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Control of Jet Noise Through Mixing Enhancement

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1. ABSTRACT

The idea of using mixing enhancement to reduce jet noise is not new. Lobed mixers have been around since shortly after jet noise became a problem. However, these designs were often a post-design fix that rarely was worth its weight and thrust loss from a system perspective.

Recent advances in CFD and some inspired concepts involving chevrons have shown how mixing enhancement can be successfully employed in noise reduction by subtle manipulation of the nozzle geometry. At NASA Glenn Research Center, this recent success has provided an opportunity to explore our paradigms of jet noise understanding, prediction, and reduction. Recent advances in turbulence measurement technology for hot jets have also greatly aided our ability to explore the cause and effect relationships of nozzle geometry, plume turbulence, and acoustic far field. By studying the flow and sound fields of jets with various degrees of mixing enhancement and subsequent noise manipulation, we are able to explore our intuition regarding how jets make noise, test our prediction codes, and pursue advanced noise reduction concepts. The paper will cover some of the existing paradigms of jet noise as they relate to mixing enhancement for jet noise reduction, and present experimental and analytical observations that support these paradigms.

2. THREE-PROCESS PARADIGM FOR JET NOISE

In trying to explain to non-experts and program managers what jet noise is all about we have taken to using a Three Process Paradigm that tries to encapsulate the physics of jet noise. While this is hardly a revolutionary insight, the clarity and simplicity of this expression of the jet noise problem is noteworthy. This Paradigm starts with the total kinetic energy of the jet, commonly expressed as thrust and more explicitly given by the gas conditions, e.g. nozzle pressure ratio and jet temperature, at the nozzle exit. The first process of interest, Thrust to Turbulence is the conversion of the total kinetic energy into turbulent kinetic energy (TKE) through the instabilities of the jet flow. The second process of interest, Turbulence to Acoustic Source is the transfer of a very minute amount of this TKE to acoustic energy. The third process, Acoustic Source to Far-field Noise is the propagation of the acoustic energy through the initial inhomogenous near field of the jet and on to the far-field observer.

Using this Three Process Paradigm we can cover the three main activities of noise engineering—Understanding, Prediction, and Reduction. Let us start by covering the Three-Process Paradigm from the point of view of Understanding first, and then show how it guides our efforts at developing prediction tools and noise reduction technologies.

A. Understanding

Thrust to Turbulence—Overall Scaling and Flow Instabilities

Before delving into complicated details, we must first recognize the simple scaling laws for round jets (and even jets which are approximately round). Sound intensity scales as nozzle diameter squared and jet velocity to the eighth power. Thrust scales as diameter squared, velocity squared, neglecting thermal changes. Clearly, setting the balance between exit velocity and diameter has a large impact on jet noise. Knowledge of flow instabilities is the key to understanding the thrust to turbulence conversion. Although poorly understood, partly because in all but a few simple flows the instabilities are highly three-dimensional and quickly become nonlinear, this is the starting point of all turbulence. From the classic turbulence energy budget viewpoint, energy is extracted from the mean flow, e.g. the thrust, by the

instabilities of the mean flow, transferred to smaller lengthscale turbulent motions via the ‘energy cascade’ until the lengthscales reach molecular scales, whereupon the energy becomes heat. As mechanical engineers we can view this process as a conversion of energy from one form to another, and we can study and describe the various methods of its conversion, the instability modes, turbulence spectra, back-scatter of energy, etc. However, this much seems true from fundamental understanding: we can’t transfer the energy from the thrust to heat without turbulence.

Turbulence to Acoustic Source—An Energy Conversion Process

We make a point of saying that turbulence is inescapable because turbulence is the feedstock of jet noise. No unsteady motion of fluid, no sound. Acoustic energy was not included in the turbulence energy budget because it represents a very small fraction of the TKE, roughly 5 to 7 orders of magnitude less than the kinetic energy of the flow. From the mechanical engineers’ point of view this is a very inefficient energy conversion process. The smallness of this efficiency does mean that it is mercurial—indeed, the robustness of the scaling laws and the repeatability of jet noise measurements taken in different rigs attests to the consistency of the efficiency in both the first and second Processes. Cases that highlight this second Process independent of the complexities of turbulence, such as simplified vortex flows, are rare and generally evade simple intuitive explanations.

Observations of far-field acoustics¹ indicate that jet noise may have two different types of sources, often referred to fine-scale and large-scale sources. At this time, it is unclear how much this is a difference in source physics and how much may be better described as an effect of propagation. However, it is generally thought that the fine-scale source is relatively independent of the flow geometry, whereas there is evidence that the large-scale source is related to such large-scale features as the azimuthal modes of the turbulence that produce it. Analytical approaches of all flavors show that TKE with azimuthal modes greater than $m=\pm 2$ do not couple with the acoustic far field,^{2,3} and experiments⁴ show that the azimuthal sound field of jets do not contain significant energy in these higher modes.

Another observation that should be mentioned here is the significant tie between the location and frequencies of noise sources as measured by phased arrays. It is no surprise that low frequency sources seem to be located downstream where the lengthscales of the flow are larger.

Acoustic Source to Far-Field Noise—Inhomogeneous Propagation

Finally, the propagation of the acoustic energy is considered a separate Process for two reasons. First, if we can formulate theories that localize acoustic sources within the jet then the acoustic waves created must propagate through the inhomogeneous jet near field where refraction can be quite complicated. Second, an important aspect of jet noise is the bias of the human observer, the source motion and position relative to that observer in flight, and non-continuum effects such as atmospheric attenuation. The first reason is actually even more complicated than just tracing acoustic rays through the jet because this encompasses the impedance match between source and acoustic medium that partially determines what part of the acoustic energy becomes transmitted to the far field. In this regard it can be tricky to separate these last two Processes. This is why the ‘two-source’ description of jet noise may have as much to do with propagation as with acoustic energy conversion.

B. Prediction

Next, consider the implications for the engineers’ first need: predicting jet noise.

Thrust to Turbulence—Enhanced CFD

From our understanding of the first Process we see that being able to predict turbulent kinetic energy of a jet given its geometry and exit flow conditions is critical. This is a problem today as the turbulence models in most CFD codes are tuned to produce accurate predictions of the mean flow, not accurate predictions of the turbulence. In fact, being able to predict jet noise may require knowledge not only of the TKE, but also of its lengthscales. These are typically obtained through RANS TKE-dissipation ($k-\epsilon$) models as the ratio of k and ϵ . Lengthscales are used to associate frequencies with the energy in the various regions of the jet.

One challenge is how to improve CFD turbulence models so that they give accurate predictions of TKE. From scaling laws of our current aeroacoustic model we see that the far-field intensity scales as $TKE^{7/2}$, making accurate prediction of this quantity crucial. Another challenge is to improve the predictions of dissipation, although it is not a directly measurable quantity.

Aeroacoustic theory predicts that the efficiency of the conversion of TKE to acoustic energy depends upon the degree of isotropy of the turbulence.⁵ This leads to the requirement that CFD not only predict the TKE at every point in the flow, but that it predict the Reynolds stress tensor as well. Currently, algebraic stress models are being explored to satisfy this requirement.⁶

Turbulence to Acoustic Source—Aeroacoustic Modeling

On the outset, let us be clear that of the two sources, fine-scale and large-scale, only the fine-scale source is understood well enough to model and predict. Several studies are underway to model the large-scale source, but they are strictly exploratory, not to be used for prediction possibly for years to come.⁷

The key to predicting the fine-scale source is the assignment of an acoustic source spectrum from the TKE and lengthscale predicted by CFD. Theoretical guidance, either from acoustic analogies⁸ or other approaches,⁹ leads to two-point space-time correlation of velocity (the Lighthill stress tensor) as the prime characteristic in modeling this process. Although density fluctuation terms are present, their role is not as well understood and hence not used in most aeroacoustic models. The most significant advances in source modeling have come from incorporating turbulence anisotropy¹⁰ and fine-tuning the model for the source spectrum from each source region.

Acoustic Source to Far-Field Noise—CAA Issues

Classically, the acoustic source energy was propagated to the far-field using Green function methods to predict the linear propagation of sound through the inhomogeneous acoustic medium.^{9,11} Previously this Process was computed using approximate analytic Green function methods, producing poor results at angles near the jet axis.¹² Recent attacks on this problem have featured computational aeroacoustic approaches and often turn to an adjoint method¹³ to improve computational efficiency. Here one often trades speed of solution for simplifications, such as quasi-axisymmetric solutions. Also, at this time there are very few codes to predict the propagation of the sound from internal sources, such as those generated by internally mixed turbofan nozzles and ejectors.

C. Reduction

Finally we come to the task that actually earns the noise engineer his money—noise reduction. It should be noted here that it is rare that overall reduction can be achieved at all angles and frequencies. Often what is needed is to reduce jet noise at certain angles and frequencies where it is the dominant source of aircraft noise, and suffer an increase in noise at other frequencies and angles that can be tolerated. What approaches does the Paradigm suggest?

Thrust to Turbulence—Geometry and Active Control

In the first Process, we find the most significant way to reduce jet noise while maintaining thrust is to increase the jet diameter, reducing the jet velocity. This has been the basis for almost all jet noise reduction technology flying today. However, there are practical limits to this approach that have largely been reached.

If we cannot reduce the exit velocity of the jet, then we can first try to modify the turbulence that must result from the mean flow. The first idea is to change the relationship between TKE and lengthscale, often synonymous with changing the region of the jet where the turbulence is strongest. Although if done properly, overall reduction can be achieved, this works best for modifying the noise field without necessarily reducing overall sound power. The best approach found so far is to modify the jet geometry to promote turbulent mixing closer to the jet using mixing enhancement devices.¹⁴ These devices reduce the turbulence downstream that produces the low frequency noise that often dominates aero engine noise.

However, any technology that can be developed to reduce TKE in jets is of interest as a noise reduction concept.

Turbulence to Acoustic Source—Anisotropy and Modal Content

While it has been noted that the conversion of TKE to acoustic energy seems relatively robust, there is still hope that this Process' efficiency can be reduced. From theoretical considerations it appears that turbulence becomes less efficient as it becomes more isotropic, it makes sense then to explore how to make the turbulence more isotropic.⁵ Similarly, as lengthscales are reduced and the source regions become more compact, the efficiency of the source is reduced. Thus, if the turbulence can be manipulated either in spectra or in isotropy noise reduction can be expected.

Another possibility which keys on the observation that the large-scale jet noise sources must have low azimuthal order to couple to the far-field is to shift turbulent energy from low modes to high ones, possibly using time-dependent jet excitation devices. This possibility has largely been unexplored as most jet excitation studies have used low order modal excitation. Perhaps modal consideration is another reason that geometric changes to enhance mixing, such as chevrons, are effective on the low frequency jet noise.

Acoustic Source to Far-Field Noise—Using Directionality, Shielding, Atmospheric Attenuation

There are a few reduction ideas that can be pursued in propagation from our understanding of the Process. First, we list the possibility of having non-axisymmetric directionality of the sound field that could be exploited. Such might come about from having non-axisymmetric mean field such as an offset fan nozzle or thermal layer on one side of the plume. In principle one could use a very hot sheet of fluid on one side of the jet to cause the jet noise to be totally internally reflected in that side of the jet. Second, because engines must be mounted on airplanes to be of any use there are problems and opportunities to obtain noise reduction by using the plane's structure as a shield for some angles and possibly by the non-axisymmetric effect of wing downwash and angle of attack. Perhaps as we better understand these effects they can be harnessed to yield better installed jet noise. Finally, since it is critical to remember that we are dealing with a heavily biased observer, a human ear, we can work to put more of the sound into very high frequencies where not only is the human less aware of it, but also where atmospheric attenuation reduces the amplitude more effectively.

3. THREE PROCESS PARADIGM APPLIED TO MIXING ENHANCEMENT DEVICES

To exemplify the points made above, we highlight some work from NASA GRC research in the past few years on mixing enhancement devices added to nozzles.

A. Separate Flow Nozzle Tests

In 1996 NASA asked major American aircraft engine manufacturers to propose jet noise reduction concepts for a combined test. The idea behind the vast majority of these concepts was to use enhanced mixing to decrease the mean jet velocity downstream where the low frequency jet noise is produced. In this regard the understanding was similar to that which produced lobed mixers a generation ago.¹⁵ From this test emerged the current generation of separate flow nozzles with serrated edges. The 1997 test done at NASA's Glenn Research Center included plume surveys, IR imagery, and acoustic phased array measurements along with the standard far-field acoustic measurements.¹⁶ In a second test in 2000 Particle Image Velocimetry (PIV) was employed to measure the turbulence produced by the enhanced mixing devices.¹⁷ The flow field measurements provided understanding of how mixing enhancement affected both the flow and noise, filling in several missing pieces in the paradigm puzzle as summarized below.

From our analysis of acoustic data it appears that chevrons and tabs on nozzles modify the far-field noise spectra primarily by shifting energy from low frequencies to high frequencies (see Figure 1). In addition to PIV measurements of the turbulence, TKE and lengthscales, acoustic phased arrays viewing the jet from near 90° polar angles measured the perceived acoustic source density (ASD), expressed as third-octave energy per unit length of the jets. Figure 2 shows TKE and ASD for the same baseline and chevron nozzles

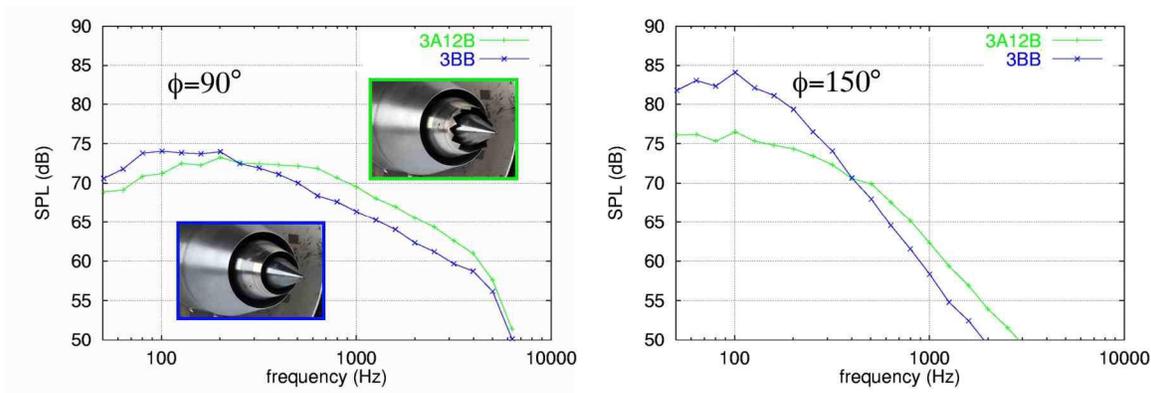


Figure 1.—Typical spectral change with mixing enhancement devices. Full-scale third octave spectra at 90° (left) and 150° (right) polar angles. Data transformed to 1500 ft level flyover scaling.

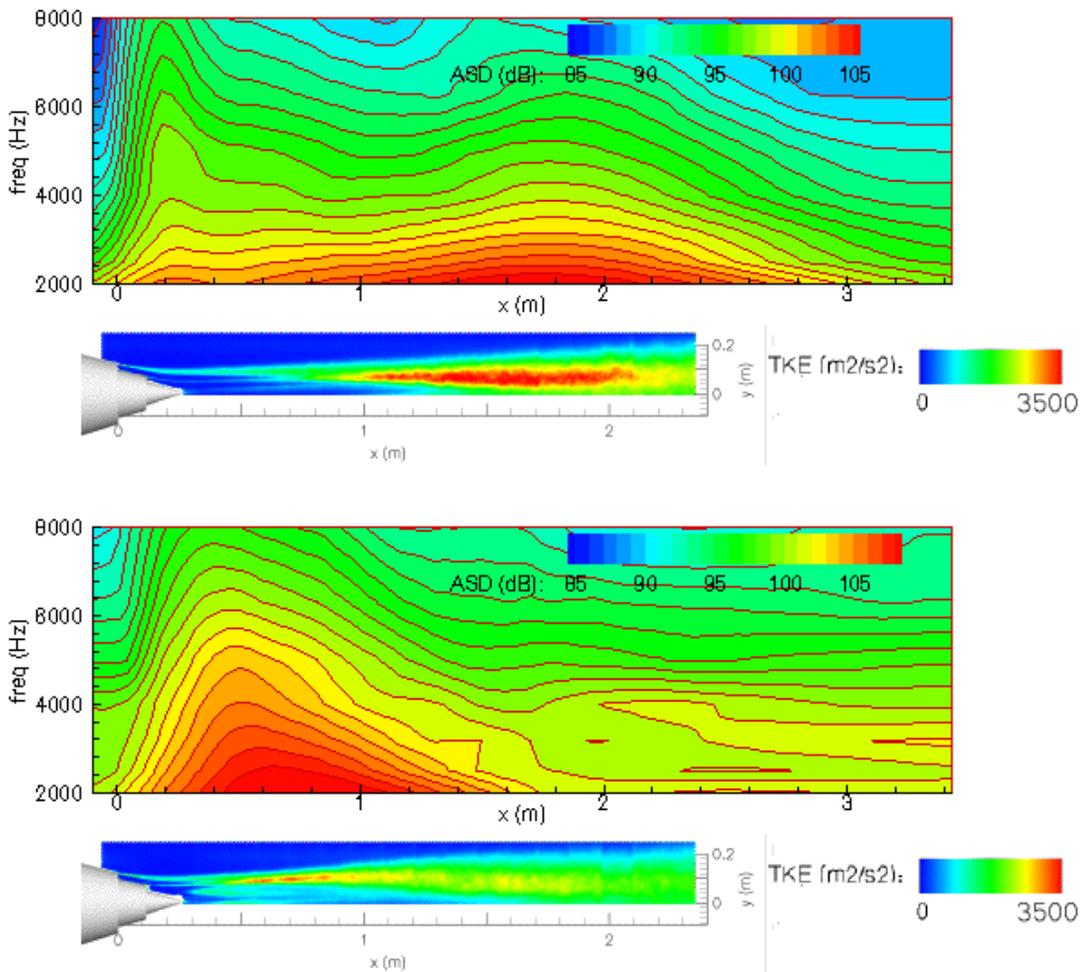


Figure 2.—Acoustic source location measurements and TKE maps for separate flow nozzle system with axisymmetric core nozzle (top) and with core nozzle with alternating chevrons (bottom). The frequency range at model scale corresponds to frequencies 250 Hz to 1 kHz in Figure 1.

as Figure 1. The chevron and tab configurations greatly increased the TKE in the near field where lengthscales were small and showed very strong reduction in TKE at the downstream locations where lengthscales were large. There was a significant change in the distribution of lengthscales that further pushed the TKE into higher frequencies as well. The good correspondence between the TKE and ASD shows that the first Process defined above was a valuable way to understand the changes in jet noise using these mixing enhancement devices.

Using TKE as input for a jet noise model has been successful at predicting the trends for chevron nozzles in published cases,¹⁸ and in proprietary studies. It will be a profitable way to look for additional noise reduction ideas in the future.

Some insight was gained into the second Process, conversion of TKE to acoustic energy, by the chevron tests. First, it was noted that there was a substantial reduction in overall sound power, pointing to some reduction in the efficiency of the Processes. The question was whether this was strictly due to shifting the energy to higher frequencies or by other changes in the turbulence that might make the second Process less efficient. It had been noted above that acoustic analogy theory shows that turbulence becomes less efficient as becomes more isotropic. In the turbulence measurements of the chevron nozzles it was found that the chevrons did in fact increase the isotropy of the turbulence over the round baseline nozzle. According to calculations using acoustic analogy theory, this change in isotropy was worth around 2dB in reduction of peak sound by itself, independent of the reduction obtained by reduction of the TKE.¹⁹ This has lead us to include turbulence anisotropy in our jet noise predictions and to look for other means to reduce the efficiency of jet turbulence at producing noise through manipulation of the turbulence.

Being able to consider the third Process, the propagation of sound to the far field, as an independent process, is difficult to justify. Sound levels in the jet near field, estimated from the far-field using spherical spreading, are too high to call linear. One of the concepts tested during the chevron test, the offset fan nozzle, inadvertently gave a good illustration of how well this assumption works. An offset fan nozzle was designed which sought to simultaneously increase mixing on one side of the jet and shield the other side by offsetting the hot, high speed core flow to one side of the lower speed fan flow. However, the implementation used an asymmetric fan nozzle that did not quite turn the flow back collinear with the core flow. Consequently, the core stream penetrated the sheathing fan flow at a point roughly 5 diameters downstream, producing a very strong hot spot of turbulence on one side of the jet as documented by PIV measurements shown in Figure 3. The acoustic phased array clearly identified the strong sound source, concentrated within a fan diameter, when viewed from the side of the hot spot. When viewed from the opposite side, the peak in ASD appeared shifted downstream roughly a fan diameter. This makes sense when one considers that sound produced at the hot spot is advected downstream as it propagates through the roughly $M=1$ jet toward the offside phased array. This interesting result shows the utility of considering the propagation to be an independent step in jet noise paradigm and supports the kind of propagation models used in prediction codes.

B. Single flow chevron studies

Recently we have gone back to studying chevrons on single flow nozzles in a small hot jet rig. This has allowed us to better explore the various steps in the jet noise paradigm, testing our understanding of the jet noise production processes, providing good test cases for developing robust noise prediction codes, and hopefully leading to better ideas for noise reduction. Several chevron nozzles were designed to parametrically vary characteristics that seem important to the flow and noise field: number of chevrons (varying the spacing of axial vorticity), chevron penetration (varying the strength of the axial vorticity), and chevron length (varying the distribution of the vorticity within the axial vortices). These nozzles are shown in Figure 4.

Far-field noise measurements and plume survey measurements have been done so far, with some initial interesting observations being derived from these experiments. Although we do not yet have TKE for the different nozzles we do have the mean velocity fields that can be related to the TKE in the downstream regions via the local shear. Nor do we have phased array results yet. For now we have to assume that high frequencies are produced near the nozzle, while low frequencies are produced downstream.

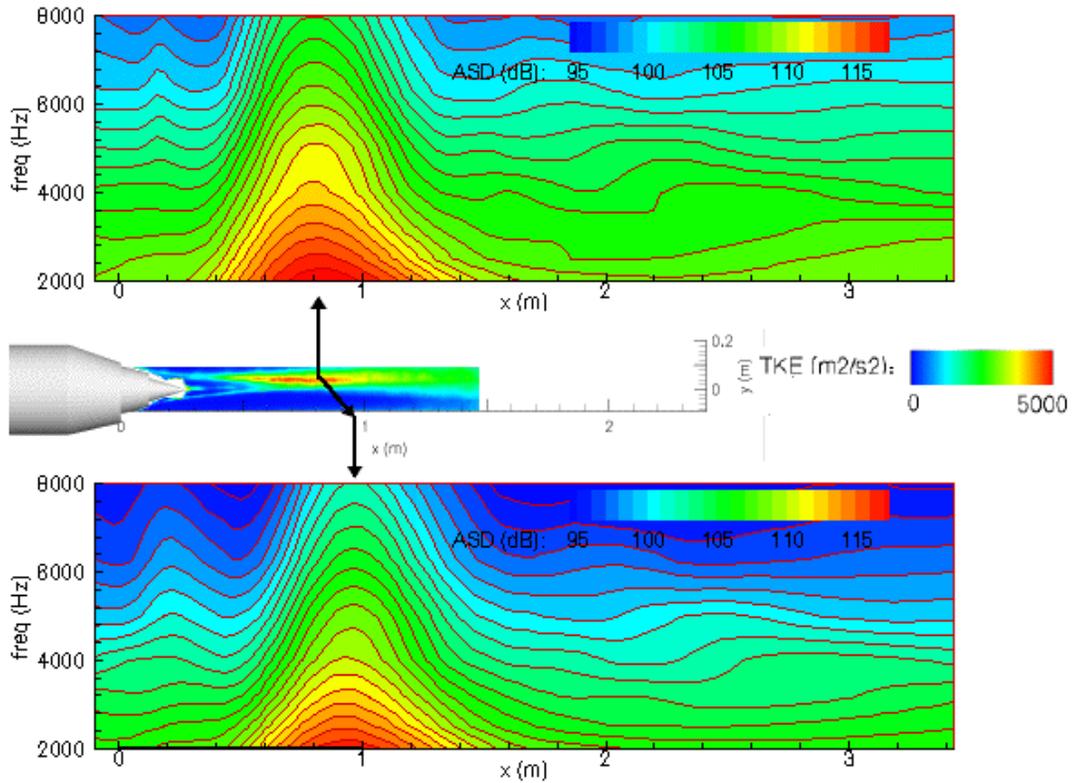


Figure 3.—Offset fan nozzle on separate flow nozzle system. Measured TKE contours in symmetry plane of plume are shown in middle of figure while above and below are acoustic source density (ASD) as measured by acoustic phased array from the two sides of the jet.



Nozzle ID	Chevron N	Chevron Length(inch)	Chevron Angle (deg)
SMC000	0		
SMC001	6	0.89	5.0
SMC002	4	1.26	5.0
SMC003	10	0.55	5.0
SMC004	5	1.048	5.0
SMC005	6	0.89	0.0
SMC006	6	0.89	18.2
SMC007	6	1.26	13.3
SMC008	10	0.76	13.0
SMC009	12	0.5	0.0, 5.0, 14.3
SMC010	10	0.6	9.8

Figure 4.—Chevron nozzles run on SHJAR. Table gives values for number of chevrons, chevron length, and angle of chevron with jet axis.

Focusing on the first Process, the first observation is that the length of the chevron has little impact on either the flow or the noise as long as the penetration is the same. The second observation is that having more spacing between axial vortices of the same strength, accomplished by having fewer chevrons, allows more cross-stream transport. Presumably this is because the axial vortices do not destructively interfere with each other as rapidly downstream. Nozzles with few chevrons produce more mixing, more outward ejection of jet fluid into the ambient than nozzles with more chevrons, and have lower mean velocities downstream. We also noted that the amount of transport could be controlled by keeping the spacing constant and changing the strength of the axial vorticity as shown in Figure 5 by varying the chevron penetrations. Figure 6 gives the mean velocity on the jet centerline and the OASPL for three 6-chevron nozzles with different penetrations. It is clear that the more aggressive the penetration the more the jet is mixed out. It is also clear that the sound radiated over much of the polar angle, the fine-scale source, is increased with penetration, while the large-scale source is reduced as the downstream velocity is reduced.

At this point we can make very little direct observation concerning the second Process other than to confirm that the high mixing rates in the upstream portions of the chevron nozzle do seem to create a strong amount of high frequency noise, noise that correlates with the local shear. One interesting observation is that even when the chevrons have negligible penetration, and nearly negligible impact on the centerline decay, they still seem to cause some reduction of the low frequency, 'large-scale' sound source. In Figure 7 the two 10-chevron nozzles have negligible impact on the centerline decay yet reduce noise at the peak

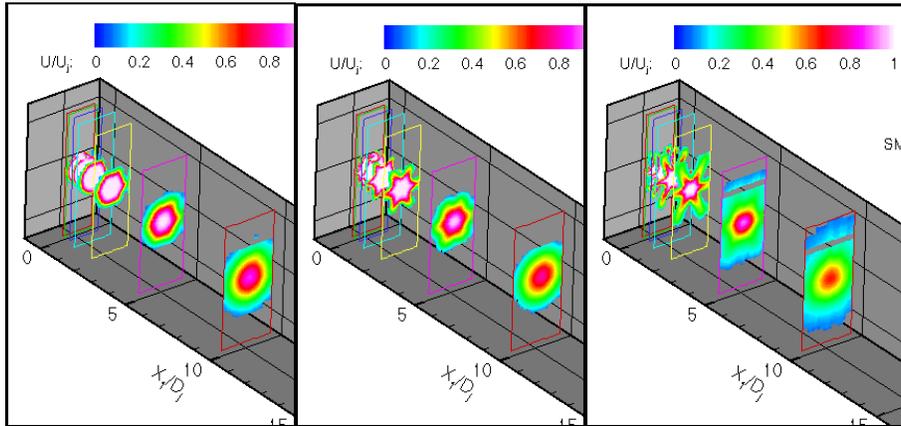


Figure 5.—Mean velocity fields from N=6 chevron single flow nozzles with different penetration angles: 0°, 5°, 18°. $M_j=0.9$, cold.

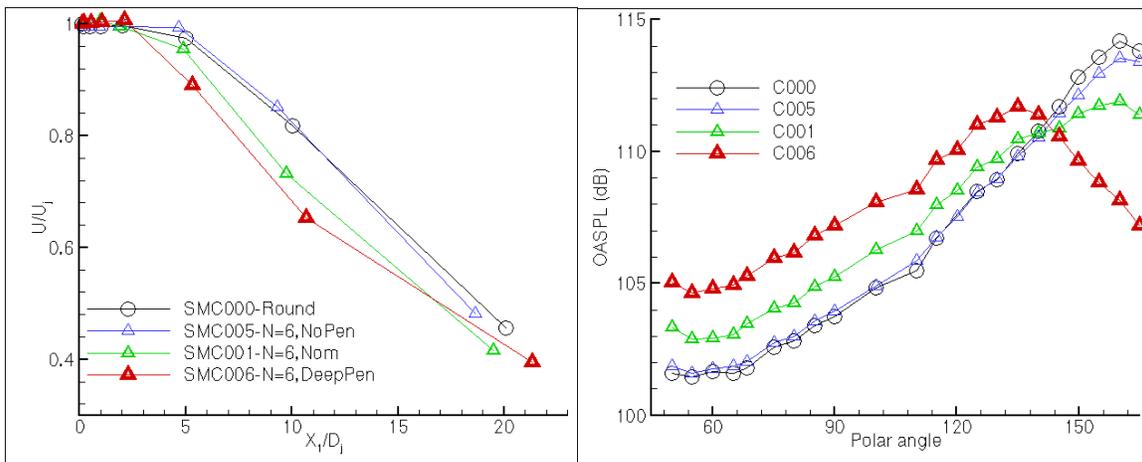


Figure 6.—Round and N=6 chevron nozzles with different penetrations at $M_j=0.9$. Mean velocity on centerline (left), OASPL (right). Nozzle definitions given in Figure 4.

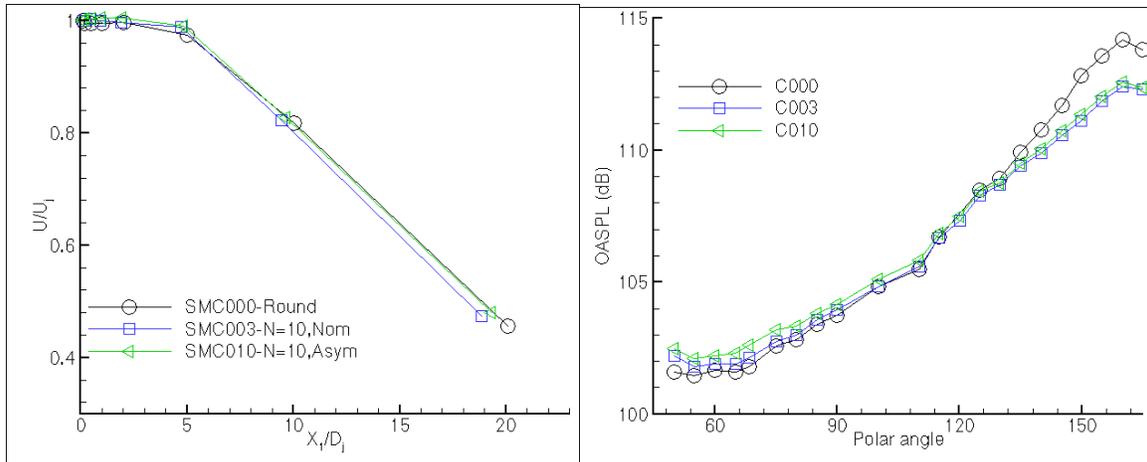


Figure 7.—Baseline and N=10 chevron nozzles. Mean velocity on centerline (left), OASPL (right). Nozzle definitions given in Figure 4.

angle by several dB. This points to the possibility that the introduction of small azimuthal perturbations can change the efficiency of the radiation, perhaps by transferring some of the TKE to higher order modes where they cannot radiate. It is hoped that future experiments can quantify the azimuthal modal content of the turbulence, confirming such a connection.

4. FUTURE DIRECTIONS

It is hoped that the Three Process Paradigm outlined in this paper and exemplified using recent experimental observations will continue to work as a framework for advancing jet noise research in all three areas of noise engineering: Understanding, Prediction, and Reduction. For instance, it is very clear how changes in the engine cycle, reflected as changes in initial kinetic energy, can bring about very large noise reductions. It is also clear that this will continue to be the best lever the engineer has to affect noise reduction until we become much more proficient at manipulating the three Processes that inevitably connect this energy to far-field noise. This is state of the art today.

In the future, this Paradigm will guide thinking about what changes one would like to see in the turbulence, such as using mixing enhancement devices to affect spectral changes beneficial to a specific propulsion system. Or of understanding how to achieve ‘quiet mixing’ that provides the benefits of mixing enhancement without the penalties. It provides some structure to consideration of how to use spatial/geometric modifications to the flow and how to use active control to reduce jet noise. Perhaps more importantly, from the current state of understanding incorporated in the Paradigm, detailed research programs can be planned to focus on the various Processes, testing and improving upon the components of the Paradigm in an organized manner. This is our goal in planning future research programs.

The Paradigm provides a framework for designing nozzles from an acoustic perspective. It cleanly decouples the flow calculation from the acoustic model, allowing separate development of the CFD TKE prediction tools needed for jet noise, and of acoustic source modeling grounded in physics. Optimization of enhanced mixing devices for noise reduction hinges upon our ability to predict their impact on the flow and subsequently on the acoustic energy produced. To the extent that the large-scale source in jets can be incorporated into the Paradigm, a total prediction tool can be built around this structure. If the Paradigm continues to hold, the prediction tools for the propagation of acoustic energy from the modeled sources can be separately developed to as fine a degree as required. Development of noise engineering tools based upon this Paradigm is an overarching objective of NASA’s jet noise programs.

Finally, the Paradigm contains the necessary simplification of the problem required to synthesize new ideas for noise reduction. Concepts can be developed that concentrate on turbulence manipulation, either by reducing TKE, modifying length and timescales, or by reducing the efficiency of the turbulence to acoustic energy transfer. Test results can be profitably described not only by their EPNL benefits, but also by their

ability to either reduce this efficiency or redistribute the energy spectrally and directionally. Concepts that do not impact EPNL on a given design may be useful in other systems with other acoustic needs, providing noise reduction for these systems. Use of near-field propagation effects for noise reduction can be envisioned and intelligently pursued once the propagation tools are improved and validated. Noise reduction technology will only come from clever use of the understanding and prediction tools that the Three Process Paradigm provides.

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13. ABSTRACT (<i>Maximum 200 words</i>) The idea of using mixing enhancement to reduce jet noise is not new. Lobed mixers have been around since shortly after jet noise became a problem. However, these designs were often a post-design fix that rarely was worth its weight and thrust loss from a system perspective. Recent advances in CFD and some inspired concepts involving chevrons have shown how mixing enhancement can be successfully employed in noise reduction by subtle manipulation of the nozzle geometry. At NASA Glenn Research Center, this recent success has provided an opportunity to explore our paradigms of jet noise understanding, prediction, and reduction. Recent advances in turbulence measurement technology for hot jets have also greatly aided our ability to explore the cause and effect relationships of nozzle geometry, plume turbulence, and acoustic far field. By studying the flow and sound fields of jets with various degrees of mixing enhancement and subsequent noise manipulation, we are able to explore our intuition regarding how jets make noise, test our prediction codes, and pursue advanced noise reduction concepts. The paper will cover some of the existing paradigms of jet noise as they relate to mixing enhancement for jet noise reduction, and present experimental and analytical observations that support these paradigms.			
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