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Jet Surface Interaction Noise in a High Aspect Ratio Rectangular Exhaust

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Science Applications International Corporation, Cleveland, Ohio

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Contents

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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 θ is with respect to downstream jet axis, and azimuthal angle ϕ 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.

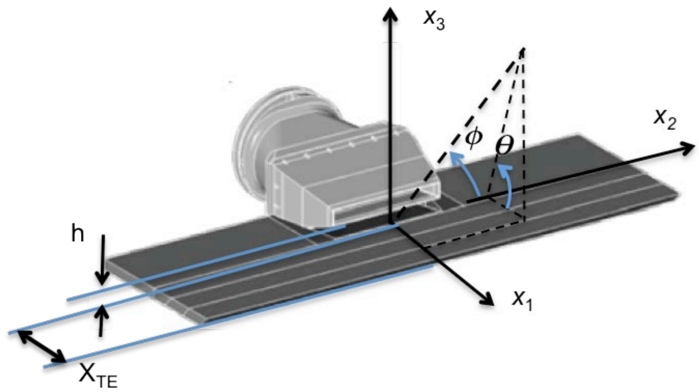

Figure 1.—Geometry—a high aspect ratio rectangular exhaust near a solid surface.

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–ε or a k–ω 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).

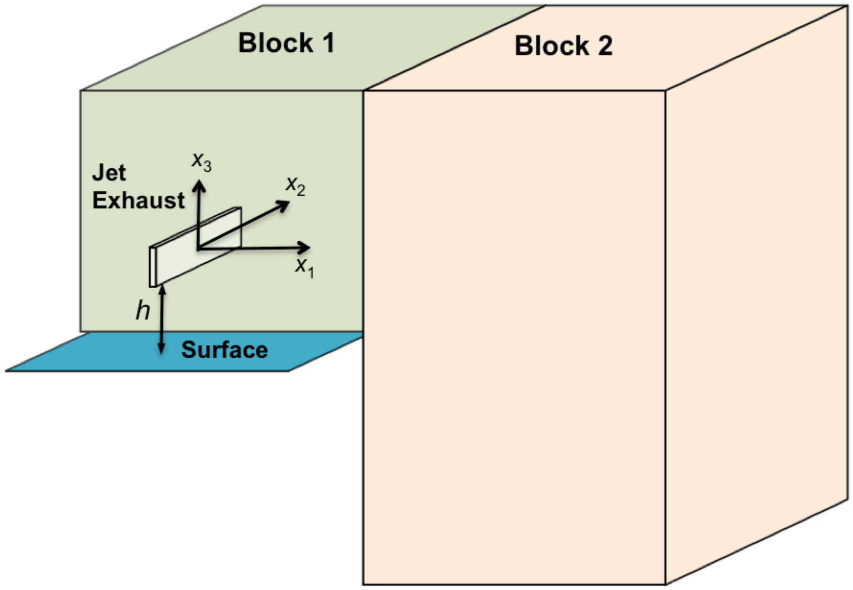

Figure 2.—Example of block structure—rectangular jet exhaust near a flat surface.

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 γ 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) `= Lref(ft), Tinf(R), Pinf(psf),` are deployed to define normalization parameters listed in Table I

$$a_r^2 = \gamma \Re T_r \ , \qquad \rho_r = \frac{p_r}{\Re T_r} \tag{1}$$

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 (`JMAX,KMAX,LMAX`). 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_{eq} denotes the area-equivalent diameter for the rectangular nozzle $\pi D_{eq}^2 / 4 =$Area). Cartesian coordinates $\vec{x}$ and $\vec{y}$ 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

$$\begin{aligned} Q_1 &= \rho / \rho_r \\ Q_2 &= \rho u / (\rho_r a_r) \\ Q_3 &= \rho v / (\rho_r a_r) \\ Q_4 &= \rho w / (\rho_r a_r) \\ Q_5 &= E / (\gamma p_r)\,, \end{aligned} \tag{2}$$

and the mean static pressure p is evaluated as

$$\frac{p}{\gamma p_r} = (\gamma - 1)\left(Q_5 - \frac{1}{2} \frac{Q_2^2 + Q_3^2 + Q_4^2}{Q_1} \right) \tag{3}$$

TABLE I.—NORMALIZING FACTORS

Property	Notation	Normalizing parameter	JSI variable
Coordinates	X, Y, Z	L_r (ft)	`Lref`
Temperature	T	T_r (R)	`Tinf`
Velocity component	u, v, w	a_r (ft/s^2)	`Aref`
Pressure	p	$\gamma\, p_r$ (lbf/ ft^2)	`Gamma*Pinf`
Density	ρ	ρ_r (Slug/ft^3)	`Rhoref`
Time	t	L_r / a_r (sec)	
Total internal energy/unit volume	E	$\rho_r\ a_r^2$ (lbf/ft^2)	
Turbulent kinetic energy	k	-	
Turbulent dissipation rate	ε	-	
Omega	ω	-	

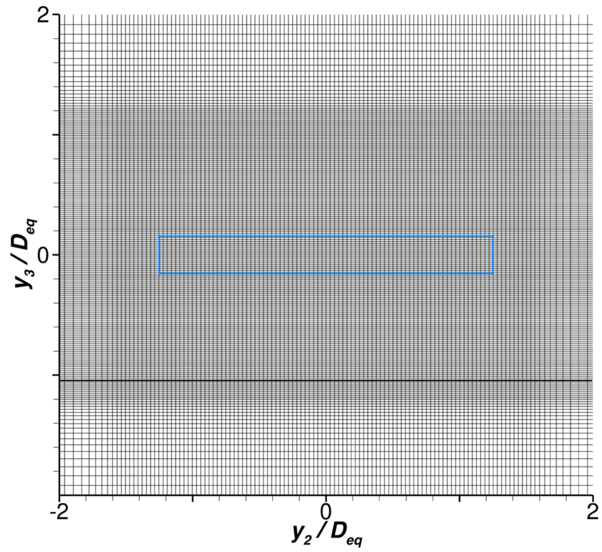

Figure 3.—Acoustic grid in a span-wise plane.

The turbulence file (QT) consists of two variables. An input FLAG "`TurbModel`" identifies each variable as either (k and ε) or (k and ω). For convenience, the turbulence variables are provided in dimensional form: k (ft^2/s^2), ε (ft^2/s^3), and ω (1/s). Conversion from ω to ε is carried out according to

$$\varepsilon = 0.90 \times k \times \omega . \tag{4}$$

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

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 (α,β) are a pair of empirical constants and U is the local mean axial velocity. The Strouhal frequency is $\mathrm{St} = f\,D_j/U_j$ 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

$$10\log_{10}\left(U_J D_J^{-1}\overline{p^2}\Big/p_o^2\right) \tag{5}$$

and the 1/3-octave predictions are

$$10\log_{10}\left(BW\times\overline{p^2}\Big/p_o^2\right) \tag{6}$$

where the bandwidth at frequency f is

$$BW = f\times(2^{1/6}-2^{-1/6}) \tag{7}$$

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 $p_o = 0.0002$ $\mu bar = 4.17\times10^{-7}$ 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.

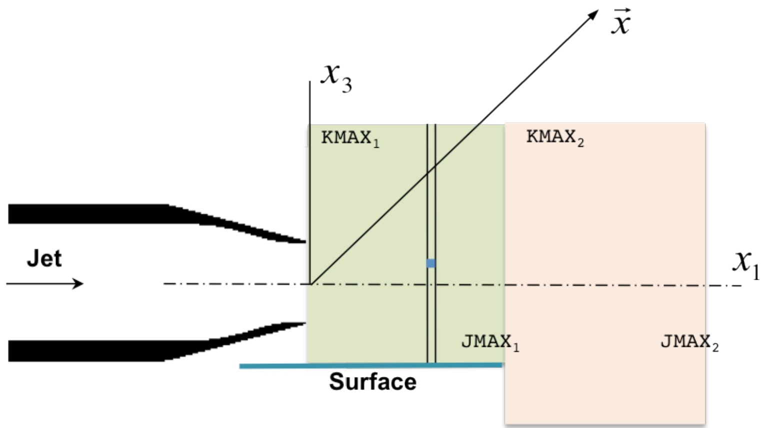

Figure 4.—Input parameters—stream-wise plane.

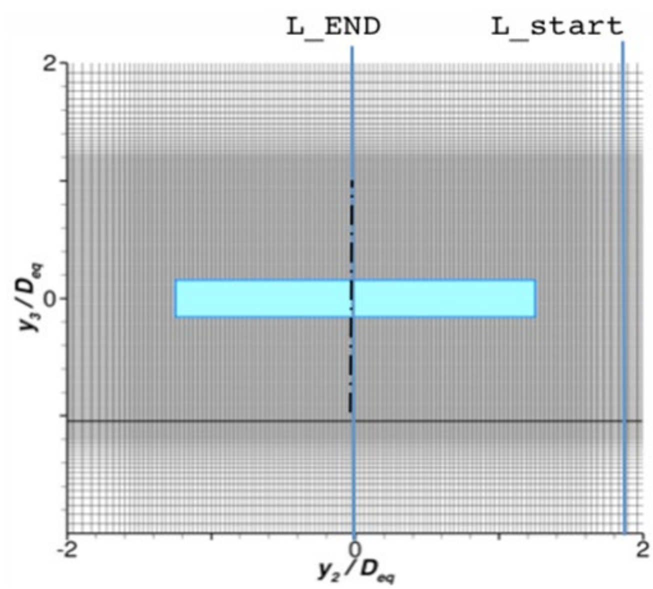

Figure 5.—Input parameters—span-wise plane.

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 x_1x_3 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 (`Pinf, Tinf`), and `Lref` is the reference length. Other parameters of interest utilized in presentation of the output are Strouhal number range `(St_min, St_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 (`Tinf`) 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, ρ, 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_{TE} = 12.0-in. Input file applicable to the shielded side is slightly different and will be discussed in Section 3.1.4.

```
$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
```

```
      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)=  6.680269272284703E-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:
   o Freq Range     (f)   =      160  100000 (Hz)
   o Nozzle Minor Side(a) =       0.5580E-01 (ft)
   o Exit Velocity (U)    =       0.1028E+04 (fps)
   o Strouhal Range       =   0.8686E-02  0.5429E+01

   o          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#           2  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
  Freq  Band      St      40      60      90     120
   160    22   0.009   67.94   67.36   65.94   64.69
   200    23   0.011   71.20   70.52   68.99   67.62
   250    24   0.014   74.27   73.47   71.79   70.28
   315    25   0.017   77.21   76.25   74.39   72.73
   400    26   0.022   79.99   78.82   76.76   74.93
   500    27   0.027   82.33   80.92   78.68   76.68
   630    28   0.034   84.50   82.82   80.39   78.25
   800    29   0.043   86.49   84.51   81.91   79.63
  1000    30   0.054   88.15   85.88   83.14   80.74
  1250    31   0.068   89.66   87.08   84.22   81.74
  1600    32   0.087   91.14   88.24   85.31   82.70
  2000    33   0.109   92.27   89.17   86.19   83.46
  2500    34   0.136   93.24   90.02   86.95   84.10
```

```
  3150    35   0.171   94.07   90.85   87.53   84.59
  4000    36   0.217   94.64   91.51   88.16   85.20
  5000    37   0.271   94.55   91.77   88.33   85.02
  6300    38   0.342   94.47   92.11   88.24   84.93
  8000    39   0.434   94.29   91.97   88.14   84.67
 10000    40   0.543   93.92   91.99   87.90   84.13
 12500    41   0.679   93.37   91.32   87.40   83.74
 16000    42   0.869   92.52   90.93   86.77   82.99
 20000    43   1.086   91.66   90.41   86.15   82.26
 25000    44   1.357   90.74   89.93   85.62   81.42
 31500    45   1.710   89.68   89.10   84.65   80.60
 40000    46   2.171   88.50   88.32   83.59   79.85
 50000    47   2.714   87.44   87.58   81.70   78.91
 63000    48   3.420   86.25   86.69   82.19   77.97
 80000    49   4.343   85.05   85.85   81.17   77.01
100000    50   5.429   83.96   84.88   80.43   76.07
 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
  Freq  Band      St      40      60      90     120
   160    22   0.009   67.92   67.34   65.93   64.68
   200    23   0.011   71.18   70.51   68.97   67.60
   250    24   0.014   74.25   73.45   71.77   70.26
   315    25   0.017   77.19   76.23   74.37   72.71
   400    26   0.022   79.96   78.79   76.73   74.90
   500    27   0.027   82.29   80.88   78.64   76.65
   630    28   0.034   84.44   82.76   80.33   78.19
   800    29   0.043   86.41   84.43   81.83   79.55
  1000    30   0.054   88.03   85.76   83.01   80.62
  1250    31   0.068   89.48   86.90   84.04   81.55
  1600    32   0.087   90.85   87.95   85.02   82.41
  2000    33   0.109   91.82   88.72   85.74   83.01
  2500    34   0.136   92.55   89.32   86.25   83.41
  3150    35   0.171   92.98   89.76   86.44   83.49
  4000    36   0.217   92.88   89.75   86.41   83.45
  5000    37   0.271   91.82   89.04   85.61   82.29
  6300    38   0.342   90.17   87.81   83.93   80.63
  8000    39   0.434   87.41   85.09   81.26   77.78
 10000    40   0.543   83.27   81.34   77.26   73.49
 12500    41   0.679   76.98   74.93   71.01   67.35
 16000    42   0.869   66.34   64.75   60.60   56.82
 20000    43   1.086   52.17   50.92   46.66   42.77
 25000    44   1.357   32.14   31.34   27.03   22.84
 31500    45   1.710    5.13    4.73    3.01    3.01
 40000    46   2.171    3.01    3.01    3.01    3.01
 50000    47   2.714    3.01    3.01    3.01    3.01
 63000    48   3.420    3.01    3.01    3.01    3.01
 80000    49   4.343    3.01    3.01    3.01    3.01
100000    50   5.429    3.01    3.01    3.01    3.01
 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 x_1x_2 surface, i.e., a negative sign multiplies transverse coordinate x_3 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 x_3 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

   Unattenuated spectra /  Angle from down-stream axis
  Freq  Band      St      40      60      90     120
   160    22   0.009   62.00   61.42   60.01   58.75
   200    23   0.011   65.26   64.59   63.04   61.67
   250    24   0.014   68.31   67.53   65.84   64.32
   315    25   0.017   71.24   70.31   68.43   66.75
   400    26   0.022   73.99   72.86   70.79   68.92
   500    27   0.027   76.29   74.95   72.68   70.66
   630    28   0.034   78.39   76.83   74.37   72.19
   800    29   0.043   80.30   78.49   75.85   73.52
  1000    30   0.054   81.84   79.82   77.04   74.57
  1250    31   0.068   83.17   80.97   78.05   75.45
  1600    32   0.087   84.37   82.06   78.98   76.22
  2000    33   0.109   85.18   82.87   79.62   76.69
  2500    34   0.136   85.68   83.49   80.06   76.94
  3150    35   0.171   85.85   83.91   80.26   76.96
  4000    36   0.217   85.66   84.08   80.20   76.72
  5000    37   0.271   85.15   83.99   79.92   76.30
  6300    38   0.342   84.31   83.67   79.43   75.69
  8000    39   0.434   83.20   83.13   78.75   74.93
 10000    40   0.543   81.99   82.48   78.01   74.13
 12500    41   0.679   80.68   81.73   77.19   73.27
 16000    42   0.869   79.17   80.81   76.22   72.28
 20000    43   1.086   77.79   79.93   75.32   71.35
 25000    44   1.357   76.44   79.02   74.39   70.41
 31500    45   1.710   75.10   78.06   73.41   69.43
 40000    46   2.172   73.75   77.05   72.39   68.40
```

```
 50000    47   2.715   72.54   76.09   71.43   67.44
 63000    48   3.421   71.31   75.10   70.43   66.44
 80000    49   4.344   70.06   74.07   69.40   65.41
100000    50   5.430   68.94   73.10   68.43   64.44
 OASPL DIRECTIVITY     95.71   94.83   91.03   87.77
```

3.1.6 File Summary

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

TABLE II.—INPUT FILES

Unit	Description
10	Namelist file "*jsi-mix*"—defines input parameters
27	Unformatted grid file—specify file name in *jsi-mix*
28	Unformatted Q file—specify file name in *jsi-mix*
29	Unformatted turbulence file—specify file name in *jsi-mix*
53	Restart file *fort.53* (see output unit 54)

TABLE III.—OUTPUT FILES

Unit	Description
6	Formatted output shows—calculation progress
54	Formatted restart file *fort.54*—should be copied to *fort.53* when `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., $\partial U/\partial y_3 \to 0$)). 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 `j_start=49` is assigned to the location of the integration plane (selected as two grid points upstream of the surface TE, `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"

```
$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 --------------------

  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 =   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
 ------------------------------------
 GFILE 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
```

2000	33	0.109	83.06	84.06	84.04	83.61
2500	34	0.136	79.52	80.51	80.47	80.04
3150	35	0.171	75.41	76.39	76.35	75.91
4000	36	0.217	70.84	71.81	71.76	71.32
5000	37	0.271	66.36	67.33	67.28	66.83
6300	38	0.342	61.59	62.56	62.50	62.05
8000	39	0.434	56.56	57.53	57.47	57.02
10000	40	0.543	51.82	52.78	52.72	52.27
12500	41	0.679	47.03	48.00	47.93	47.48
16000	42	0.869	41.71	42.68	42.62	42.16
20000	43	1.086	36.89	37.86	37.79	37.34
25000	44	1.357	32.06	33.03	32.96	32.51
31500	45	1.710	27.05	28.02	27.96	27.50
40000	46	2.172	21.87	22.84	22.77	22.32
50000	47	2.715	17.03	18.00	17.93	17.48
63000	48	3.421	12.01	12.98	12.92	12.46
80000	49	4.344	6.83	7.79	7.73	7.28
100000	50	5.430	1.98	2.95	2.89	2.43
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			
Freq	Band	St	40	60	90	120
160	22	0.009	72.95	74.28	74.73	74.66
200	23	0.011	76.46	77.77	78.20	78.11
250	24	0.014	79.79	81.08	81.47	81.36
315	25	0.017	82.96	84.22	84.56	84.42
400	26	0.022	85.81	87.03	87.32	87.13
500	27	0.027	87.94	89.11	89.35	89.11
630	28	0.034	89.43	90.56	90.73	90.45
800	29	0.043	90.04	91.13	91.24	90.92
1000	30	0.054	89.65	90.71	90.77	90.41
1250	31	0.068	88.29	89.33	89.36	88.97
1600	32	0.087	85.75	86.76	86.75	86.35
2000	33	0.109	82.62	83.61	83.59	83.17
2500	34	0.136	78.83	79.81	79.78	79.35
3150	35	0.171	74.32	75.30	75.25	74.81
4000	36	0.217	69.09	70.06	70.01	69.56
5000	37	0.271	63.64	64.61	64.55	64.11
6300	38	0.342	57.29	58.26	58.20	57.75
8000	39	0.434	49.68	50.65	50.59	50.14
10000	40	0.543	41.17	42.13	42.07	41.62
12500	41	0.679	30.64	31.61	31.54	31.09
16000	42	0.869	15.54	16.50	16.44	15.99
20000	43	1.086	0.00	0.00	0.00	0.00
25000	44	1.357	0.00	0.00	0.00	0.00
31500	45	1.710	0.00	0.00	0.00	0.00
40000	46	2.172	0.00	0.00	0.00	0.00
50000	47	2.715	0.00	0.00	0.00	0.00
63000	48	3.421	0.00	0.00	0.00	0.00
80000	49	4.344	0.00	0.00	0.00	0.00
100000	50	5.430	0.00	0.00	0.00	0.00
OASPL DIRECTIVITY			97.42	98.52	98.66	98.35

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 ration (NTR), and exhaust Mach number $M_j = U_j/a_j$, and the acoustic Mach number $M_a = U_j/a_\infty$ 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–ε 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_1y_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_∞, and normalized turbulent length-scale $\kappa^{3/2}/(\varepsilon D_{eq})$, 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_2y_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 ℓ_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 IV.—SET POINT CONDITIONS

Set Point	*NPR*	*NTR*	M_j	M_a
SP03	1.19	1.0	0.51	0.50
SP05	1.42	1.0	0.72	0.70
SP07	1.86	1.0	0.98	0.90

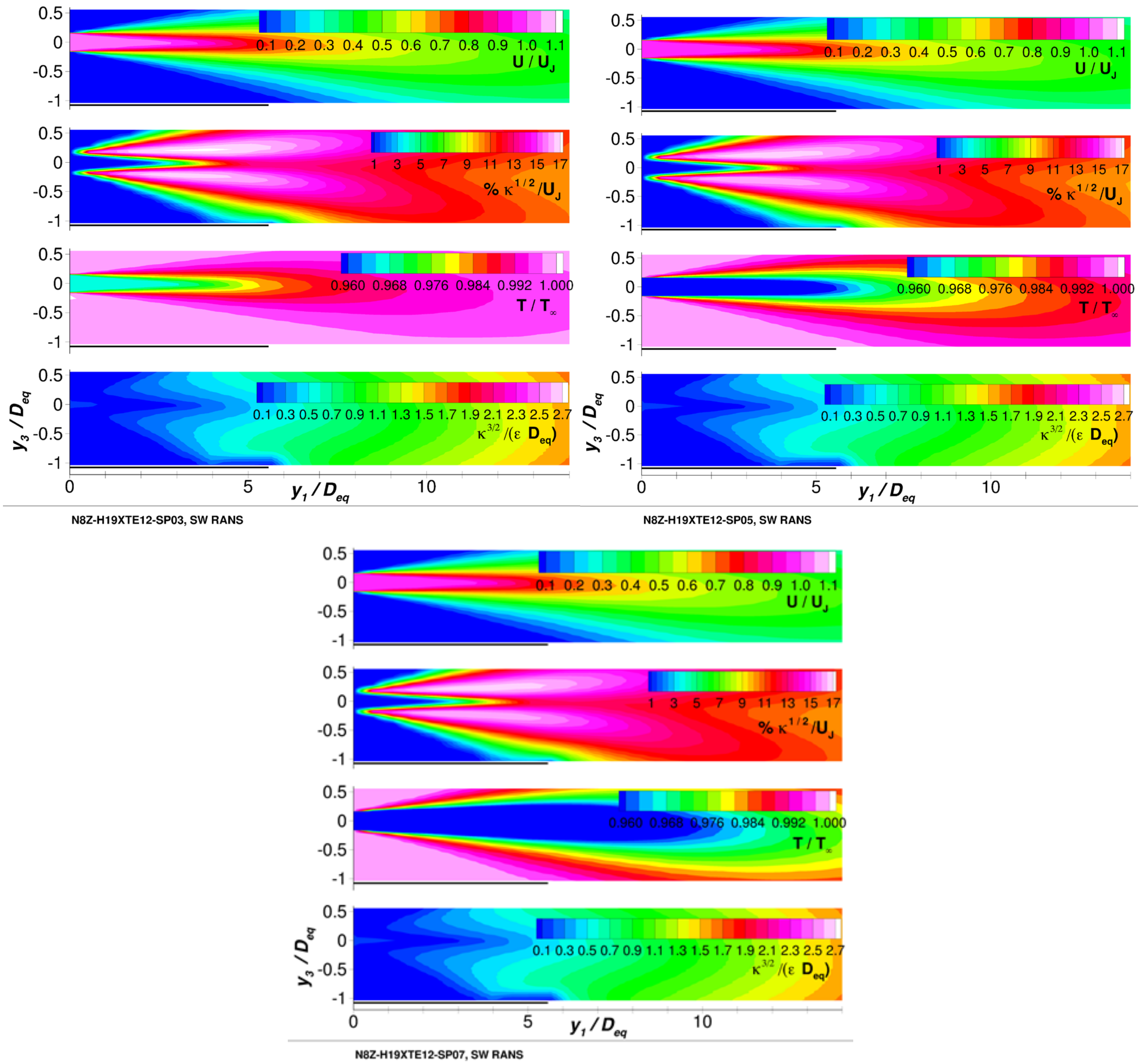


Figure 6.—Mean axial velocity, turbulent kinetic energy, static temperature, and turbulent length-scale in a stream-wise plane of symmetry at acoustic Mach numbers $M_a = 0.50$ (top-left); 0.70 (top-right); and 0.90 (bottom) figures.

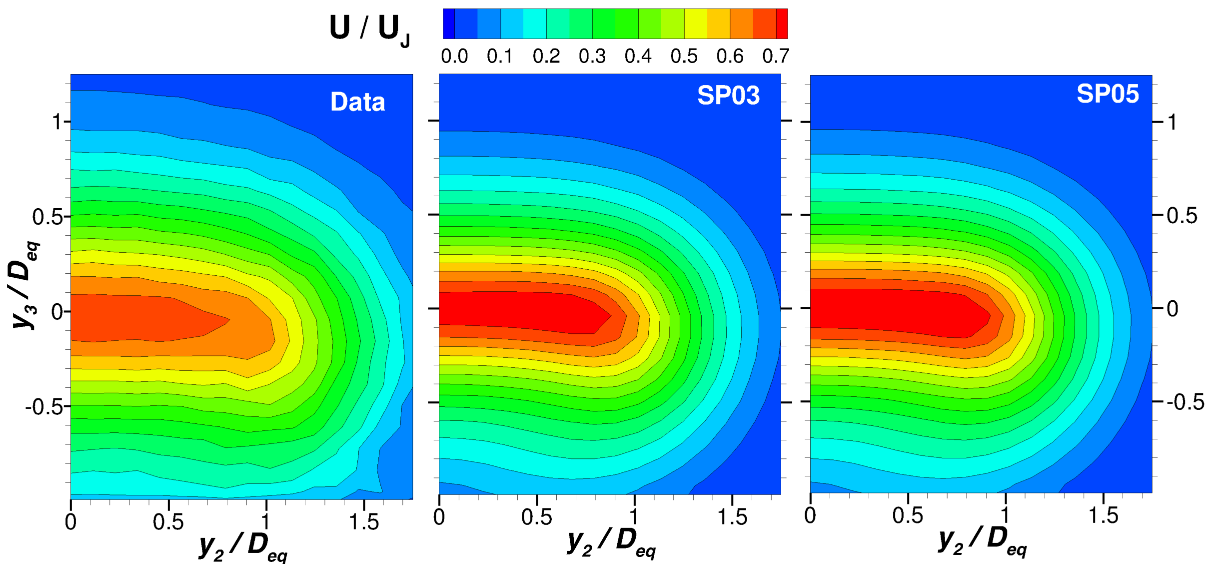


Figure 7.—Mean flow simulations in a span-wise plane at the TE at acoustic Mach numbers of 0.50 and 0.70, and comparison with measurements (left) at Mach 0.22.

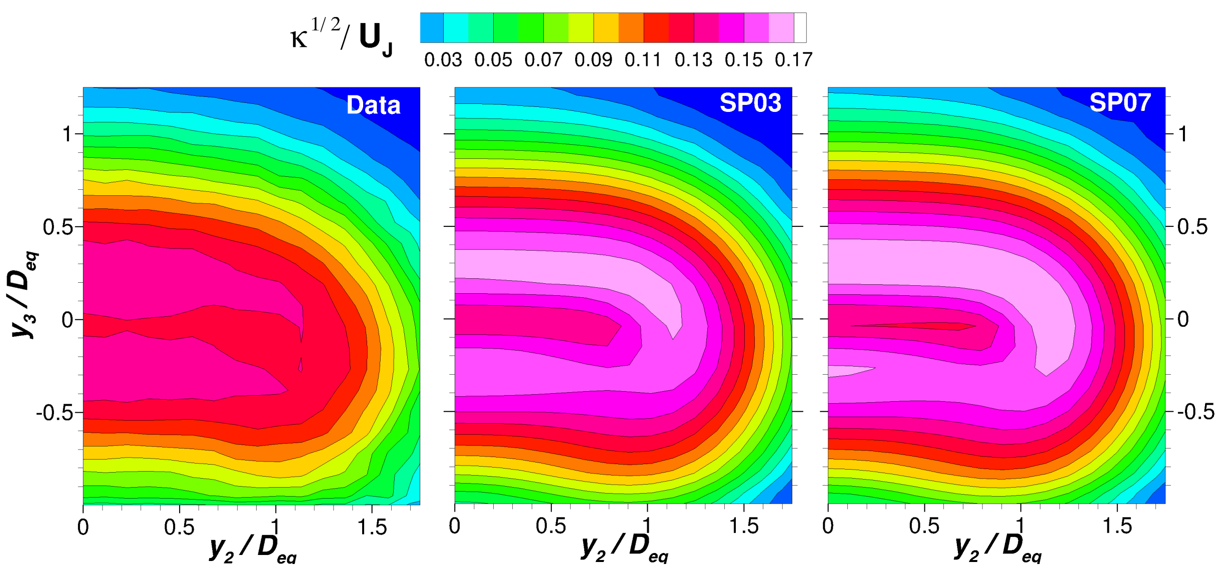


Figure 8.—Turbulent kinetic energy in a span-wise plane at the TE at acoustic Mach numbers of 0.50 and 0.90, and comparison with measurements (left) at Mach 0.22.

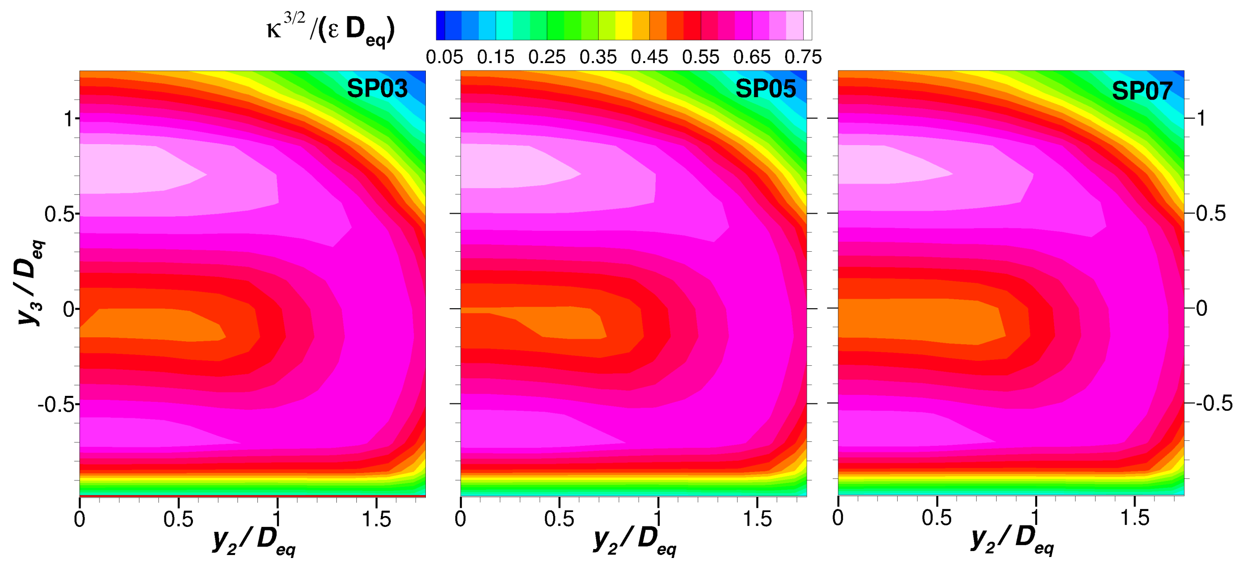


Figure 9.—Turbulent length-scale in a span-wise plane at the TE at M_a = 0.50, 0.70, and 0.90.

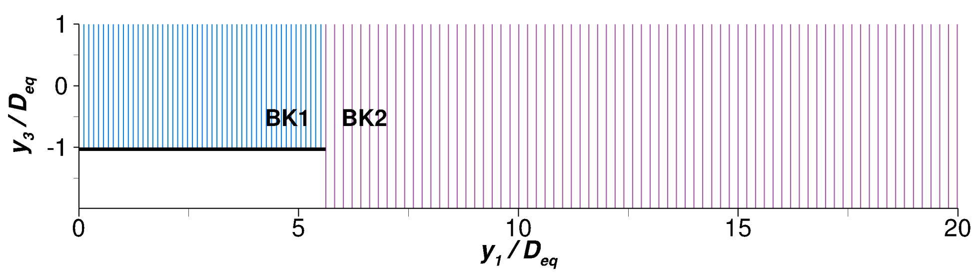


Figure 10.—Stream-wise interpolation slices—acoustic grid.

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 ϕ = 90°. Results are presented on an arc R = 17.80-ft (i.e., R = 100D_{eq}) on both sides of

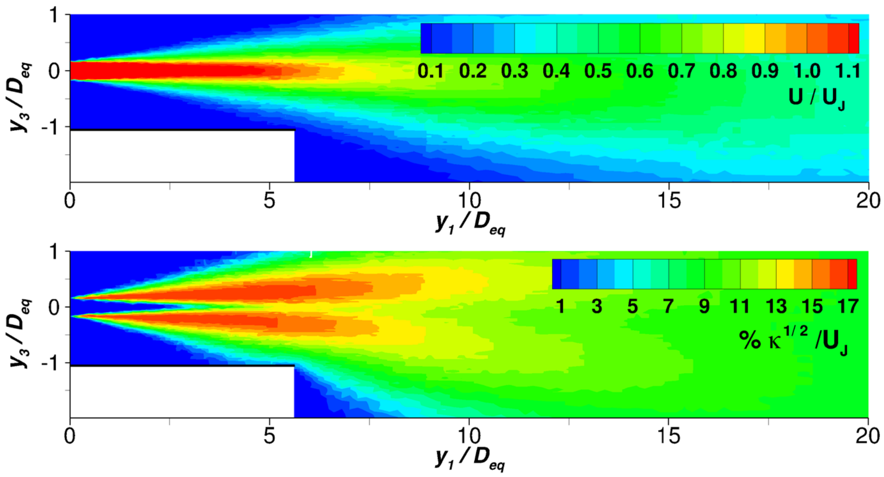


Figure 11.—Interpolated flow—stream-wise plane of symmetry. Mean axial velocity (top), turbulent kinetic energy (bottom) at set point SP05.

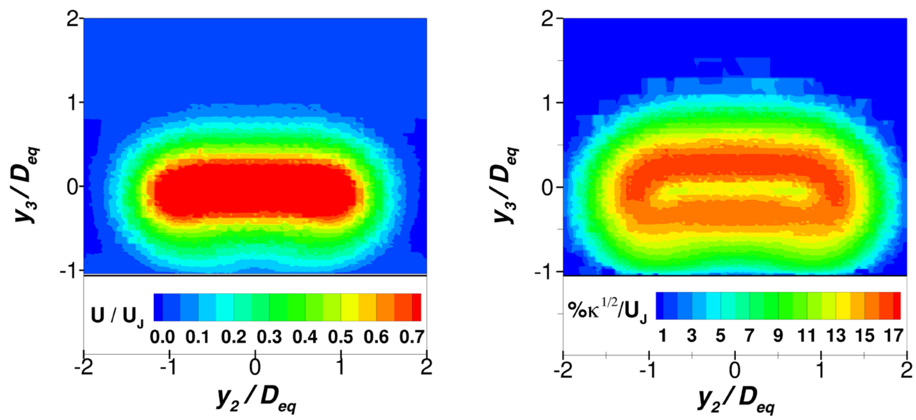


Figure 12.—Interpolated flow—span-wise plane at the TE of the nearby surface. Mean axial velocity (left), turbulent kinetic energy (right) at set point SP05.

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.

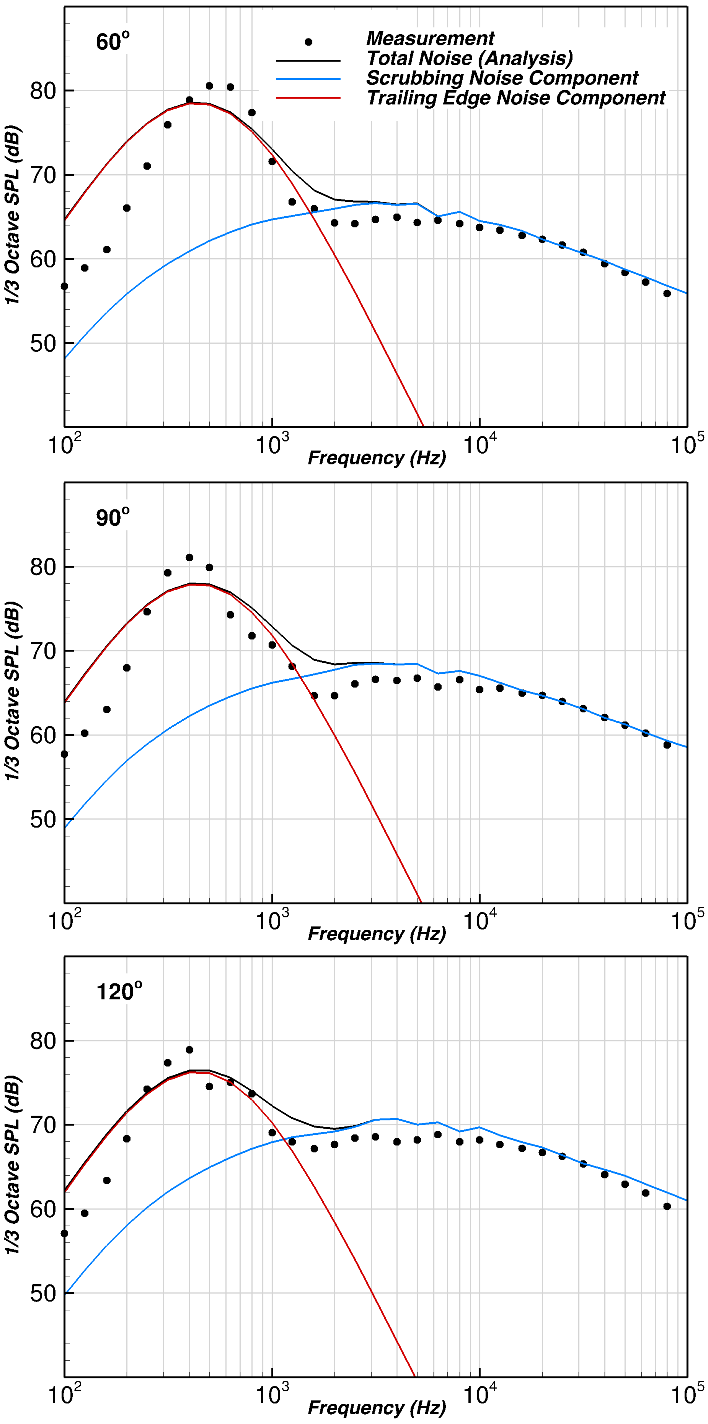


Figure 13.—Spectrum on the reflected side of Mach 0.51 jet (*SP03-N8ZH19XTE12*) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

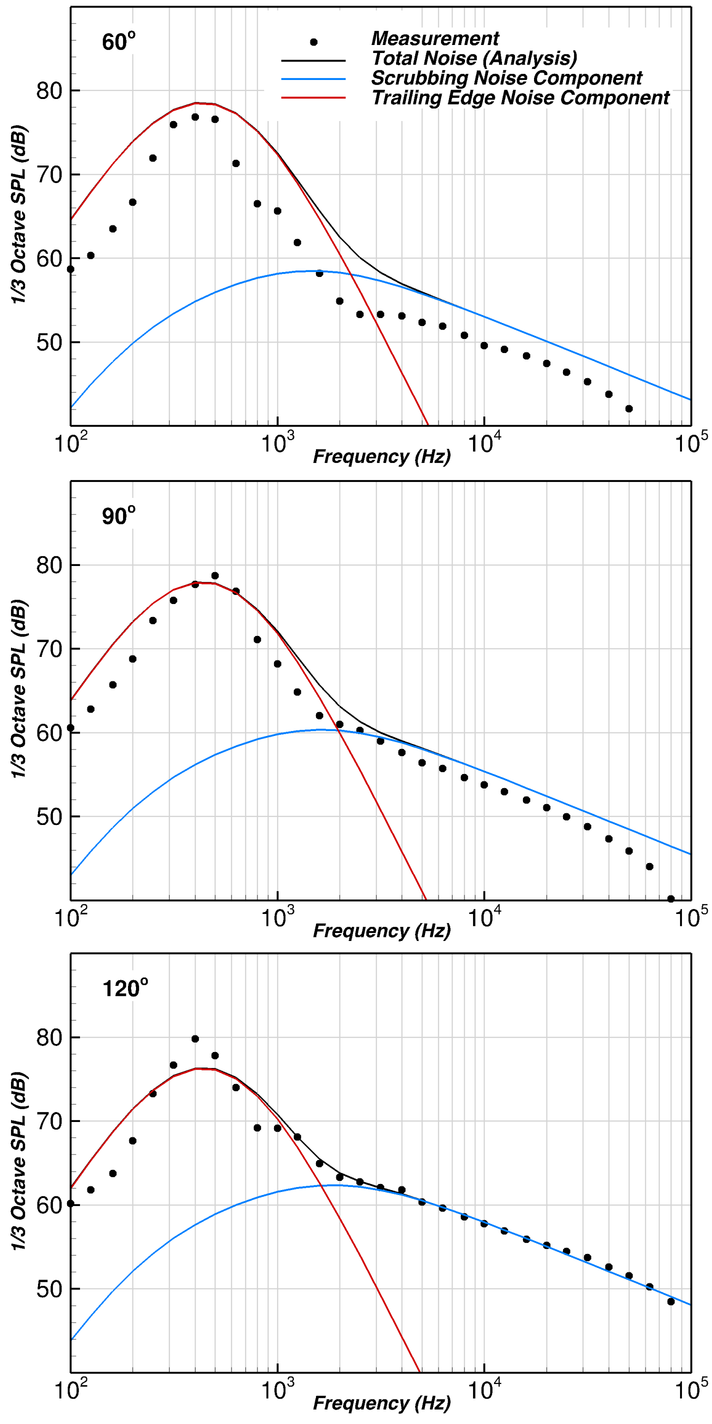


Figure 14.—As in Figure 13, but on the shielded side.

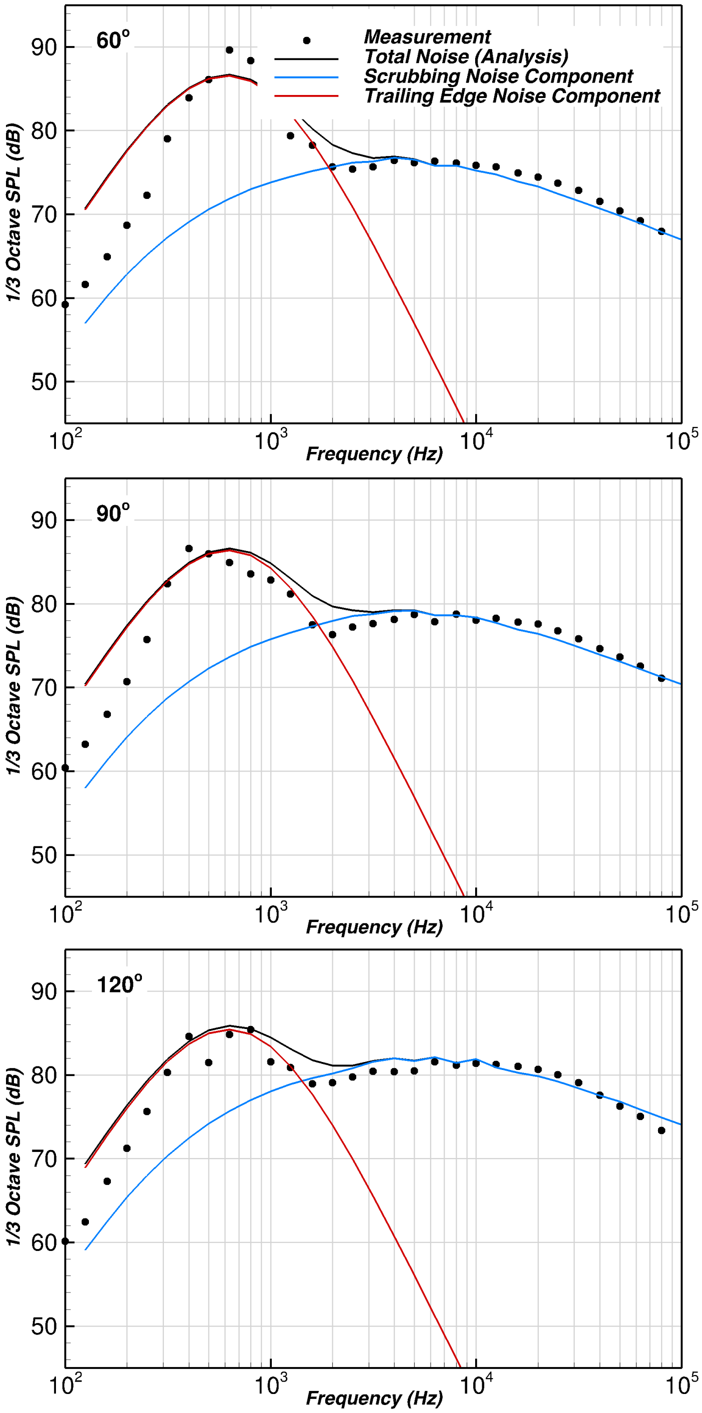


Figure 15.—Spectrum on the reflected side of Mach 0.72 jet (*SP05-N8ZH19XTE12*) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

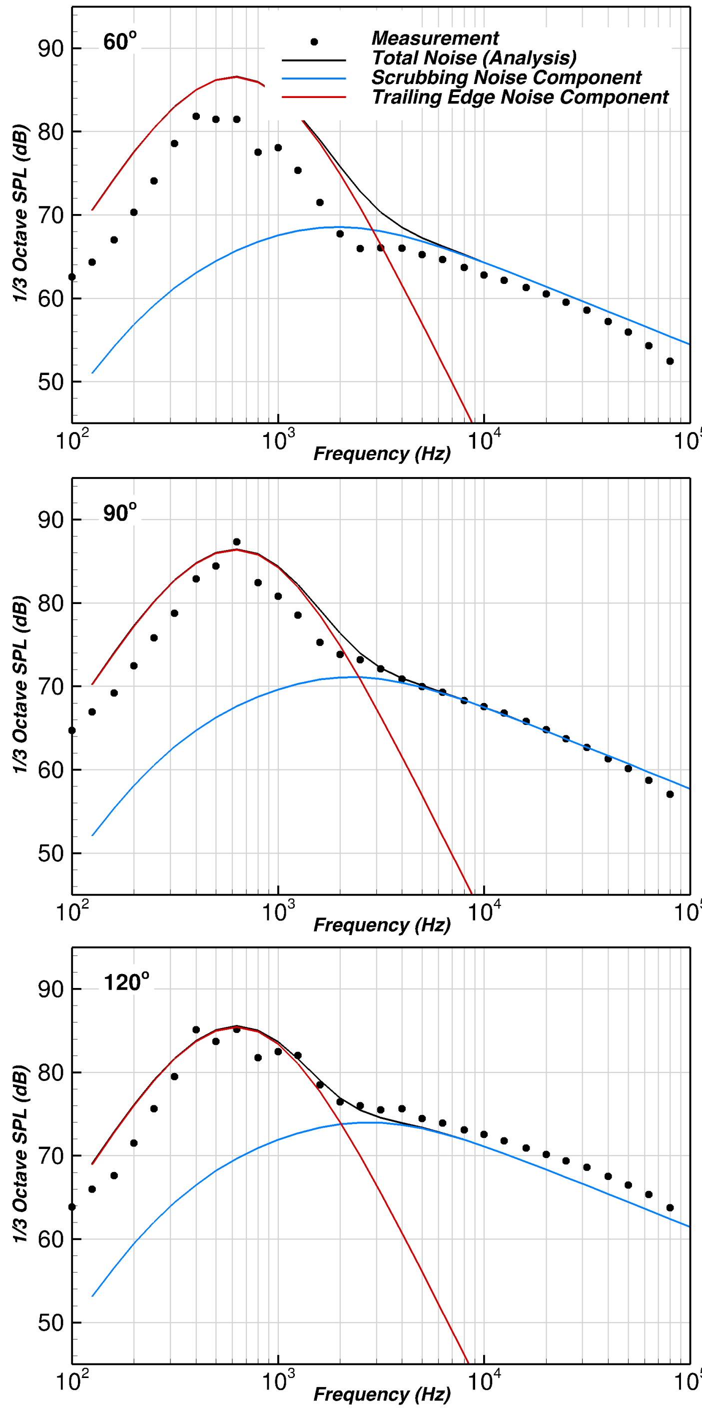


Figure 16.—As in Figure 15, but on the shielded side.

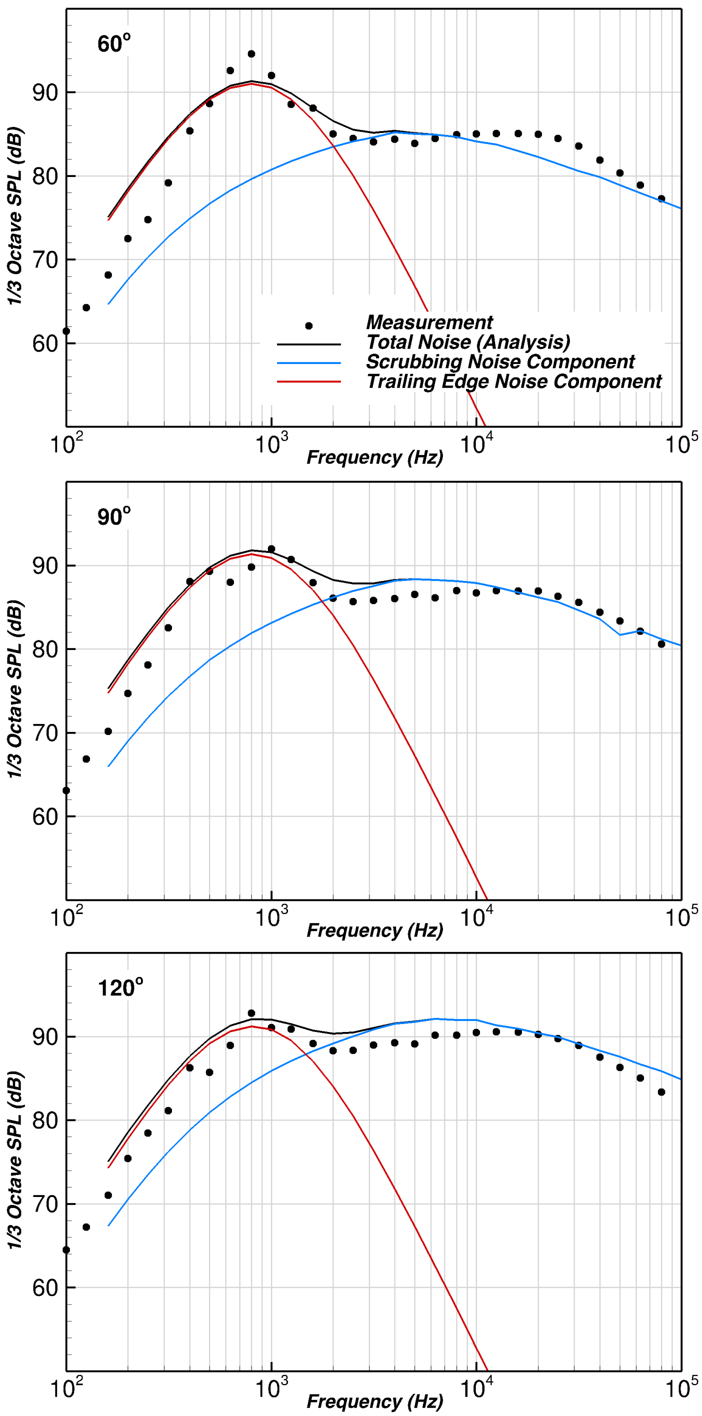


Figure 17.—Spectrum on the reflected side of Mach 0.98 jet (SP07-N8ZH19XTE12) at inlet polar angles of 60°, 90°, and 120°: Jet mixing/scrubbing noise (blue), TE noise (red), total predicted (dark line), measured data for total noise (symbol).

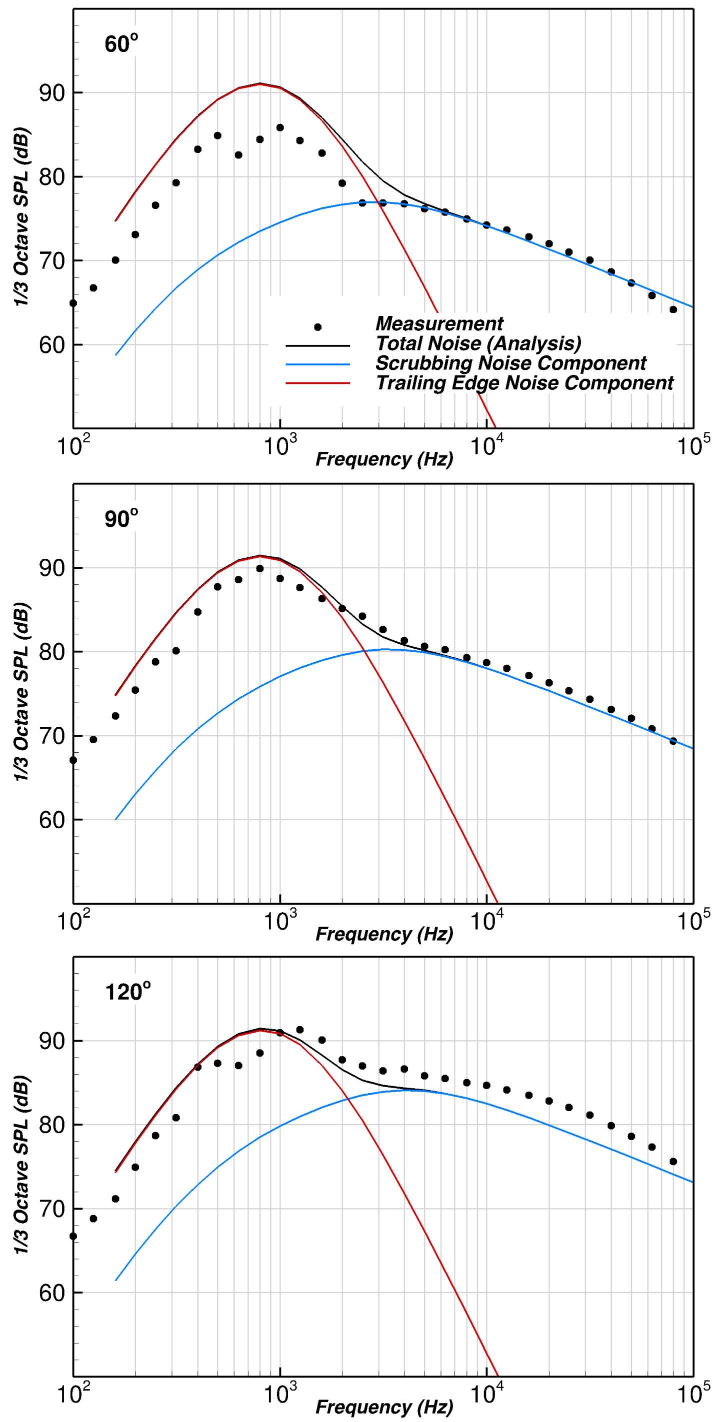
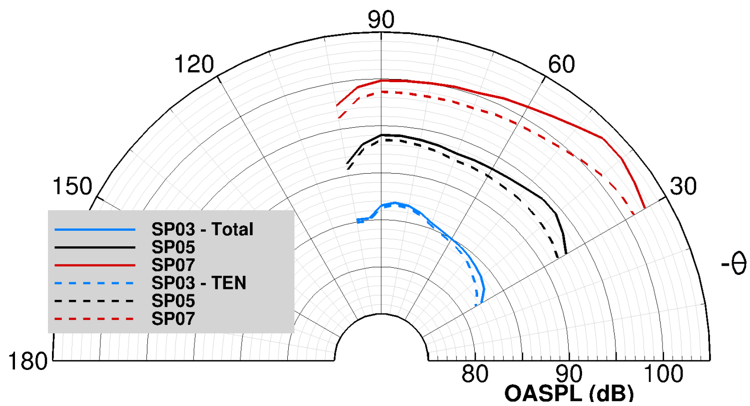


Figure 18.—As in Figure 17, but on the shielded side.



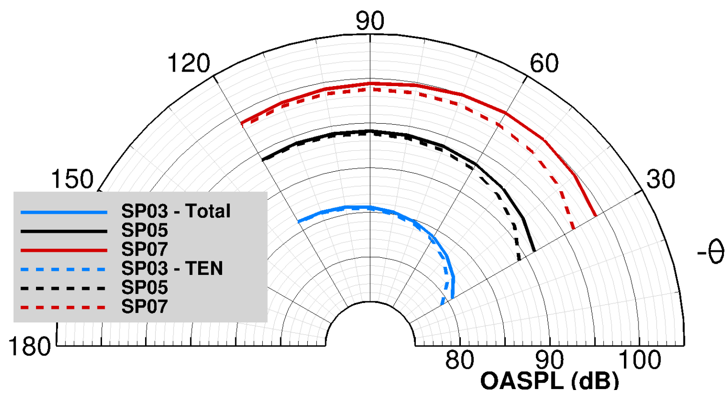


Figure 19.—OASPL directivity—shielded side of Mach 0.51, 0.72, and 0.98 rectangular jets (*N8ZH19XTE12*), measurements (top), predictions (bottom).

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