secondary nozzles, and thrust reversers can indeed be complicated. In spite of these factors, a future SST is inconceiveable without some sort of jet suppression device.

Summary

In conclusion, although an extensive data base exists on jet noise, our ability to predict in-flight jet noise accurately is not yet satisfactory. More research is required to obtain a better understanding of the fundamentals involved in jet noise generation, suppression, and in-flight effects.

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