Jet Surface Interaction Noise in a High Aspect Ratio Rectangular Exhaust

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## Contents

Abstract ......................................................................................................................................................... 1

1.0 Overview ............................................................................................................................................... 1

2.0 Mean Flow Computation Details .......................................................................................................... 2
  2.1 File Recommendations ......................................................................................................................... 2
  2.2 Normalization Rule ............................................................................................................................... 4

3.0 Acoustic Simulation .............................................................................................................................. 5
  3.1 Mixing/Scrubbing Noise Component—“JSI-MIX” ............................................................................. 5
    3.1.1 Input Preparation ......................................................................................................................... 6
    3.1.2 Primary Input File—“jsi-mix.inp” ............................................................................................ 8
    3.1.3 Primary Output File—“fort.55” ............................................................................................ 9
    3.1.4 Shielded Side Primary Input File—“jsi-mix.inp” ........................................................... 12
    3.1.5 Shielded Side Primary Output File—“fort.55” ............................................................... 14
    3.1.6 File Summary .................................................................................................................. 15

  3.2 Trailing Edge Noise Component—“JSI-TEN” ................................................................................. 15
    3.2.1 Primary Input File—“jsi-ten.inp” ................................................................................... 15
    3.2.2 Primary Output File—“fort.55” ...................................................................................... 16
    3.2.3 File Summary .................................................................................................................. 20

4.0 Code Implementation .......................................................................................................................... 20
  4.1 Obtaining the Source Code ................................................................................................................. 20
  4.2 Creating the Executable ..................................................................................................................... 20

5.0 Sample Computational Results ........................................................................................................... 21
  5.1 Flow Simulations—RANS Solver ....................................................................................................... 21
  5.2 Post Processing of the Mean Flow—Interpolation to Acoustic Grid ............................................. 24
  5.3 Acoustic Results ............................................................................................................................... 24

References ................................................................................................................................................... 29
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Abstract

A physics-based prediction model is employed to simulate jet surface interaction (JSI) noise in a transversely sheared jet exhaust. The methodology finds application in jets with a high aspect ratio (AR) rectangular exhaust in the proximity of a flat surface. Two component spectra are simulated: (i) mixing/scrubbing noise; (ii) trailing edge noise—and are superimposed to obtain the far field exhaust noise on either side of a nearby surface. This document describes the necessary input parameters (including mean flow and turbulence information for the nozzle exhaust of interest) that should be prepared in order to initiate the simulation for each noise component. Sample input/output files in connection with an 8:1 aspect ratio rectangular exhaust at Mach 0.98 near a rigid surface are described.

1.0 Overview

A schematic of a transversely sheared mean flow, such as a high aspect ratio (HAR) rectangular jet near a solid surface, is shown in Figure 1. The coordinate axes (1, 2, 3) denote the stream-wise, span-wise, and transverse (i.e., normal) directions, respectively. Parameters $h$ and $X_{TE}$ refer to the standoff distance (measured from the lower lip of the nozzle to the flat surface), and the stream-wise plate length (measured from jet exit plane to the trailing edge of the surface). Polar angle $\theta$ is with respect to downstream jet axis, and azimuthal angle $\phi$ is from the span-wise direction $x_2$. For now, we consider the surface as infinitely long in the span-wise direction, and the mean flow as locally parallel in both $x_1$ and $x_2$ directions such the flow gradients of significance occur in the normal direction only (a planar flow). Our goal is to implement an acoustic analogy approach to simulate the far field jet exhaust noise.

The analysis, as detailed in (Refs. 1, 2, and 3), considers the exhaust noise as a superposition of two component spectra:

(i) Combined turbulent mixing noise and scrubbing noise in the presence of a nearby surface (referred to as mixing noise, MIX)
(ii) Trailing edge noise (TEN)

Noise component (i) is governed by the inhomogeneous Rayleigh equation and its source is the generalized Reynolds stress (includes product of fluctuating temperature and velocity in addition to velocity and velocity). This broadband noise component covers a full three octave spectrum and dominates the latter two octaves of the total spectrum. Noise component (ii) is governed by the inhomogeneous adjoint Rayleigh equation. Its source, as formulated in the context of Rapid Distortion Theory (RDT), is described as an arbitrary convective quantity (Ref. 4) that, among other factors, relates to the transverse momentum perturbations upstream of the trailing edge (TE)—and its power spectrum dominates the low frequency end of the total spectrum.

Each noise component is evaluated as a convolution product of a source and an appropriate Green’s function (GF) integrated over a specified jet region.
In the following, we describe computational tools that use the above acoustic analogy approach to accurately predict the far-field sound pressure level due to jet surface interaction (JSI) in a transversely sheared jet exhaust. Two Fortran-90 computer codes designated as “JSI-MIX” and “JSI-TEN”, and designed to output tables of spectral density for the mixing/scrubbing noise and the trailing edge noise, will be discussed. The Alpha version of the JSI codes implies that prediction model should be viewed as an on-going research effort open to future improvements in compliance with flow and noise measurements.

Code input must include the mean flow solution from a Reynolds-Averaged Navier Stoke (RANS) solver. Turbulence kinetic energy and its dissipation rate from a $k-\varepsilon$ or a $k-\omega$ turbulence model must also be provided. Recommendations will be made concerning the topology of the structured grids, which could simplify the process of preparing the input for each code. It is understood that it may not always be feasible to meet these recommendations within a particular RANS solver. Subsequently, flow solutions obtained on unstructured grids must be mapped onto a structured grid suitable for such noise calculations. This is done externally and with appropriate interpolation routines.

2.0 Mean Flow Computation Details

It is recognized that significant effort may be devoted to mean flow simulation prior to acoustic predictions. As is commonplace in most physics-based acoustic analogy applications, three files are supplied pursuant to the RANS calculations for the nozzle flow of interest: a grid file, a solution file, and a turbulence file.

2.1 File Recommendations

Simulation of jet surface interaction noise in planar flows is best achieved through an H-grid topology. The assumption that the mean flow be locally parallel in stream- and span-wise directions requires a summation of the convolution product over elementary jet volume slices in $x_1$ and $x_2$ directions. Ideally separate blocks may be deployed to identify plume segments upstream and downstream of the TE when a nearby surface is present. Sample file structure consisting of two blocks is shown in Figure 2. Only the jet segment downstream of the jet exit plane enters noise simulation. The GF applicable to the mixing/scrubbing noise component deploys a local boundary condition, i.e., initial conditions at the surface upstream of the TE (block 1); and the radiation condition at $x_3 = -\infty$ if we suppose the observer is positioned at $x_3 = +\infty$ (block 2).
RANS files follow the usual Plot3D standards (i.e., multi-block, whole-format):

!!!!!!!!!!!!
!
Write (LUNG) NBLK ! Grid File
Write (LUNG) (JMAX(I), KMAX(I), LMAX(I), I = 1, NBLK)
DO I = 1, NBLK
  J_MAX = JMAX(I) ! stream-wise x1
  K_MAX = KMAX(I) ! transverse (normal) x3
  L_MAX = LMAX(I) ! span-wise x2
  ! fill work-space with Block I grid coordinates
  Write (LUNG) (((( XYZ(J,K,L,n),J=1,J_MAX),K=1,K_MAX),L=1,L_MAX), n=1,3)
ENDDO
!
Write (LUNQ) NBLK ! Q File
Write (LUNQ) (JMAX(I), KMAX(I), LMAX(I), I = 1, NBLK)
DO I = 1, NBLK
  J_MAX = JMAX(I) ! stream-wise
  K_MAX = KMAX(I) ! transverse (normal)
  L_MAX = LMAX(I) ! span-wise
  ! fill work-space with Block I solution variables
  Write (LUNQ) FSMACH, ALPHA, RE, TIME ! condition at Block I
  Write (LUNQ) ((( QQ((J,K,L,n),J=1,J_MAX),K=1,K_MAX),L=1,L_MAX), n=1,5)
ENDDO
!
Write (LUNT) NBLK ! T File
Write (LUNT) (JMAX(I), KMAX(I), LMAX(I), I = 1, NBLK)
DO I = 1, NBLK
  J_MAX = JMAX(I) ! stream-wise
  K_MAX = KMAX(I) ! transverse (normal)
  L_MAX = LMAX(I) ! span-wise
  ! fill work-space with Block I solution variables
  Write (LUNT) FSMACH, ALPHA, RE, TIME ! condition at Block I
  Write (LUNT) ((( QT(J,K,L,n),J=1,J_MAX),K=1,K_MAX),L=1,L_MAX), n=1,2)
ENDDO
!
!!!!!!!!!!!!!
2.2 Normalization Rule

Parameters stored in the grid file (XYZ), Q file (QQ), and turbulence file (QT) are expected to follow the normalization standards in Table I.

When the ideal gas law holds, and with \( \gamma \) as the specific heat ratio and \( \Re \) as the gas constant, specified reference values for length, temperature, and pressure – \((L_r, T_r, p_r) = (L_{\text{ref}} \text{ (ft)}, T_{\text{inf}} \text{ (R)}, P_{\text{inf}} \text{ (psf)}))\), are deployed to define normalization parameters listed in Table I.

\[
a^2_r = \gamma \Re T_r, \quad \rho_r = \frac{p_r}{\Re T_r}
\]

Parameters \( T_r \) and \( p_r \) are usually selected as the ambient temperature and pressure, and \( a_r \) is the reference sound speed.

Cartesian coordinates \((x_1, x_2, x_3)\) are normalized relative to reference length \( L_r \). Grid size within each block, in the order of \( x_1, x_3, \) and \( x_2 \) directions, is \((J_{\text{MAX}}, K_{\text{MAX}}, L_{\text{MAX}}))\). Ideally grid construction slated for noise work should be an assortment of parallel slices stacked in the stream-wise direction.

Figure 3 shows an H-grid construct in the span-wise plane within Block 2. Projection of the rectangular nozzle (blue) and the surface TE (dark) are also highlighted \((D_{\text{eq}} \text{ denotes the area-equivalent diameter for the rectangular nozzle } \pi D_{\text{eq}}^2 / 4 = \text{Area})\). Cartesian coordinates \( \tilde{x} \) and \( \tilde{y} \) are used interchangeably to denote dependent and source coordinates. Within Block 1 the grid geometry excludes nodes shown below the surface (i.e., shielded side).

The mean flow variables stored in file (QQ) are density, momentum components, and internal energy per unit volume \((\rho, \rho u, \rho v, \rho w, E)\), normalized as

\[
Q_1 = \rho / \rho_r \quad Q_2 = \rho u / (\rho_r a_r) \quad Q_3 = \rho v / (\rho_r a_r) \quad Q_4 = \rho w / (\rho_r a_r) \quad Q_5 = E / (\gamma \rho_r),
\]

and the mean static pressure \( p \) is evaluated as

\[
\frac{p}{\gamma \rho_r} = (\gamma - 1) \left( Q_5 - \frac{1}{2} \frac{Q_2^2 + Q_3^2 + Q_4^2}{Q_1} \right)
\]

<table>
<thead>
<tr>
<th>TABLE I.—NORMALIZING FACTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>Coordinates</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Velocity component</td>
</tr>
<tr>
<td>Pressure</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Total internal energy/unit volume</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
</tr>
<tr>
<td>Omega</td>
</tr>
</tbody>
</table>
The turbulence file (QT) consists of two variables. An input FLAG “TurbModel” identifies each variable as either \((k, \varepsilon)\) or \((k, \omega)\). For convenience, the turbulence variables are provided in dimensional form: \(k\) (ft\(^2\)/s\(^2\)), \(\varepsilon\) (ft\(^2\)/s\(^3\)), and \(\omega\) (1/s). Conversion from \(\omega\) to \(\varepsilon\) is carried out according to
\[
\varepsilon = 0.90 \times k \times \omega .
\] (4)

Normalization of turbulence variables for the purpose of evaluating turbulence scales is carried out internally as \(\left(\frac{k}{a_r^2}\right), \left(\frac{\varepsilon}{L_r/a_r^3}\right), \text{ and } \left(\frac{\omega L_r}{a_r}\right)\).

### 3.0 Acoustic Simulation

Two jet-surface interaction codes, “JSI-MIX” and “JSI-TEN”, evaluate mixing/scrubbing (MIX) and trailing edge noise (TEN), respectively. A superposition of two component spectra provides the total noise spectrum in a planar jet exhaust near a surface.

#### 3.1 Mixing/Scrubbing Noise Component—“JSI-MIX”

This noise component requires an integration of the source/GF product over jet volume elements (or source correlation volumes) that radiate to a far-field observer. A criterion based on the line-of-sight argument determines the extent of volume integration. For an observer on the reflected side of a nearby surface, jet slice integration starts following the exit plane and marches downstream. As an example, both blocks are included in the simulation for such an observer when using block structure in Figure 2. On the other hand, we consider source correlation elements above the surface, i.e., block 1, as masked relative to an observer on the shielded side of the surface (although this argument may not be quite accurate if the observer angle is close to the downstream axis). Subsequently, slice integration starts immediately following the TE (block 2 in Figure 2). Details of the GF calculation and the numerical solution to a second-order ODE contributing to this GF are provided in (Ref. 1). While initial values for solving the ODE are specified on the surface upstream of the TE, such near-field boundary is missing in block-2, and the initial values are stated at \(x_3 = \mp \infty\) depending on observer location at \(x_3 = \pm \infty\).
A pseudo-code outline of the “JSI-MIX” computation is given below, followed by more detailed information about each step:

For each observer location
   For each frequency
      For each grid element
         1) calculate the source intensity
         2) calculate the propagator (GF) assuming a locally parallel mean flow
         3) calculate the SPL (source/GF convolution integral)
      Repeat each grid element
   Repeat each frequency
   Repeat each observer location

Jet exit conditions are evaluated at a user-specified location along the jet. This information is used to evaluate a nominal exhaust velocity $U_j$ that is employed to calculate source convection velocity $U_c = \alpha U_j + \beta U$ where $(\alpha, \beta)$ are a pair of empirical constants and $U$ is the local mean axial velocity. The Strouhal frequency is $St = f D_j / U_j$ where length $D_j$ may be selected as the minor side of the rectangular nozzle.

Sound pressure level (SPL) is evaluated in either narrow-band or 1/3-octave band. The narrow-band calculations are performed per Strouhal number at each center frequency $f$ (Hz) in a third-octave band

$$10 \log_{10} \left( U_j D_j^{-1} \overline{p^2} / p_0^2 \right)$$

and the 1/3-octave predictions are

$$10 \log_{10} \left( BW \times \overline{p^2} / p_0^2 \right)$$

where the bandwidth at frequency $f$ is

$$BW = f \times (2^{1/6} - 2^{-1/6})$$

and the band number is defined as $Band = 10 \log_{10} (f)$. Parameter $\overline{p^2}$ in (5) and (6) refers to the mean-square acoustic pressure at an observer location, and $p_0 = 0.0002 \mu bar = 4.17 \times 10^{-7} \text{ psf}$ is the standard acoustic reference pressure. In either case, the Overall Sound Pressure Level (OASPL) is calculated by integrating the SPL on a 1/3-octave basis.

3.1.1 Input Preparation

An example of an input file “jsi-mix.inp” assigned to an 8:1 aspect ratio rectangular exhaust (N8Z) with dimensions (5.3- by 0.67-in.) near a solid surface “h19_xte12” ($h = 1.9$-in., $X_{TE} = 12$-in.) is provided in Section 3.1.2. Solution files generated by a typical RANS solver have been post-processed (interpolated) to a new grid that consists of two blocks—the first block (51 by 65 by 137) consists of 51 axial planes (measured from nozzle exit), 65 points in transverse direction (above the surface), and 137 points in the span-wise ($x_2$) direction. Block 2 covers the remaining jet volume following the TE of the nearby surface—it extends below the surface ($-x_3$ direction) with dimensions (77 by 93 by 137) as seen in Figure 4 and Figure 5.
A short description of variables appearing in “Namelist” is also provided in comment statements that follow. The CaseTitle and RANS files information are subsequently followed, under header “JET_DATA”, by parameters that define a nominal exit plane and source-volume integration range (stream- and span-wise directions). For clarity, some of the parameters are highlighted in Figure 4 and Figure 5. In this example, exit conditions are evaluated at the third slice within block 2 (Exit_block = 2, Jexit =3), and integration starts in block 1 and ends in block 2 (Start_block =1, End_block =2) at slice numbers identified through j_start and j_end, respectively. Required source integration range in the span-wise direction is defined for half of the jet volume from L_start (near the jet boundary) to L_END (at the x3 plane of symmetry). As expected, careful selection of parameters in the input file is required for best results. For example, jet exit velocity $U_j$ (when evaluated from nozzle upstream conditions) may not exactly develop at the nozzle exit plane—as the mean flow could accelerate and reach this velocity at some distance further downstream. This is known to influence the source convection velocity, which in turn has an impact on the SPL levels particularly at observer angles closer to the jet axis.

A restart file (fort.54) is written (or updated) following the treatment of each axial slice as source/GF volume integration proceeds (see File Summary, Section 3.1.6). This file needs to be copied to a new file.
(fort.53) if stream-wise slice integration is to be continued from a previous terminal point. This type of output is useful if one is interested in inspecting the contributions to the jet noise from various segments in a plume. Ambient values for pressure and temperature are usually assigned to reference values \((P_{\text{inf}}, T_{\text{inf}})\), and \(L_{\text{ref}}\) is the reference length. Other parameters of interest utilized in presentation of the output are Strouhal number range \((St_{\text{min}}, St_{\text{max}})\), observer locations (distance and angles), and output type (third-octave vs. narrow-band sound spectral density). Polar angles are provided relative to the downstream \(x_1\) axis, and a single azimuthal angle is also specified. Tables of predicted spectra are presented as lossless as well as with atmospheric loss (attenuation) at ambient temperature \((T_{\text{inf}})\) and relative humidity \((h_r)\).

Since any physics-based prediction model may be viewed as an on-going research effort in its utility range and compliance with measurements, a host of other parameters are accessible in the input “Namelist” that are currently commented out within the source code, and could be modified from their preset default values.

The primary output file “fort.55” is listed in Section 3.1.3. It presents a reflection of the input parameters, RANS files, their blocks and grid sizes, mean flow parameters such as \((U, \rho, T, a, M)\) at the designated exit plane, frequency and Strouhal number range, and finally tables of far field sound spectral density at angles of choice.

Sample listing for the two main input/output files is provided below, followed by a file summary in Section 3.1.6.

3.1.2 Primary Input File—“jsi-mix.inp”

The following input file is used when the far-field observer is positioned on the reflected side of a nearby surface. The RANS files, designated as “N8Z_sp07 h19_xte12”, are prepared for an 8:1 aspect ratio rectangular exhaust with nozzle upstream conditions of: pressure ratio \(NPR = 1.86\), and temperature ratio \(NTR = 1.0\) (i.e., Set Point sp07). The nearby surface is positioned at standoff \(h = 1.90\)-in. with length \(X_T = 12.0\)-in. Input file applicable to the shielded side is slightly different and will be discussed in Section 3.1.4.

```plaintext
$TITLE
  CaseTitle = ' JSI-MIX 8:1 Rectangular Jet, N8Z(H19, XTE12, SP07) '
&END
&CFD_FILES
  GFILE = './N8Z_sp07_h19_xte12_jsi.x'         ! Grid file
  QFILE = './N8Z_sp07_h19_xte12_jsi.q'         ! Q file
  TFILE = './N8Z_sp07_h19_xte12_jsi.t'         ! Turb file
&END
&JET_DATA
  Exit_block = 1        ! Block# for evaluating jet exit conditions
  Jexit = 4             ! Axial index for exit plane conditions within "Exit_block"
  Dj = 0.0558           ! Nozzle minor-axis (ft)
  Start_block = 1      ! Slice integration starts at "Start_block"
  End_block = 2        ! Slice integration ends at "End_block"
  ! (for complete integration, set "End_block" larger than
  ! total No. of blocks; this will also over-ride "j_end")
  I_Wall= 1            ! Block# less than or equal to I_wall interact with the surface
  I_Side = 1           ! Integer Flag
    ! (1:Reflected side; 0: Shielded side)
  j_start= 4           ! Axial slice# to start slice integration within "Start_block"
    ! (All following blocks start at j_start = 1)
  j_end =77            ! Ends slice integration at "j_end" within "End_block"
    ! (blocks prior to End block are integrated completely)
  ! (set "j_end" larger than the Max of slices in
```
! "End_block" for complete integration
j_inc= 1              ! Axial increment for slice integration - applicable
! to all blocks
L_start = 14          ! starting slice in x2-direction
L_END = 69            ! ending slice in x2-direction
L_inc= 1              ! increment for sector integration in Z-direction
Pinf = 2102.4         ! Reference pressure - psf
Tinf = 529.0          ! Reference temperature - R
h_r = 70.0            ! Percentage ambient relative humidity
Rgas=1716.0           ! Gas constant - ft^2/(s^2 * R)
Gamma=1.4             ! Specific heats ratio
Lref=1.0              ! Reference length (ft) in grid file
Noz_scale=1.0         ! A factor to scale to a new nozzle diameter
! Use 1.0 if desired nozzle diameter is not different
! from that in RANS solution
N_Arc=1               ! Integer (1: Arc;  2: sideline)
Robs = 17.81          ! Distance (ft) at 90-deg
St_min =1.0d-2        ! Strouhal limits; (St= f Dj/Uj), Dj is nozzle minor-axis
! in x3 direction
St_max= 10.0          !
I_restart = 0         ! Integer Flag ( 0: no restart file;
! 1: solution uses restart file fort.53)
I_band=3              ! Integer Flag (0 : narrow-band spectra; 3: 3rd-octave spectra)
TurbModel= 1          ! Integer Flag to identify Turbulence Model;
! (1 : k-e; 2: k-Omega )
Zimp_r = 0.0          ! Real and imaginary parts of Normalized Surface Impedance
Zimp_i = 0.0          ! default values (0.0, 0.0) indicate a rigid surface.

&END
&Polar
Nang = 4              ! No. of observer angles
Thetd =  40.0, 60.0, ! Polar Angles (deg) wrt downstream axis X1.
   90.0, 120.0
&END
&Azimuthal
Azimuth = 90.0      ! A single Azimuthal angle (deg) wrt X2 axis.
&END

3.1.3 Primary Output File—“fort.55”

***********************************************************************
* JSI-MIX.f90 (Alpha Version)                                      *
***********************************************************************
--- input ---------------------
Title= JSI 8:1 Rectangular Jet, N8Z(H19, XTE12, SP07)
Grid file:
./N8Z_sp07_h19_xte12_jsi.x
Q    file:
./N8Z_sp07_h19_xte12_jsi.q
Tke  file:
./N8Z_sp07_h19_xte12_jsi.t

Exit_block =  2
Start_block =  1
End_block =  2
I_Wall =  1
I_Side =  1
Dj =  0.55800E-01

NASA/CR—2017-219528  9
Jexit = 4
j_start = 4
j_inc = 1
j_end = 77
L_start = 14
L_inc = 1
L_end = 69
Pinf = 2102.40
Tinf = 529.00
h_r = 70.00
Rgas = 1716.00
Gamma = 1.40
Lref = 1.000000
Noz_Scale = 1.000000
Robs = 17.81
N_Arc = 1
St_min = 0.01
St_max = 10.00
I_restart = 0
I_band = 3
TurbModel = 1
* Nearby surface is considered as rigid *
Nang = 4
Polar Angles (deg. from X1) = 40.0 60.0 90.0 120.0
Azimuthal Angle (deg. from X2) = 90.0

GFILE was opened successfully.
QFILE was opened successfully.
TFILE was opened successfully.

RANS input consists of 2 Blocks
Grid pts in order of StreamWise(X1), Transverse(normal-X3), SpanWise(X2):
Block# 1 Grid: 51 65 137
Block# 2 Grid: 77 93 137
Aref= 0.11273E+04fps, Rhoref= 0.23160E-02 slug/cft

Exit/Ambient conditions are evaluated at Block# 1 as:
Max Velocity at J= 4 (K,L)=(17,67) is Uexit= 1027.87 fps

Calculated AMBIENT values (from CFD)
Velocity = 0.752202657172966 fps
Density = 2.336729508750347E-003 slug/cft
Pressure = 2116.22673422241 psf
Static Temp = 527.759998742854 R
Sound Speed = 1126.00649242348 fps
Ambient Mach(Mamb)= 6.68026927284703E-004

Exit values are evaluated within Block# 1 at Jexit = 4
Exit Plane is at X_exit = 0.318382E+00 ft
Diameter = 5.580000000000000E-002 ft

At X_exit, at the point of Max Velocity (j,k) = (4, 17) :
Uexit = 1027.87177083866 fps
Density = 2.700998103378933E-003 slug/cft
Pressure = 2120.08356161499 psf
Static Temp = 457.416067588307 R
Sound Speed = 1048.28257677696 fps
Mach No. = 0.980529290107004
Jet Thickness = 5.580000000000000E-002 ft
Stag Temp. Ratio = 1.03094797155550
Umax = 1027.87 is used for Convection velocity and Strouhal Freq.

Uexit/Ainf = 0.91

Texit/Tinf = 0.86 Static Temp Ratio

Deallocation (Evaluate_At_Exit) in Block# 1 was successful

Strouhal number (f a/U) calculated based on:
- Freq Range  (f) = 160 100000 (Hz)
- Nozzle Minor Side (a) = 0.5580E-01 (ft)
- Exit Velocity (U) = 0.1028E+04 (fps)
- Strouhal Range = 0.8686E-02 0.5429E+01
- X_exit = 0.318382E+00 (ft)

* ************************************************ *
* RANS Turb. file was read as a k-epsilon solution *
* ************************************************ *

Block# 1 Grid: 51 65 137 & Q file were successfully processed

Integrating Block# 1 from J= 4 to J= 51 with j_inc= 1

Block# 1 J_loc= 5
FIRST SLICE WAS CALLED AT (J_loc, L_azimuth) = 5 14

LAST SLICE WAS CALLED AT (J_loc, L_azimuth) = 5 69

Block# 2 J_loc= 76
FIRST SLICE WAS CALLED AT (J_loc, L_azimuth) = 76 14

LAST SLICE WAS CALLED AT (J_loc, L_azimuth) = 76 69

Deallocating block# in Main Prog.
Deallocation (Main program) completed in Block# 2 istat= 0

-- Azimuthal Angle FI = 90.0DEG. --

Prior 1 Block(s) are integrated within requested slices

Within Block# 2, additional jet slices j= 1 to 77 with j_inc= 1 are complete.

Spectral density is calculated in 3rd-Octave Band

*** Mixing/Scrubbing Noise ***

17.81 FT. ARC

Unattenuated spectra / Angle from down-stream axis

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**OASPL DIRECTIVITY** 105.29 103.22 99.48 96.22

*** Mixing/Scrubbing Noise ***

17.81 FT. ARC

Attenuated spectra at 70.0000000000000 % Rel. Humidity and 529.000000000000 deg. R Angle from down-stream axis

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**OASPL DIRECTIVITY** 101.60 98.82 95.67 92.88

3.1.4 Shielded Side Primary Input File—“jsi-mix.inp”

Several parameters discussed earlier in the context of file “jsi-mix.inp” should be modified when preparing input relevant to a far-field observer on the shielded side of a nearby surface. In the first place block 1 in Figure 4 is now considered as shielded from the observer—therefore stream-wise source
integration skips all blocks positioned upstream of the TE (Start_block = 2, j_start = 1),
and flag (I_Side = 0) points to the shielded side. For convenience, polar angles are introduced with a
positive sign as before, however, RANS files are flipped with respect to x1x2 surface, i.e., a negative sign
multiplies transverse coordinate x3 as well as the corresponding momentum variable. The new RANS
files, shown here with padded name “flip”, should be ordered such that an increase in x3 would point to
the shielded side of the surface. A table of the predicted “mixing/scrubbing” noise component along the
shielded side of the aforementioned surface is provided in a lossless format (Section 3.1.5).

$TITLE
CaseTitle = 'JSI-MIX 8:1 Rectangular Jet, N8Z(H19, XTE12, SP07)' 
&END
&CFD_FILES
GFILE = './N8Z_sp07_h19_xte12_jsi_flip.x' ! Grid file
QFILE = './N8Z_sp07_h19_xte12_jsi_flip.q' ! Q file
TFILE = './N8Z_sp07_h19_xte12_jsi_flip.t' ! Turb file
&END
&JET_DATA
Exit_block = 1 ! Block# for evaluating jet exit conditions
Jexit = 1 ! Axial index for exit plane conditions within "Exit_block"
Dj = 0.0558 ! Nozzle minor-axis (ft)
Start_block = 2 ! Slice integration starts at "Start_block"
End_block = 2 ! Slice integration ends at "End_block"
! (for complete integration, set "End_block" larger than
! total No. of blocks; this will also over-ride "j_end")
I_Wall = 1 ! Block# less than or equal to I_wall interact with the surface
I_Side = 0 ! Integer Flag
! (1:Reflected side; 0: Shielded side)
j_start = 1 ! Axial slice# to start slice integration within "Start_block"
! (All following blocks start at j_start =1)
j_end = 77 ! Ends slice integration at "j_end" within "End_block"
! (blocks prior to End block are integrated completely)
! (set "j_end" larger than the Max of slices in
! "End_block" for complete integration)
j_inc = 1 ! Axial increment for slice integration - applicable
! to all blocks
L_start = 14 ! starting slice in x2-direction
L_END = 69 ! ending slice in x2-direction
L_inc = 1 ! increment for sector integration in Z-direction
Pinf = 2102.4 ! Reference pressure - psf
Tinf = 529.0 ! Reference temperature - R
h_r = 70.0 ! Percentage ambient relative humidity
Rgas = 1716.0 ! Gas constant - ft^2/(s^2 * R)
Gamma = 1.4 ! Specific heats ratio
Lref = 1.0 ! Reference length (ft) in grid file
Noz_scale = 1.0 ! A factor to scale to a new nozzle diameter
! Use 1.0 if desired nozzle diameter is not different
! from that in RANS solution
N_Arc = 1 ! Integer (1: Arc; 2: sideline)
Robs = 17.81 ! Distance (ft) at 90-deg
St_min = 1.0d-2 ! Strouhal limits; (St= f Dj/Uj), Dj is nozzle minor-axis
! in x3 direction
St_max = 10.0 !
I_restart = 0 ! Integer Flag (0: no restart file;
! 1: solution uses restart file fort.53)
I_band = 3 ! Integer Flag (0: narrow-band spectra; 3: 3rd-octave spectra)
TurbModel = 1 ! Integer Flag to identify Turbulence Model;
! (1 : k-e; 2: k-Omega)
Zimp_r = 0.0 ! Real and imaginary parts of Normalized Surface Impedance
Zimp_i = 0.0 ! default values (0.0, 0.0) indicate a rigid surface.
&END
&Polar
Nang = 4 ! No. of observer angles
Thetd = 40.0, 60.0, ! Polar Angles (deg) wrt downstream axis X1.
90.0, 120.0
&END
&Azimuthal
Azimuth = 90.0 ! A single Azimuthal angle (deg) wrt X2 axis.
&END

3.1.5 Shielded Side Primary Output File—“fort.55”

****************************************************
* JSI-MIX.f90 (Alpha Version) *
****************************************************
------------------------ input --------------------
Title= JSI 8:1 Rectangular Jet, N8Z(H19, XTE12, SP07)
Grid file:
./N8Z_sp07_h19_xte12_jsi_flip.x
Q file:
./N8Z_sp07_h19_xte12_jsi_flip.q
Tke file:
./N8Z_sp07_h19_xte12_jsi_flip.t
.

Spectral density is calculated in 3rd-octave Band

*** Mixing/Scrubbing Noise ***
17.81 FT. ARC

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3.1.6 File Summary

Simulation of mixing/scrubbing noise component uses the following input (Table II) and output files (Table III).

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| 54 | Formatted restart file fort.54—should be copied to fort.53 when \texttt{I
restart=1} |
| 55 | Primary output file fort.55—sound spectral density tables |

3.2 Trailing Edge Noise Component—“JSI-TEN”

The source/GF integration is now carried out on a span-wise plane $dA = dy_2dy_3$ along the TE of the surface. In the transverse direction $y_3$ starts from the surface and reaches as far as $y_o$ where $U(y_o)$ attains a maximum (i.e., $\partial U/\partial y_3 \rightarrow 0$). In the span-wise direction $y_2$ covers the wetted edge of the surface, i.e., sources that make relatively significant contribution to the TE noise component. Since source strength as related to turbulent kinetic energy (TKE) is stored as per unit volume, its stream-wise span should be scaled with an appropriate length-factor $L$. This parameter is ultimately combined with a second calibration constant present in front of the equation. The directivity factor (or GF) comprises of two observer angles in addition to the local mean velocity and flight Mach number, and displays a cardioid pattern centered at the edge. The integrated spectrum, as formulated for power spectral density (Ref. 2) exhibits a $U^5$ velocity scaling.

Here the input parameter \texttt{j_start=49} is assigned to the location of the integration plane (selected as two grid points upstream of the surface TE, \texttt{j_Edge=51}). Additionally, a new sub-list within block data, declared as “EdgeData”, identifies the TE for a nearby surface.

Since the TE noise directivity factor is symmetric with respect to the edge, the predicted spectra are considered as valid on both sides of the surface. A complete input file applicable to this noise component is provided in Section 3.2.1, followed by the associated primary output in Section 3.2.2.

3.2.1 Primary Input File—“jsi-ten.inp”

```bash
$TITLE
   CaseTitle = ' JSI 8:1 Rectangular Jet, N8Z(H19, XTE12, SP07) ' 
&END 
&CFD_FILES 
GFILE = './N8Z_sp07_h19_xte12_jsi.x' ! Grid file
```
QFILE = './N8Z_sp07_h19_xte12_jsi.q'         ! Q    file
TFILE = './N8Z_sp07_h19_xte12_jsi.t'         ! Turb file
&END
&JET_DATA
Exit_block = 1        ! Block# for evaluating jet exit conditions
Jexit = 1             ! Axial index for exit plane conditions within "Exit_block"
Dj = 0.0558           ! Nozzle minor-axis (ft)
H_offset = 0.158333   ! Standoff distance h (ft)
!K_start= 1            ! Starting index – transverse direction (defaults to 1)
j_start= 49           ! J_start should be < (j_Edge - j_inc) within "Edge_block"
! Noise is always evaluated at (j_Edge - j_inc)
j_inc= 1             ! Increment for slice integration - (stream-wise x1)
L_start = 14          ! Starting slice index (span-wise x2)
L_END = 69            ! Ending slice index, plane of symmetry (span-wise x2)
L_inc= 1             ! Increment in sector index (span-wise x2)
Pinf = 2102.4         ! Reference pressure - psf
Tinf = 529.0          ! Reference temperature - R
h_r = 70.0            ! ambient relative humidity - %
Rgas=1716.0           ! Gas constant - ft^2/(s^2 * R)
Gamma=1.4             ! Specific heats ratio
Lref=1.0              ! Reference length (ft) in grid file
Noz_scale=1.0         ! A factor to scale nozzle diameter
! Use 1.0 if desired diameter equals that in RANS solution
N_Arc=1              ! Integer (1: Arc; 2: sideline)
Robs = 17.81          ! Distance (ft) at 90-deg
St_min =1.0d-2        ! Strouhal limits; (St= f Dj/Uj), Dj is nozzle minor-axis
! parallel to the surface
St_max= 10.0          !
I_band=3              ! Integer Flag (0 : narrow-band spectra; 3: 3rd-octave spectra)
TurbModel= 1          ! Integer Flag to identify Turbulence Model
! (1 : k-e; 2: k-Omega )
&END
&Polar
Nang  = 4             ! No. of observer angles
Thetd =   40.0, 60.0, ! Polar Angles (deg) wrt downstream axis X1.
   90.0, 120.0
&END
&Azimuthal
Azimuth =   90.0      ! Azimuthal Angles (deg) wrt X2 axis.
&END
&EdgeData
Edge_block = 1        ! Block# at the Trailing Edge (TE)
j_Edge = 51           ! Axial slice index for TE within "Edge_block"
&END

3.2.2 Primary Output File—“fort.55”

*********************************************************
* JSI-TEN.f90 (Alpha Version) *
*********************************************************
------------------------ input ------------------------
Exit_block = 1
Dj = 0.55800E-01
H_offset = 0.15833E+00
Jexit = 1
K_start = 1
j_start = 49
j_inc = 1
L_start = 14
L_inc = 1
L_end = 69
Pinf = 2102.40
Tinf = 529.00
h_r = 70.00
Rgas = 1716.00
Gamma = 1.40
Lref = 1.000000
Noz_Scale = 1.000000
Robs = 17.81
N_Arc = 1
St_min = 0.0100
St_max = 10.00
Edge_block = 1
J_Edge = 51
I_band = 3
TurbModel = 1
Nang = 4
Polar Angles (deg. from X1) =
40.0   60.0   90.0  120.0

Azimuthal Angle (deg. from X2) = 90.0

GFFILE was opened successfully.
QFILE was opened successfully.
TFILE was opened successfully.

RANS input consists of 2 Blocks
Grid points in the order of:
Axial, Radial (normal to surface), Azimuthal (spanwise)
Block# 1 Grid: 51 65 137
Block# 2 Grid: 77 93 137
*** Note:
- Edge is within the specified integration range -
***
Deallocating block# 1 in Evaluate_At_Exit
Deallocation (Evaluate_At_Exit) in Block# 1 was successful
Aref= 0.11273E+04fps, Rhoref= 0.23160E-02 slug/cft

Exit/Ambient conditions are evaluated at Block# 1 as:
Max Velocity at J= 1 (K,L)=(19 60) is Uexit= 1027.67 fps

Calculated AMBIENT values (from CFD)

Velocity = 0.752202657172966 fps
Density = 2.336729508750347E-003 slug/cft
Pressure = 2116.22673422241 psf
Static Temp = 527.759998742854 R
Sound Speed = 1126.00649242348 fps
Ambient Mach(Mamb)= 6.680269272284703E-004
Exit values are evaluated within Block# 1 at Jexit = 1
Exit Plane is at X_exit = 0.258379E+00 ft
Diameter = 5.580000000000000E-002 ft
---
At X_exit, at the point of Max Velocity (j,k)= (1, 19):
Uexit = 1027.67159986442 fps
Density = 2.720093119774312E-003 slug/cft
Pressure = 2137.67619625854 psf
Static Temp = 457.974045096322 R
Sound Speed = 1048.92175396423 fps
Mach No. = 0.979740953965824
Jet Thickness = 5.580000000000000E-002 ft
Stag Temp. Ratio = 1.03193799692194

Umax = 1027.67 is used for Convection velocity and Strouhal Freq.
Uexit/Ainf = 0.91
Texit/Tinf = 0.87 Static Temp Ratio
Deallocation (Evaluate_At_Exit) in Block# 1 was successful

Strouhal number (f a/U) calculated based on:
o Freq Range (f) = 160 100000 (Hz)
o Exit Minor Axis (a) = 0.5580E-01 (ft)
o Exit Velocity (U) = 0.1028E+04 (fps)
o Strouhal Range = 0.8688E-02 0.5430E+01

o X_exit = 0.258379E+00 (ft)

* ************************************************ *
* RANS Turb. file was read as a k-epsilon solution *
* ************************************************ *

Block# 1 Grid: 51 65 137 & Q file were successfully processed
Integrating Block# 1 Along Slice At J = 50
FIRST SLICE WAS CALLED AT (J_loc, L_azimuth) = 50 14

********************************************************
* Trailing Edge Noise is evaluated at J= 50 in Block 1 *
********************************************************
...
LAST SLICE WAS CALLED AT (J_loc, L_azimuth) = 50 69
Deallocating block# 1 in Main Prog.
Deallocation (Main program) completed in Block# 1 istat= 0

-- Azimuthal Angle FI = 90.0DEG. --
Spectral density is calculated in 3rd-Octave Band

*** Trailing Edge Noise ***
17.81 FT. ARC
Unattenuated spectra / Angle from down-stream axis
Freq Band St 40 60 90 120
160 22 0.009 72.96 74.29 74.74 74.68
200 23 0.011 76.48 77.79 78.22 78.13
250 24 0.014 79.81 81.10 81.49 81.38
315 25 0.017 82.98 84.24 84.59 84.44
400 26 0.022 85.84 87.06 87.35 87.16
500 27 0.027 87.98 89.15 89.38 89.15
630 28 0.034 89.48 90.62 90.79 90.51
800 29 0.043 90.12 91.21 91.33 91.00
1000 30 0.054 89.77 90.83 90.89 90.53
1250 31 0.068 88.48 89.51 89.54 89.15
1600 32 0.087 86.04 87.05 87.05 86.64
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**OASPL DIRECTIVITY** 97.55 98.65 98.78 98.47

Spectral density is calculated in 3rd-Octave Band

*** Trailing Edge Noise ***

17.81 FT. ARC

Attenuated spectra at 70.0 % Rel. Humidity and 529.0 deg. R Angle from down-stream axis

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</table>

**OASPL DIRECTIVITY** 97.42 98.65 98.78 98.47
3.2.3 File Summary

The input/output files applicable to the TE noise component are numbered similar to those stated earlier for the mixing/scrubbing noise component in Section 3.1.6. The only caveat is that a restart file ‘fort.54” is not generated.

4.0 Code Implementation

Each noise component is packaged with two Fortran codes.

4.1 Obtaining the Source Code

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1) mixing/scrubbing noise
   jsi-mix.f90
   jsi-mix-modules.f90

2) trailing edge noise
   jsi-ten.f90
   jsi-ten-modules.f90

4.2 Creating the Executable

JSI codes are written in FORTRAN-90. The current version runs on a single processor platform. The execution may be achieved in a command mode such as a Unix environment. For example, using an available Intel Fortran compiler, the executable “a.out” is created as:

```
ifort -c jsi-mix-modules.f90
ifort -c jsi-mix.f90
ifort *.o
rm –rf *.o *.mod
```

The last command removes “*.o” and “*.mod” files created during compilation. The executable could be submitted interactively, and with the standard “fort.6” output directed to an arbitrary file “ProgressFile”

```
./a.out > ProgressFile &
```

or, alternatively, the executable may be addressed within a PBS script for queue submission. Code “jsi-mix.f90” represents the main program as well as all associated subroutines, in one package.

The executable for the trailing edge noise component is generated in a similar fashion:

```
ifort -c jsi-ten-modules.f90
ifort -c jsi-ten.f90
ifort *.o
rm –rf *.o *.mod
```
The path to three RANS files is specified within input “jsi-mix.inp” and “jsi-ten.inp” as noted earlier.

### 5.0 Sample Computational Results

Numerical simulations are presented for an aspect ratio 8:1 rectangular jet exhaust with a nearby semi-infinite surface place at standoff $h = 1.90$-in., and length $X_{TE} = 12.0$-in. Table IV details nozzle pressure ratio (NPR), stagnation temperature ratio (NTR), and exhaust Mach number $M_j = U_j/a_j$, and the acoustic Mach number $M_a = U_j/a_c$ at three subsonic conditions.

#### 5.1 Flow Simulations—RANS Solver

Computational fluid dynamic simulations were carried with a commercially available RANS solver, SolidWorks® (SW) (SolidWorks Corporation) (Refs. 5 and 6), using a $k-\varepsilon$ turbulence model. The flow solver employs an automatic (adaptive) gridding methodology that is convenient for jet simulation problems, however the solution needs to be post-processed, and mapped to a user-friendly grid for follow-on applications such as GF calculations in noise prediction. Representative SW results at three set points SP03, SP05 and SP07 (Table IV) are shown in Figure 6 in a stream-wise $y_{1/3}$ plane of symmetry. Each figure shows, from top, normalized mean axial velocity $U/U_j$, turbulent kinetic energy ratio $\kappa^{1/2}/U_j$, static temperature ratio $T/T_\infty$, and normalized turbulent length-scale $\kappa^{3/2}/(\epsilon D_{eq})$, to a distance of $y_1/D_{eq} = 14$ downstream of the jet exit ($D_{eq} = 2.136$-in)). The nearby surface is highlighted (dark line) at $y_3/D_{eq} = 1.04$ below the nozzle geometric center extending to $y_1/D_{eq} = 5.62$.

Simulations are also shown on a span-wise $y_{2/3}$ plane at the trailing edge of a nearby surface, and compared with measurements (Ref. 7) at Mach number of $M = 0.22$. Mean velocity (Figure 7), turbulent kinetic energy TKE (Figure 8), and turbulent length scale (Figure 9), are all normalized to highlight self-similarity across Mach numbers.

Figure 8 shows that predicted TKE levels are slightly higher than measurements on the left. The self-similarity of the turbulent length-scale $\ell_o/D_{eq}$ in Figure 9 shows that normalized time-scale $\tau_o/(D_{eq}/U_j) = (\ell_o/D_{eq})/(\kappa^{0.5}/U_j)$ should exhibit self-similarity as well. This fact is reflected in the source modeling, i.e., Strouhal scaling of the peak spectra for each noise components (Ref. 2).

<table>
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<th>Set Point</th>
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<th>NTR</th>
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<th>$M_a$</th>
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<td>1.0</td>
<td>0.72</td>
<td>0.70</td>
</tr>
<tr>
<td>SP07</td>
<td>1.86</td>
<td>1.0</td>
<td>0.98</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Figure 6.—Mean axial velocity, turbulent kinetic energy, static temperature, and turbulent length-scale in a streamwise plane of symmetry at acoustic Mach numbers $M_a = 0.50$ (top-left); 0.70 (top-right); and 0.90 (bottom) figures.
Figure 7.—Mean flow simulations in a span-wise plane at the TE at acoustic Mach numbers of 0.50 and 0.70, and comparison with measurements (left) at Mach 0.22.

Figure 8.—Turbulent kinetic energy in a span-wise plane at the TE at acoustic Mach numbers of 0.50 and 0.90, and comparison with measurements (left) at Mach 0.22.
5.2 Post Processing of the Mean Flow—Interpolation to Acoustic Grid

Mean flow and turbulence parameters suitable for input to JSI codes require an H-Grid structure. An example was presented earlier (Figure 4 and Figure 5) using an Acoustic Grid with 2 blocks—each block comprised of slices stacked normal to the stream-wise $x_1$ direction as highlighted in Figure 10. A dedicated interpolation routine is essential to the process, and it is crucial to examine the results carefully for possible “iblank” spots where zeros may have been inserted due to numerical failures. Such nodes could be corrected with an average value of the surrounding grid points. Sample mapping output for mean velocity and turbulent kinetic energy is shown in Figure 11. Interpolation outcome on a span-wise plane at the trailing edge of the nearby surface is also shown in Figure 12 at set point 5 (Table IV).

5.3 Acoustic Results

Jet noise spectra are examined below at operating conditions listed in Table IV. Individual noise components, designated as Scrubbing Noise and Trailing Edge Noise, are presented and their sum Total Noise (Analysis) is compared with Measurement (Refs. 8 and 9) at selective number of observer polar angles at azimuth $\phi = 90^\circ$. Results are presented on an arc $R = 17.80$-ft (i.e., $R = 100D_{eq}$) on both sides of
Figure 11.—Interpolated flow—stream-wise plane of symmetry. Mean axial velocity (top), turbulent kinetic energy (bottom) at set point SP05.

Figure 12.—Interpolated flow—span-wise plane at the TE of the nearby surface. Mean axial velocity (left), turbulent kinetic energy (right) at set point SP05.

a nearby surface. Although the predicted TE noise component is symmetric with respect to the edge due to symmetry in the propagator, measurements for the majority of cases are not quite symmetric and exhibit a slightly larger peak on the reflected side of the surface. Turbulent mixing/scrubbing noise component has a greater presence on the reflected side, as expected. Figure 13 to Figure 18 show that the peak in the predicted TE component could differ from measurements by as much as 4 dB due to lack of symmetry in measured data, however, the general trend is in agreement with data across the three Mach numbers. The overall sound pressure level (OASPL) associated with the TE noise component follows a $U^5$ velocity scaling in the current modeling (Ref. 4).

Directivity predictions for the TE noise component as well as the total noise are shown in Figure 19 (bottom)—and are compared with measurements (top figure) at conditions of Table IV. As anticipated, the TE noise component (dashed-line) overwhelms the directivity factor due to its dominant spectral peak level. Only at small angles to the jet axis the mixing noise component contributes significant enough to weight noticeably on the total noise.
Figure 13.—Spectrum on the reflected side of Mach 0.51 jet (SP03-N8ZH19XTE12) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

Figure 14.—As in Figure 13, but on the shielded side.
Figure 15.—Spectrum on the reflected side of Mach 0.72 jet (SP05-N8ZH19XTE12) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

Figure 16.—As in Figure 15, but on the shielded side.
Figure 17.—Spectrum on the reflected side of Mach 0.98 jet (SP07-N8ZH19XTE12) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

Figure 18.—As in Figure 17, but on the shielded side.
Figure 19.—OASPL directivity—shielded side of Mach 0.51, 0.72, and 0.98 rectangular jets (N8ZH19XTE12), measurements (top), predictions (bottom).

References
