NASA/TM—97-206221

AIAA–97–1682

Noise Reduction With Lobed Mixers: Nozzle-Length and Free-Jet Speed Effects

Vinod G. Mengle and William N. Dalton
Allison Engine Company, Indianapolis, Indiana

James C. Bridges
NYMA Inc., Cleveland, Ohio

Kathy C. Boyd
NASA Lewis Research Center, Cleveland, Ohio

Prepared for the
Third Aeroacoustics Conference
cosponsored by the American Institute of Aeronautics and Astronautics and the
Confederation of European Aerospace Societies
Atlanta, Georgia, May 12–14, 1997

National Aeronautics and
Space Administration

Lewis Research Center

November 1997

This report contains preliminary findings, subject to revision as analysis proceeds.

Available from

NASA Center for Aerospace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
Price Code: A03

National Technical Information Service
5287 Port Royal Road
Springfield, VA 22100
Price Code: A03

NOISE REDUCTION WITH LOBED MIXERS: NOZZLE-LENGTH AND FREE-JET SPEED EFFECTS

Vinod G. Mengle*, **William N. Dalton**
Allison Engine Company
Indianapolis, Indiana

James C. Bridges
NYMA, Inc.
Cleveland, Ohio

Kathy C. Boyd
NASA Lewis Research Center
Cleveland, Ohio

Abstract

Acoustic test results are presented for 1/4th-scaled nozzles with internal lobed mixers used for reduction of subsonic jet noise of turbofan engines with bypass ratio above 5 and jet speeds up to 830 ft/s. One coaxial and three forced lobe mixers were tested with variations in lobe penetration, cut-outs in lobe-sidewall, lobe number and nozzle-length. Measured exit flow profiles and thrusts are used to assist the inferences from acoustic data. It is observed that lobed mixers reduce the low-frequency noise due to more uniformly mixed exit flow; but they may also increase the high-frequency noise at peak *perceived* noise (PNL) angle and angles upstream of it due to enhanced mixing inside the nozzle. Cut-outs and low lobe penetration reduce the annoying portion of the spectrum but lead to less uniform exit flow. Due to the dominance of internal duct noise in unscalloped, high-penetration mixers their noise is not reduced as much with increase in free-jet speed as that of coaxial or cut-out lobed mixers. The latter two mixers also show no change in PNL over the wide range of nozzle-lengths tested because most of their noise sources are outside the nozzle; whereas, the former show an increase in noise with decrease in nozzle-length.

Introduction

Advanced lobed mixers, also called *forced* exhaust mixers, are used in aircraft turbofan engines to mix fan and hot core flows inside the nozzle duct so that the ensuing jet noise can be reduced while maintaining a high thrust efficiency. The more uniform the flow is at the nozzle exit-plane the better is the thrust efficiency and, it is generally believed that, the lower is the far-field noise. However, to achieve that uniform state in a given nozzle length the two flows need to be mixed "sufficiently" rapidly inside the nozzle. This can raise its high-frequency noise content, which crucially influences the *perceived* noise level (PNL) and may be acoustically penalizing at take-off conditions.

The rate of mixing inside the nozzle depends primarily on the lobe mixer geometry. The flow uniformity at the nozzle exit plane, on the other hand, also depends on the distance from the mixer exit plane to the nozzle exit plane or the nozzle-length, L. Obviously, if L can be reduced without affecting the exhaust noise some weight savings can be achieved. Further, the acoustic benefit due to the ambient free-jet surrounding the nozzle (simulating the aircraft forward motion), usually attributed to reduction in shear from the static free-jet case (no free-jet), can change depending on the exit flow profile. Studying the far-field noise with variations in free-jet speed also allows one to infer whether the predominant jet noise sources in a given spectral band are outside the nozzle or inside it. In this paper we experimentally explore and quantify these noise characteristics for several high-bypass ratio, sub-scale lobed mixers with varying nozzle lengths at subsonic mixed jet speeds and a range of free-jet Mach numbers.

Lobed mixers have been studied quite extensively from mid-seventies to early eighties, especially, for improving thrust efficiency, for example, under NASA's Energy Efficient Engine (E^3) program. Both far-field noise data for lobed mixers[1] and detailed measurements of fluid-dynamic and aerodynamic properties[2-4] have been reported in the literature. Previously published noise data[1,5] is typically for *low* bypass ratio (BPR) mixers around 1.5 with high ideally expanded jet velocities of 1330 ft/s or so. Recently, there has been a resurgence in the study of aircraft engine noise, especially, for such lobed-mixer nozzles due to stringent noise regulations at airports and anticipated increase in aircraft-traffic throughout the world. The noise characteristics and reductions of such lobed mixers over unmixed coaxial nozzles may depend significantly on the operating cycle conditions. In this paper we explore them for sub-scaled mixers at *higher* bypass ratios of above 5 with mixed jet exhaust speeds up to 830 ft/s, typical of modern small to medium size jet aircraft engines at take-off conditions.

The results reported here form the first part of a two-part series of tests Allison Engine Company has conducted in NASA's anechoic Aeroacoustic and

Propulsion Laboratory (APL) at Lewis Research Center. Booher et al[6] discuss the development of few of the mixers reported here. These mixers were also tested earlier for their aerodynamic performance in ASE FluiDyne's static thrust-stand. The acoustic data for higher jet speeds (up to 1075 ft/s) and several other mixers from the second test will be reported later. It is hoped that these test results and insights will add to the acoustic test data base on such lobed mixers in a parametric space which is being explored only recently.

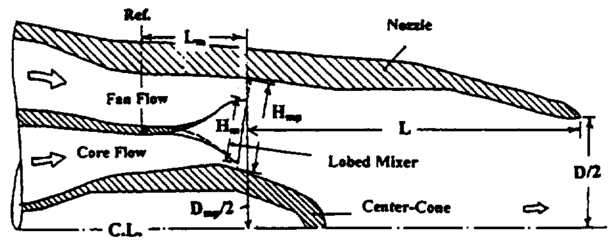


Figure 1. Schematic of mixer-nozzle configuration and geometrical definitions.

Experimental Setup & Models

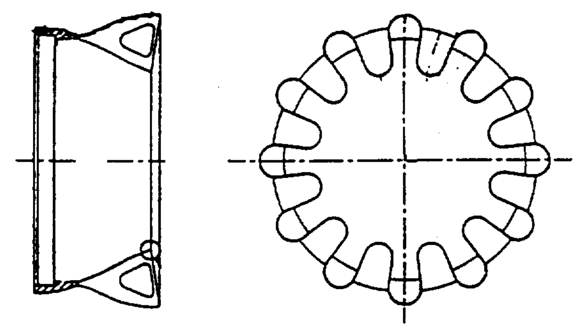
Mixer-Nozzle Models

Figure 1 shows a schematic of the general arrangement of the mixer-nozzle configurations and geometrical definitions. Four 1/4th-scaled mixers were tested in the first series of tests reported here: (i) coaxial mixer (later referred to as confluent or CON) which acted as a reference nozzle, (ii) 12-lobed, low-penetration mixer with cut-outs on the lobe sidewalls (conventional or 12C), (iii) 12-lobed, high-penetration, unscalloped mixer (advanced or 12A), and (iv) 16-lobed, high-penetration, unscalloped mixer (acoustic or 16A). Table 1 lists their non-dimensional geometric properties. Figure 2 shows the relative shapes of the lobed mixers. The nozzle-length, L, could be varied as 50%, 75%, 100% and 125% of the baseline nozzle-length (with nominal L/D_{mp} ratio of 1.1). This gives nominal L/D_{mp} = 0.55, 0.825, 1.1 and 1.375. The nominal ratio of diameters at the ends of the mixing region is D_{mp}/D = 1.379.

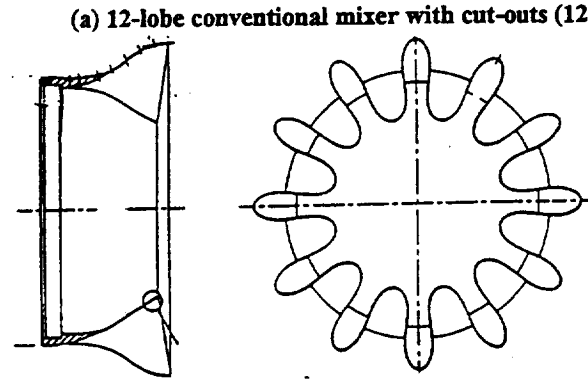
Acoustic Test Facility

The mixer-nozzle models were mounted in the jet rig in NASA's APL at Lewis Research Center. This dome facility is anechoic with acoustic wedges on the floor[7]. The jet rig provides two-stream flows whose flow rates are measured by a venturi-meter. The total pressure and total temperature are monitored at a charging station just upstream of the lobe mixer exit plane. The free-jet exiting a round nozzle surrounding the nozzle model is capable of providing Mach numbers up to 0.3. The ratio of free-jet diameter to model-nozzle exit diameter is about 7.31.

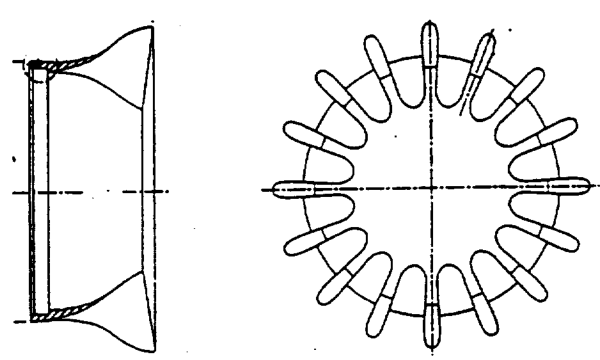
Narrow band acoustic data was acquired using 1/4" Bruel & Kjaer microphones. The microphones were positioned on a 48 ft radius from the nozzle exit center in a horizontal plane through the nozzle axis. Several microphones were positioned in the upstream and downstream quadrants of the jet ranging from θ = 45° to 165°. (θ is the angle between the jet *inlet* axis and the radial line from the nozzle-center to the microphone.)



(a) 12-lobe conventional mixer with cut-outs (12C)



(b) 12-lobe advanced mixer (12A)



(c) 16-lobe acoustic mixer (16A)

Figure 2. Relative shapes of lobed mixers.

Mixer	Code	Lobe No.	Cut-Outs	Lobe Penetration H_m/H_{mp}	Lobe Length[1] L_m/D_{mp}	Area Ratio A_{fan}/A_{core}	Nozzle Length L/D_{mp}	Perimeter[2] $P*L/D_{mp}^2$
Confluent	CON	-	-	-	0.27	2.554	1.15	2.19
Conventional	12C	12	Triangular	0.48	0.33	2.637	1.10	6.28
Advanced	12A	12	None	0.68	0.34	2.637	1.09	7.94
Acoustic	16A	16	None	0.72	0.34	3.199	1.09	10.51

[1] L_m is measured from reference station (Ref.) where mixer is attached to the upstream duct (see fig. 1)
[2] P is the wetted perimeter at the mixing plane (mp)

Table 1. Exhaust Mixer Parameters

Acoustic Data Processing

The measured spectra were corrected for microphone calibration, spherical spreading, atmospheric absorption and free-jet shear layer refraction to reduce them to 1-foot lossless conditions for the sub-scale nozzle. Finally, these spectra were extrapolated to full-scale values at 150 ft radius, 70° F and 77 % relative humidity. These sound pressure levels (SPL), referred to as "polar SPL" in the following section, give the third-octave-band sound at band center frequencies *in the reference frame of the moving nozzle or the moving aircraft.*

In order to assess the noise for a stationary observer when the aircraft flies by, we further apply a Doppler-shift correction to frequency using the free-jet Mach number as the moving aircraft Mach number. This is done for a fly-over altitude of 1500 ft to produce the PNL-directivity on the ground below the flight path, assuming that the ground is anechoic.

Test Results and Discussion

All the mixers were acoustically tested under three operating conditions shown in Table 2.

Operating Condition	Nozzle Pressure Ratio Fan (f)	Core (c)	Temperature Ratio, T_{tc}/T_{tf}
A	1.44	1.38	2.34
B	1.33	1.28	2.27
C	1.21	1.17	2.21

Table 2. Nominal Operating Conditions

For each operating condition the free-jet Mach number, M_{fj}, was varied from 0 to 0.3 in increments of 0.1. All the mixers were tested for all nozzle-lengths mentioned earlier, except that (i) the 12-lobe advanced mixer (12A) was tested only for the reference nozzle-length and 50% shorter and (ii) the 16-lobe acoustic mixer (16A) with 25% longer nozzle-length was tested only for $M_{fj} = 0$ and 0.3. Thus a reasonably wide acoustic data base for such lobed mixers has been generated. However, in this paper we focus on only a portion of it to obtain key physical insights into the noise characteristics of such mixers, predominantly at the highest nozzle pressure ratios tested (condition A of Table 2, typical for sideline noise measurements during take-off).

First we examine the static free-jet case for all mixers and then study the effect of free-jet speed variation. Finally the effect of nozzle-length variation is examined for all mixers.

Static Free-Jet Case ($M_{fj} = 0$)

Before comparing the noise characteristics of all mixers let us first compare some of their exit flow and aerodynamic characteristics.

Exit Temperature Non-uniformity

For hot jets the exit flow non-uniformity can be characterized by the exit total temperature distribution. Figure 3(a) shows the measured total temperature contours for these mixers with baseline nozzle-length. Figure 3(b) shows the radial distribution of total temperature and the fully-mixed total temperature calculated from the conservation of total enthalpy and measured mass-flow rates for each mixer. This data was obtained at ASE's FluiDyne facility with total temperature probes. There is hot flow at the center, due to the partially mixed core flow over the center-cone, and hot-spots away from the central axis for the lobed mixers. The reason for the outer hot-spots is by now well-known[8]. They stem predominantly from the axial vortices generated at the mixer exit plane due to the mismatch of vertical velocity components of the fan and the core flows. These axial vortices allow the interface between the two flows to increase tremendously leading to enhanced mixing as compared to coaxial flows where there is no such axial vorticity. These vortices convect downstream and finally diffuse. It is clear from figure 3(b) that due to lesser deviation of the temperature from the fully-mixed value the acoustic mixer (16A) is the most well-mixed, closely followed by the advanced (12A) mixer and then the conventional (12C) mixer. The confluent (CON) nozzle is the least mixed. Does

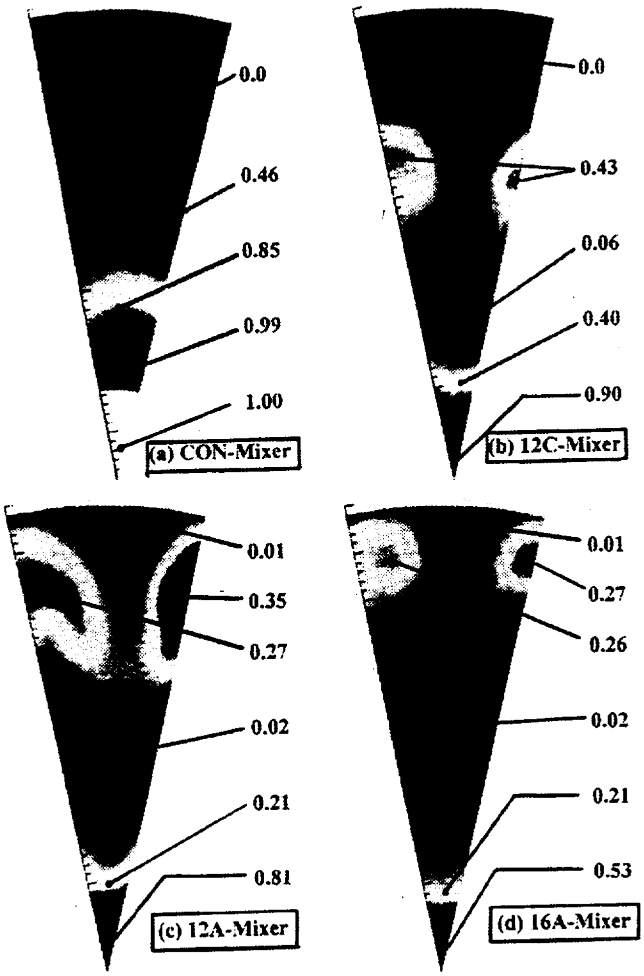


Figure 3(a). Total temperature, T_t, contours at nozzle exit plane for condition A with $M_\eta = 0$ showing extreme values of $(T_t - T_{t\theta})/(T_{tc} - T_{t\theta})$.

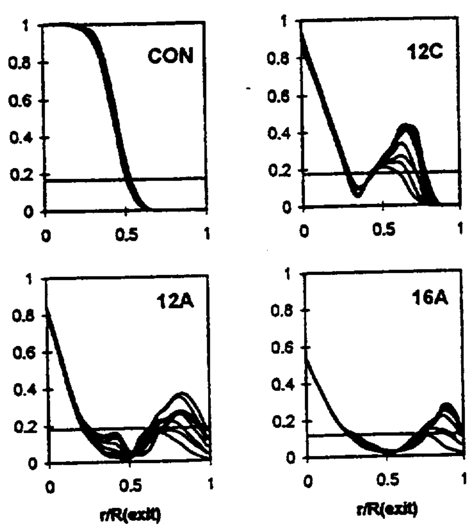


Figure 3(b). Radial distribution of total temperature at nozzle exit plane for condition A with $M_\eta = 0$ for various azimuthal angles. The horizontal line is the fully-mixed value. Vertical coordinate = $(T_t - T_{t\theta})/(T_{tc} - T_{t\theta})$.

this exit-plane flow non-uniformity, say, in 12C or CON mixers mean that they are noisier than 12A or 16A ?

Aerodynamic Data

Before we answer the above question we also need to compare the variation in aerodynamic properties, like thrust and mass flow-rate when we compare noise characteristics for different mixers at same operating conditions.

Table 3 lists these quantities on a relative basis as measured at FluiDyne's static thrust stand. T is the measured thrust, and the ideal unmixed thrust, T_i, is defined here as the sum of ideal thrusts of fan and core flows using measured mass-flow rates and isentropic velocities with expansion of each stream to the ambient pressure from the measured total pressure and temperature. The effective jet exit velocity, V_{eff}, is proportional to the specific thrust.

Mixer Code	Δ Measured Thrust % $(T-T_{CON})/T_{CON}$	Δ Mass Flow-Rate % $(\dot{m} - \dot{m}_{CON})/\dot{m}_{CON}$	Bypass Ratio BPR	Thrust Coeff. T/T_i *	Effective Jet Velocity V_{eff} (ft/s) †
CON	0	0	5.19	0.9951	845.9
12C	-0.874	-1.682	4.75	0.9953	852.8
12A	-	-2.980	4.66	-	859.2
16A	-1.867	0.124	7.55	0.9914	828.9

*** T_i = Ideal *Unmixed* Thrust ; † V_{eff} = Thrust/Mass-Flow-Rate**

Table 3. Aerodynamic performance of mixers with baseline nozzle length at condition A with $M_\eta = 0$ at FluiDyne.

Note that the measured thrusts of different mixers are very close to each other and for each mixer it is less than 1% from its ideal unmixed value. Thrust was not measured during the acoustic tests at NASA. Hence, in Table 4 we compare the differences in *ideal* thrust and other aerodynamic quantities for the acoustic tests done at NASA's APL at the same nominal operating condition A with static free-jet.

Mixer Code	Δ Ideal Thrust % $(T_i-T_{iCON})/T_{iCON}$	Δ Mass Flow-Rate % $(\dot{m} - \dot{m}_{CON})/\dot{m}_{CON}$	Bypass Ratio (BPR)	Effective Jet Velocity V_{eff} (ft/s)
CON	0	0	5.51	815.8
12C	-1.423	-2.91	5.18	828.2
12A	-3.719	-5.12	4.80	827.8
16A	-5.534	-3.03	7.17	794.7

Table 4. Aerodynamic performance of mixers with baseline nozzle length under condition A and $M_\eta = 0$ at NASA's APL.

Although there are slight differences in the measured mass-flow rates from the two facilities, presumably due to small differences in operating conditions and the location of the total pressure and temperature rakes, the relative values of the thrusts are similar to that in Table 3. The effective jet velocities of the first three mixers are also very close. The 16-lobed acoustic mixer 16A, however, shows lower thrust and higher bypass ratio which is in line with its 21.3% higher fan-to-core area ratio (see Table 1). Hence, we conclude that it is reasonable to compare the acoustic characteristics of first three mixers, namely, CON, 12C and 12A and it is not unreasonable to compare 16A with them.

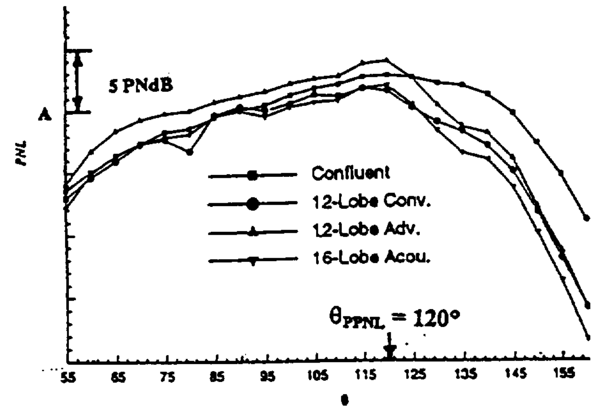


Figure 4. PNL directivity at 1500 ft with baseline nozzle-length for condition A with M_{fj} = 0.0.

Acoustic Data

With static free-jet (M_{fj} = 0) there is no correction for free-jet shear layer refraction and Doppler shift is not needed to calculate PNL. Thus a basic acoustic datum is created with it for later comparisons. The difference between fly-over PNL and SPL data is then purely due to slant distance and noy weighting.

Figure 4 shows the full-scale PNL directivity at 1500 ft. for all mixers for the static free-jet case with baseline nozzle-length. Observe how the confluent (CON) mixer is noisiest in the aft quadrant angles from 125° to 160° near the jet exit axis, and the 12-lobe advanced (12A) mixer is noisiest from 55° to 125°. 12A also has the highest peak PNL amongst all mixers. The 12-lobe conventional mixer (12C) and the 16-lobe acoustic mixer (16A) appear quieter than 12A for all angles. This is true in spite of 12C being more non-uniform at the exit plane than 12A as seen in figure 3 earlier.

An examination of the polar spectra at several pertinent angles will help us understand why this is so. We examine polar SPL's at θ = 60°, 90°, 120° and 150° in figure 5 where 120° is the peak PNL angle for all mixers.

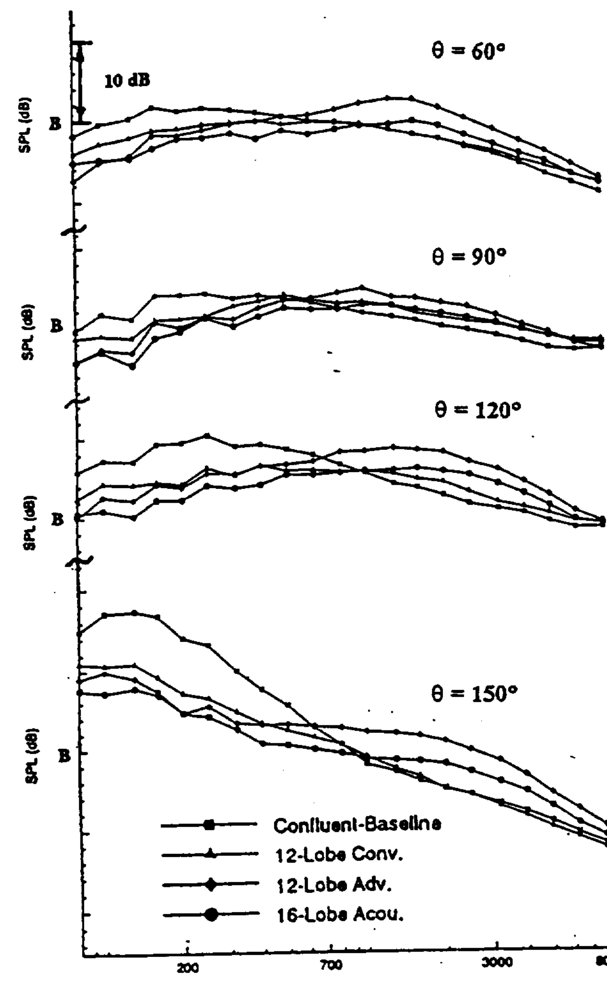


Figure 5. 1/3 rd octave-band SPL Spectra @ 150 ft. radius, baseline nozzle-length, M_{fj} = 0 for condition A.

At 120°, 12A has the highest SPL amplitude in the range of frequencies with higher noy weighting in evaluating PNL. In this "annoying" frequency range of 1500 Hz to 5000 Hz all the lobed mixers are larger in amplitude than the confluent mixer. From figure 3(b) it is clear that the confluent mixer produced minimal internal mixing compared to the lobed mixers. Hence, the mixing process in lobed mixers must be, in general, the cause of the spectral differences when compared to the confluent nozzle; the increase in the *annoying* portion of the spectra due to this mixing is especially worth noting.

The relative spectral values for these lobed mixers must depend on how the mixing evolved axially for each mixer which in turn depends on the mixer geometry. Unfortunately, in our case, the mixers differ in at least two geometric parameters (see Table 1) and we cannot pinpoint for sure which one of those parameters is the cause for differences in their spectra. This first test was, indeed, not designed to discern them. For example, 12C and 12A differ in the presence of cut-outs, as well as, lobe-penetration. Thus, the larger amplitude spectra in the 1500 Hz - 5000 Hz range for 12A, as compared to 12C, must be a compound effect of *not* having cut-outs and *not* having lower penetration; or when compared to 16A must be a compound effect of lower number of lobes and lower fan-to-core area ratio.

Typically, for unscalloped forced mixers, such as 12A or 16A, the axial gradient of mixedness and the intensity of axial vortices is very high in the initial portion of mixing near the lobe exit plane; it then gradually decreases as the vortices diffuse[8]. This means that if the flow is very well mixed by the nozzle exit plane, as seen for 16A or 12A, then this axial gradient of mixedness and the axial vortex strength and, hence, the turbulence intensity is also higher near the lobes than it is near the nozzle exit plane. However, if the flow is not as well-mixed by the nozzle exit plane, as in 12C, then the mixing must be axially progressing at a smaller rate inside the nozzle or is "gentler" than in 12A or 16A. The reason for this difference must lie in the manner in which vorticity is introduced at the beginning of mixing. The probable mechanism is that in 12A or 16A mixers the two flows "see" each other *suddenly* along the whole height of the mixer at its exit creating larger high-frequency amplitudes. In 12C, on the other hand, the vorticity is introduced *gradually* into the flow in the axial direction due to the gradually increasing height of the cut-outs and is also introduced slightly more upstream. The lower lobe height of 12C aids this process further, but the strip at the end of the cut-out may have a deleterious effect by adding dipole-type leading edge noise sources. This probable mechanism with gradual mixing in 12C means that the mixing between the fan and the core flows and, hence, the noise sources associated with it will also continue to be downstream of the nozzle exit plane; whereas, they are well confined inside the nozzle for well-mixed flows, as in 12A or 16A. We will try to examine later whether this conclusion corroborates with other data we have collected.

Returning to the low frequency portion (< 500 Hz or so) of figure 5 at $\theta = 120°$, we observe that the confluent mixer has the highest amplitude. Comparing the four mixers, an inverse relationship between the low frequency spectral amplitudes and the exit flow uniformity is observed. Exit flow uniformity also directly tracks with the wetted perimeter P (see Table 1). Now, the dominant source of lower frequencies is larger eddies which are further downstream in the jet far beyond the "potential" core length. Their intensity at any given axial station, for a single-stream or coaxial jet, is governed by the central potential core length and how fast the plume center-line velocity decays axially - the smaller the potential core length or the faster the velocity decays the lower is their intensity. Fully mixed velocities are lower than hot core velocities leading to smaller potential core lengths, earlier velocity decay and, hence, smaller low-frequency SPL's than for coaxial nozzles. For the more complicated three-dimensional partially mixed flow this simple physical explanation is not as rigorous. However, even such jets have a self-similar region further downstream where such arguments do apply.

These same conclusions gain firmer ground when we compare the spectra at remaining three angles in figure 5. In general, at all angles the lobed mixers are grouped together in the low-frequency spectrum (< 500 Hz or so) but are distinctly separated beyond 800 Hz or so. For example, at $\theta = 150°$, the confluent shows the largest low frequency contribution and at $\theta = 60°$, the 12A advanced mixer shows the largest high frequency contribution. These effects are exaggerated at these angles because for a given jet (for a given mixer) any high-frequency sound refracts further *away* from the jet exit axis compared to that for low frequencies. This leaves the low frequencies to dominate the shallow angles (large θ-values), whence, the general downward slope of SPL with frequency at 150°, and more high-frequency sound is refracted to lower θ values.

It is easy to see, using ray theory, that high-frequency sound even from sources inside the nozzle can reach the front quadrant. Consider, for simplicity, a stationary noise source inside the duct with a wave-number vector having an upstream facing axial component. The direction of the ray corresponding to it, which shows the direction of sound energy, can be found by vectorially adding the local flow velocity to a vector with magnitude equal to the local speed of sound and which is directed in the wave-number vector direction. Obviously when the duct flow has local downstream going axial component there will be downstream facing rays for some such wave-number vectors with upstream facing axial components at the source. When such rays finally emerge from the ambient/jet shear layer, perhaps, after several reflections from the duct wall or no reflection, the continuity of the axial component of the wave-number in that shear layer will demand that those rays emerge into the static ambient again having the same axial component of the wave-number as they had at the source. Thus such rays will again face upstream or transport sound to the front quadrant. A *moving* noise source simply gives Doppler shift[9] and does not change the nature of this ray tracing argument.

Going back to the PNL- directivity (figure 4) we, indeed, see that the high-frequency dominated 12A mixer is noisier in the θ-range less than 125°, and the low-frequency dominated CON mixer is noisier at shallower angles.

Thus, we see from this data that although a mixer, like advanced 12A, may mix the two flows very well by the nozzle exit plane, thus reducing the low frequency contribution, it may do so at the expense of increasing the high-frequency contribution due to more rapid mixing inside the nozzle duct. By changing some of the geometric parameters of the mixer, like introducing cut-outs and reducing the lobe penetration, as in the conventional 12C mixer, it is possible to reduce this annoying high-frequency contribution and still retain the low frequency abatement with no reduction in the total or the specific ideal thrusts (see Table 4).

<u>**The Effect of Free-Jet Speed**</u>

Figure 6 shows the effect of increasing the free-jet Mach number on the PNL-directivity of each mixer. In general, the PNL curves shift downwards and at the same time rotate clockwise about the most upstream quadrant angle. More specifically, we notice the following effects with increase in free-jet Mach number:

1. For each mixer the PNL decreases at all angles.

2. For a given mixer, there is more decrease in PNL at shallower angles than at upstream angles. In particular, for M_{fj} between 0.2 and 0.3 (roughly the take-off Mach number), the PNL curves have a very shallow gradient in a wide range of angles from 75° or so onwards to peak PNL angle near 110° - 120°.

3. The decrease in PNL for some mixers is less than others at a given angle.

The first effect by itself is not surprising and is a well-known experimental result for single-stream nozzles and the same reason must apply to at least fully-mixed nozzles with uniform exit flow. A simple explanation is given here: An increase in free-jet speed reduces the shear-layer thickness, δ, and increases the potential core length. The highest turbulence intensity and the dominant noise source is known to be just downstream of this potential core where the shear layers surrounding it interact most vigorously. The radial gradient of axial velocity, $|\partial U/\partial r|$, governs the dominant noise source intensity and the jet diameter there governs its net contribution. A first order estimate of these quantities

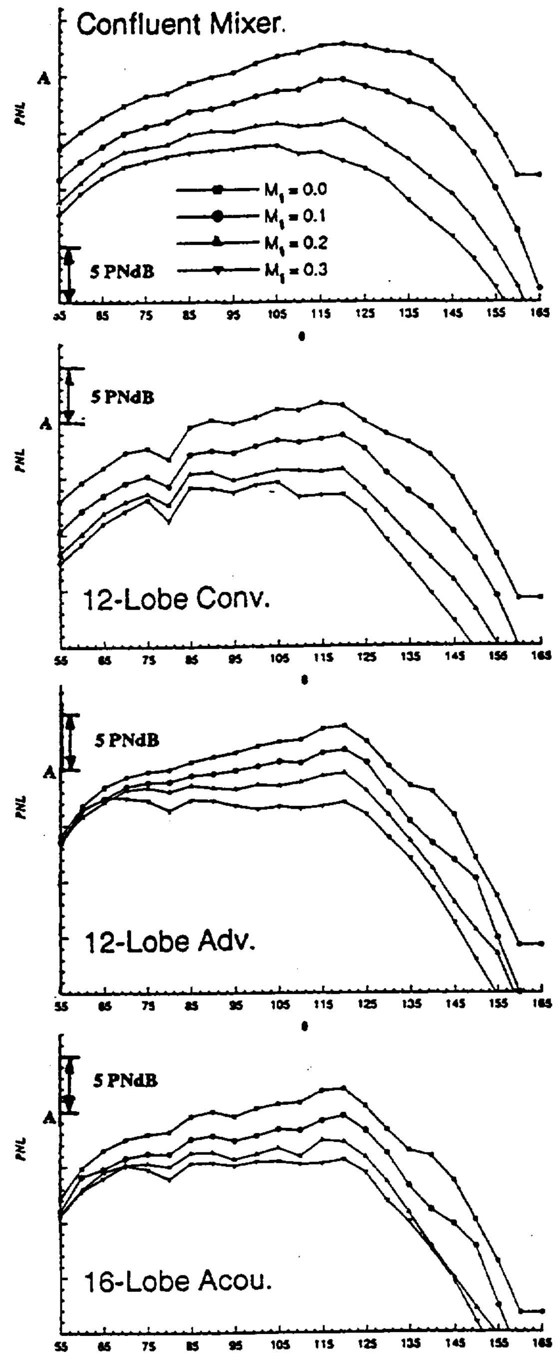


Figure 6. The effect of free-jet Mach no., M_{fj}, on fly-over PNL-directivity at 1500 ft. at condition A with baseline nozzle-length.

can be obtained by using $\partial U/\partial r \approx (U_{free-jet} - U_{jet})/\delta$. The shear layer thickness at the end of the potential core, δ_c, can be estimated using, for simplicity, Abramovich's expression[10] for incompressible, axisymmetric, turbulent jets (which assumes self-similarity in the velocity of the initial portion of the mixing layer), namely,

$\delta_c = R/\sqrt{a+bm},$ where $m = U_{free-jet} / U_{jet}$, R is nozzle exit radius and a = 0.214, b = 0.144. We can then immediately show that the ratio, η, of $|\partial U/\partial r|$ at the end of the potential core with free-jet on to that with the free-jet off is equal to $|1-m|\sqrt{1+\frac{b}{a}m}$. This ratio can be shown to decrease with increase in m for $0 \leq m \leq 1$. For observed self-similar velocity profiles[10] it turns out that η, as given above, is also the ratio of *maximum* axial velocity radial gradients in the flow there. Thus when the free-jet speed increases the potential core length increases and the shear at its end decreases. In addition the volume of noise sources there, characterized by the radius δ_c, also reduces. This leads to a decrease in peak far-field noise. For hot jets, with jet-to-ambient density ratio other than one, one may extend this argument by using more complicated expressions for the shear layer growth given by Abramovich[10]. With some modifications this argument can also be applied to coaxial jets where the ambient /jet shear layer increases the annular fan potential core length with increase in free-jet speed but not the central hot potential core length.

To understand the second and third effects on PNL, noted before, we need to scrutinize the spectra at various angles individually for each mixer at two different free-jet velocities. Figures 7 and 8 show the PNL directivity and polar SPL-spectra for M_{fj} = 0.2 for all mixers. Compare SPL's in figures 5 and 8 at same angles individually for each mixer. Points A in all PNL plots and points B in all SPL plots have the same value and, hence, can be used as anchor points for comparisons of different figures. Broadly speaking for each mixer at each angle the decrease in low frequency SPL is larger than that at higher frequencies. These SPL's are not Doppler shifted, so any decrease in SPL is a true decrease in the source strength due to free-jet and is not an artifice of Doppler shifting the frequency.

The second effect, noted before for the PNL, can then be understood due to the following two reasons:

(a) Source convective amplification - Due to the motion of the aircraft (simulated by the free-jet) the SPL's for a *stationary* observer are Doppler shifted. This amplifies the sound in the upstream quadrant and reduces that in the rear quadrant. This results in a clockwise rotation of the PNL-θ curves with increase in free-jet speed.

(b) Source distribution - Shallower angles are dominated by lower frequencies for a given jet, whereas, non-shallow angles (say, θ < 125°) by intermediate-to-high frequencies, as seen earlier in figure 5. This remains true also at higher free-jet Mach numbers as

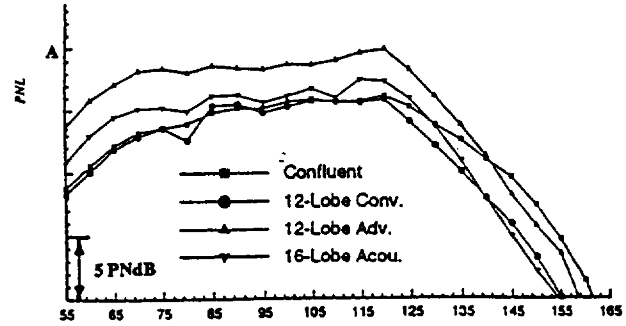


Figure 7. PNL directivity at 1500 ft with baseline nozzle-length for condition A with M_{fj} = 0.2.

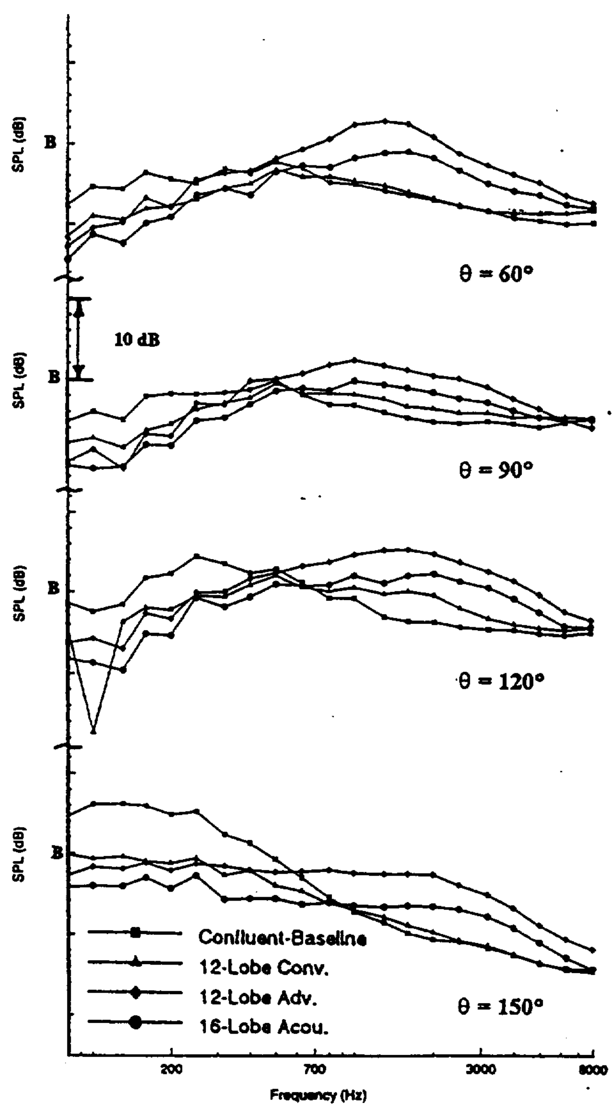


Figure 8. 1/3 rd octave-band SPL Spectra @ 150 ft. radius, baseline nozzle-length, M_{fj} = 0.2 for condition A.

seen in figure 8. Now the lower frequencies are associated with the larger eddies further downstream in the jet, and the higher frequencies with the smaller eddies inside the nozzle or close to its exit plane. Increase in free-jet speed affects predominantly only the noise source strengths outside the nozzle decreasing their strength as seen before. Noise sources internal to the nozzle-duct or those outside the nozzle close to the exit plane but not yet affected by the ambient/jet shear layer (e.g. those surrounded by it) presumably do not change much in intensity; only their directivity as measured in the far-field will change slightly due to change in refraction at the ambient/jet shear layer. Thus for a given mixer-nozzle there should be more reduction in noise at low-frequency dominated shallow angles than that in the front quadrant.

The third effect of free-jet speed is the significant one and allows one to infer the relative contribution of internal and external noise sources in the different mixers. Continuing the reasoning given above and comparing the spectra for a given mixer at a given angle for different free-jet speeds (comparing figs. 5 and 8), it means that:

(a) The confluent nozzle has most of its sources, in the whole frequency range, *outside* the nozzle which gain the most in quietness due to the free-jet.

(b) The gain in quietness of 12-lobe conventional mixer with cut-outs (12C) is similar in many ways to the confluent nozzle, implying that *most of its noise sources are also outside the nozzle*. However, the gains at shallower angles (larger θ) are not as spectacular as those for the confluent nozzle because 12C is already better mixed at the nozzle-exit plane. Since there is still evidence of decrease in noise at upstream angles even the high-frequency sources associated with it must be largely outside the nozzle. This corroborates with the conclusions drawn from the hot-spots seen previously in figure 3. The excess noise that such a mixer has due to its partial mixedness over a fully-mixed jet has been analyzed for low bypass ratio nozzles by Saiyed, Bridges and Krejsa[5].

(c) For the unscalloped, high-penetration 12A mixer the decrease in PNL with increase in free-jet speed is the least at the most upstream observed angles. Note the very conspicuous constancy in the SPL "hump" at 60° in the 900 Hz - 2000 Hz range and very low reduction in frequencies higher than 2000 Hz when the free-jet is on. This shows that the source of these frequencies is not affected much by the free-jet. Hence, it is either inside the nozzle or near the exit plane surrounded by the ambient/jet shear layer but not disturbed by it. However, since the exit flow profile is very well mixed for 12A most of the noise source corresponding to that SPL hump must lie inside the nozzle. Due to its well-mixed exit profile the lower frequency external noise sources however do not gain as much in quietness due to free-jet speed, as compared to previous two mixers. Since at 90° and 120° the SPL even for high frequency is still decreasing with free-jet speed, this implies that most of the sources radiating there must be external to the nozzle. Thus the high-frequency noise sources both inside the nozzle-duct and those near the nozzle exit plane play a crucial role in making such an unscalloped high-penetration mixer the noisiest in terms of peak PNL (PPNL).

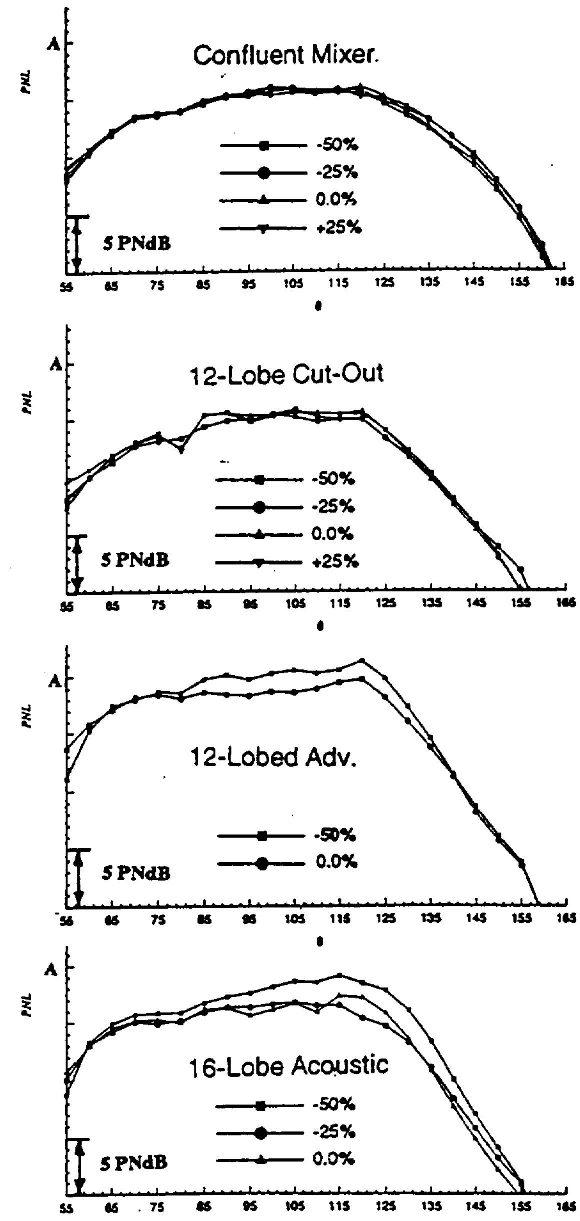


Figure 9. The effect of nozzle-length on fly-over PNL-directivity at 1500 ft. @ condition A with M_{fj} = 0.2.

(d) Mixer 16A, with similar high-penetration, unscalloped lobes as 12A, shows somewhat similar reduction characteristics in PNL and SPL with free-jet speed as for 12A. However, its intermediate to high frequency SPL has a lower amplitude than 12A's and it also decreases slightly more with increase in free-jet speed. Recall from the aerodynamic data (Tables 3 and 4) that this mixer produced the least thrust and highest bypass ratio due to its higher fan-to-core area ratio. Hence, a noise level lower than 12A is not unexpected. However, compared to 12C or even CON mixer, 16A is slightly noisier in terms of PPNL when the free-jet is on, having lost the advantage of free-jet noise reduction due to its faster mixing and consequent production of larger high-frequency fan-core mixing noise.

We note that when the fly-over PNL directivity is flat up to peak PNL angle and then drops steeply after that, as seen in all the lobed mixers for say $M_{fj} = 0.2$ or 0.3, the sources responsible for PNL flatness in the front quadrant gain much more importance in an effective perceived noise level (EPNL) calculation than those after the peak PNL angle. In 12A or 16A mixers the intermediate-to-high frequency noise sources due to fan-core mixing, both inside the nozzle and close to the nozzle exit plane were shown to be responsible for the flat PNL region. The reduction in low frequency for these same mixers is of less significance because it is all in the shallow angle region. The 12C mixer, on the other hand, reduced this all important high-frequency amplitude and, hence, the peak PNL. The CON mixer, although has a higher low frequency, shows the least high frequency content and one of the lower peak PNL's. This shows that it is more important from PPNL considerations to reduce the high-frequency hump than considerably reduce the low-frequency content.

The Effect of Nozzle-Length

Figure 9 shows the effect of changing the nozzle-length on the PNL directivity for each mixer at $M_{fj} = 0.2$. The confluent mixer does not show any appreciable difference throughout the whole range of angles. This is possible if most of its noise sources are outside the nozzle and their characteristics do not change with nozzle-length. The first conclusion corroborates with the one we had earlier by inspecting the effect of free-jet speed. Also we had found earlier (figure 3) that hardly any mixing occurred between the fan and the core flows inside the CON nozzle. Changing the nozzle-length in this range will not affect the growth of the shear layer between them or the noise sources embedded in them.

The 12-lobe cut-out (12C) mixer also does not show any appreciable difference with nozzle-length. This again corroborates with the previous conclusion that most of its noise sources are external to the duct. Due to the low penetration of this configuration, the axial vortices it generates, which are probably the major source of noise with high turbulence kinetic energy, are constrained by the duct wall but do not interact with it, as seen in figure 3. Thus changing the nozzle-length must not have altered their growth or evolution inside or outside the nozzle.

The other two mixers, the 12-lobe advanced (12A) and the 16-lobe acoustic (16A), however, do show an increase in noise especially near the peak PNL when the nozzle length is cut in half. This implies that (a) there are strong internal noise sources in these mixers which are being exposed now to the far-field with less of the nozzle-duct to shield it and (b) their noise source distribution characteristics also must have changed for the worse. The first conclusion agrees with the previous conclusion based on free-jet speed variations. The second one can be understood from the fact that both these mixers have high penetration and the exit total temperature profiles (fig. 3) did show the relatively mild hot-spots (invariably due to the axial vortices) close to the duct wall with which they interact. The increase in nozzle-length for these unscalloped mixers appears beneficial from noise point of view.

Finally, in figure 10 we capture the compound effect of changing nozzle-length and free-jet speed for each mixer by showing the contours of difference in peak PNL from a baseline (0, 0) case corresponding to $M_{fj} = 0$ and reference nozzle-length. This is a unique new way of presenting acoustic data for coupled parametric effects. Instead of PPNL one could have selected EPNL more appropriately but PPNL predominantly dictates EPNL anyway. Thus vertical contour lines indicate there is no change in PPNL with a change in nozzle-length; whereas, lines inclined to the left immediately indicate that there is a decrease in PPNL.

Conclusions

A reasonably wide acoustic test data base has been generated for several lobed mixers at high bypass ratios above 5. However, in this paper we analyzed only the relatively low jet velocity results of about 830 ft/s. These conclusions are, hence, restricted for these jet speeds.

1. Lobed mixers operate by reducing low frequency noise at shallow angles, as compared to coaxial nozzles, but with a possibility of corresponding increase in high frequency noise at non-shallow angles due to rapid mixing. Whether a particular lobed mixer is better than coaxial nozzle or not depends on the delicate transfer of acoustic energy from low frequencies to higher frequencies.

2. For unscalloped, high-penetration lobed mixers noise generated inside the nozzle-duct is as important as that generated outside it.

3. Cut-outs and/or low penetration in lobed mixers appear to reduce noise in the intermediate to high frequency range crucial to PNL. Cut-outs or preferably scallops appear essential for subsonic jet noise reduction. "Gentler" mixing may be preferable to extremely rapid mixing for PNL reductions.

4. The free jet eats away any acoustic advantage that a lobed mixer may have over coaxial nozzle under static free-jet conditions. The decrease in noise due to free-jet in unscalloped lobed mixers is much less than that in a coaxial mixer; lobes with lower penetration and cut-outs gain noise reductions similar to coaxial but still not as much.

5. Reductions in nozzle-lengths by 50%, with L/D_{mp} = 0.55, did not change the noise of coaxial or 12-lobed cut-out mixer nozzles, but it did increase the noise of unscalloped, high-penetration lobe mixers.

6. Our inferences about the nature and location of noise sources from acoustic test data with variations in free-jet speeds and nozzle-lengths corroborate with each other and the exit flow profiles.

References

1. Packman, A.B. and Eiler, D.C. (1977): *Internal Mixer Investigation for JT8D Engine Jet Noise Reduction, Vol. I - Results.* U.S. Dept. of Transportation, Federal Aviation Administration Report No. FAA RD-77-132.1, Dec. 1977.

2. Shumpert, P.K. (1980): *An Experimental Model Investigation of Turbofan Engine Internal Exhaust Gas Mixer Configurations.* AIAA-80-0228. AIAA 18th Aerospace Sciences Mtg., Jan. 14-16, 1980.

3. Kuchar, A. (1980): *Scale Model Performance Test Investigation of Exhaust System Mixer for an Energy Efficient Propulsion (E^3) System.* AIAA-80-0229, AIAA 18th Aerospace Sciences Mtg., Jan. 14-16, 1980.

4. Larkin, M. J. and Blatt, J. R. (1984): *Energy Efficient Engine Exhaust Mixer Model Technology Report Addendum, Phase III Test Program.* NASA CR 174799, April 1984.

5. Saiyed, N. H., Bridges, J. E. and Krejsa, E. A. (1996): *Core and Fan Stream's Mixing Noise Outside the Nozzle for Subsonic Jet Engines with Internal Mixers.* AIAA Paper 96-1667, AIAA Aeroacoustics Conf., May 6-8, 1996.

6. Booher, M.E., Kwon, O., Barta, A.B., Vittal B.R. and Krishnan, M.R. (1993): *Development of an Advanced Exhaust Mixer for a High Bypass Ratio Turbofan Engine.* AIAA 93-2435, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, June 1993.

7. Castner, R. S. (1994): *The Nozzle Acoustic Test Rig - An Acoustic and Aerodynamic Free-Jet Facility.* NASA TM 106495, 1994.

8. Elliott, J.K., Manning, T.A., Qiu, Y.J., Greitzer, E.M. and Tan, C.S. (1992): *Computational and Experimental Studies of Flow in Multi-Lobed Forced Mixers.* AIAA Paper 92-3568, 28th Joint Propulsion Conference, July 6-8, 1992.

9. Durbin, P. A. (1983): *High-Frequency Green's Function for Aerodynamic Noise in Moving Media - Part I. General Theory.* **J. Sound & Vibration**, 91(4), 1983, 519-525.

10. Abramovich, G. N. (1963): **The Theory of Turbulent Jets**. The M.I.T. Press, Cambridge, MA., ch. 5.

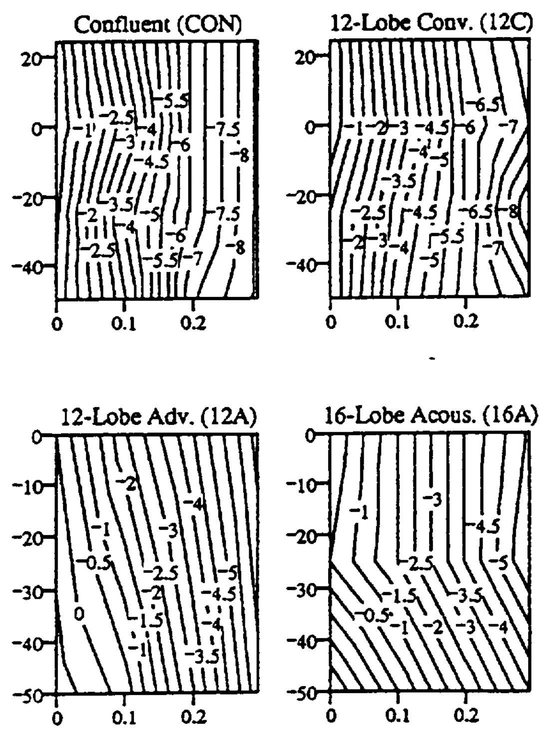


Figure 10. Difference-in-peak-PNL contour plots for the compound effect of free-jet Mach no. (horizontal axis) and % change from baseline nozzle-length (vertical axis) for condition A. [The reference PPNL for each mixer is at M_{fj} = 0 and baseline L/D_{mp} = 1.1 (nominal).]

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1997	Technical Memorandum

4. TITLE AND SUBTITLE

Noise Reduction with Lobed Mixers: Nozzle-Length and Free-Jet Speed Effects

5. FUNDING NUMBERS

WU–538–03–11–00

6. AUTHOR(S)

Vinod G. Mengle, William N. Dalton, James C. Bridges, and Kathy C. Boyd

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–10957

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—97-206221
AIAA–97–1682

11. SUPPLEMENTARY NOTES

Prepared for the Third Aeroacoustics Conference cosponsored by the American Institute of Aeronautics and Astronautics, and the Confederation of European Aerospace Societies, Atlanta, Georgia, May 12–14, 1997. Vinod G. Mengle and William N. Dalton, Allison Engine Company, 2001 S. Tibbs Avenue, Indianapolis, Indiana 46241; James C. Bridges, NYMA Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–27394); Kathy C. Boyd, NASA Lewis Research Center. Responsible person Kathy C. Boyd, organization code 5940, (216) 433–3952.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 71 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Acoustic test results are presented for 1/4th-scaled nozzles with internal lobed mixers used for reduction of subsonic jet noise of turbofan engines with bypass ratio above 5 and jet speeds up to 830 ft/s. One coaxial and three forced lobe mixers were tested with variations in lobe penetration, cut-outs in lobe-sidewall, lobe number and nozzle-length. Measured exit flow profiles and thrusts are used to assist the inferences from acoustic data. It is observed that lobed mixers reduce the low-frequency noise due to more uniformly mixed exit flow; but they may also increase the high-frequency noise at peak *perceived* noise (PNL) angle and angles upstream of it due to enhanced mixing inside the nozzle. Cut-outs and low lobe penetration reduce the annoying portion of the spectrum but lead to less uniform exit flow. Due to the dominance of internal duct noise in unscalloped, high-penetration mixers their noise is not reduced as much with increase in free-jet speed as that of coaxial or cut-out lobed mixers. The latter two mixers also show no change in PNL over the wide range of nozzle-lengths tested because most of their noise sources are outside the nozzle; whereas, the former show an increase in noise with decrease in nozzle-length.

14. SUBJECT TERMS

Jet noise; Noise reduction

15. NUMBER OF PAGES

17

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	