NASA/TM—2009-213827/PART2

Prediction of Turbulence-Generated Noise in Unheated Jets

Part 2: JeNo Users' Manual (Version 1.0)

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1.0 Getting Acoustics Predictions From JeNo

1.1 Overview

JeNo is a Fortran90 computer code that calculates the far-field sound spectral density produced by axisymmetric jets at a user specified observer location and frequency range. The user must provide a structured computational grid and a mean flow solution from a Reynolds-Averaged Navier Stokes (RANS) code as input. Turbulence kinetic energy and its dissipation rate from a k-ε or k-Ω turbulence model must also be provided.

JeNo is a research code, and as such, its development is ongoing. The goal is to create a code that is able to accurately compute far-field sound pressure levels for jets at all observer angles and all operating conditions. In order to achieve this goal, current theories must be combined with the best practices in numerical modeling, all of which must be validated by experiment. Since the acoustic predictions from JeNo are based on the mean flow solutions from a RANS code, accurate acoustic predictions hinge on accurate aerodynamic predictions. This is why acoustic source modeling, turbulence modeling, together with the development of advanced measurement systems are the leading areas of research in jet noise research at NASA Glenn.

Currently JeNo has been validated for unheated axisymmetric jets [1,2,3] at subsonic and shock-free supersonic conditions. While the current version of JeNo could be used to calculate sound from jets at high Mach numbers, it is noted that accuracy of the predictions is best at observer inlet angles less than 130° when the acoustic Mach number (U_J/a_∞) exceeds 1.0. As the jet acoustic Mach number grows supersonic, near-axis predictions become increasingly tenuous due to the instability-associated noise, which is believed to be responsible for the peak noise directivity of supersonic jets at shallow angles. A detailed investigation of the parallel Green's function indicates that jet spread may also be a factor at shallow angles. *This is the subject of continuing research, as is the ability to predict sound for hot jets.* While the fluctuations in the momentum flux are attributed to the quadrupole-type sources in the classical Acoustic Analogy, Lilley argues that the fluctuations in the pressure/density term that appear in Lighthill's stress tensor become the dominant source of noise in heated jets [4]. Unfortunately, the limited level of information available through a RANS solution requires careful examination of this source term and its turbulence statistics in a physics-based modeling approach.

In calculating the mean flow and turbulence, recommendations will be made concerning the topology of the structured grids, which could simplify the process of preparing the input for JeNo. It is recognized, though, that it may not always be possible to meet these recommendations. In particular, mean flow solutions obtained on unstructured grids must be mapped onto a structured grid suitable for these noise calculations. This must be done externally with appropriate 2D interpolation routines. Efforts have been made to make the source code modular to facilitate improvements, and to aid users in tailoring the code to handle specific cases, which may differ from the examples provided here.

1.2 JeNo Installation Guide

1.2.1 Obtaining the Source Code

The code is available to all US citizens who can access the NASA Glenn Software Repository. You will be asked to complete and return a request form. If your request is approved, you will be notified via e-mail within 2 weeks with instructions on how to download the code. Links to the Repository are available from the NASA Glenn Acoustics Branch Website:

http://www.grc.nasa.gov/WWW/Acoustics/analysis/support/jetnoise.htm

And the direct link to NASA Glenn Software Repository is:

https://technology.grc.nasa.gov/software/

1.2.2 Creating the Executable

JeNo is coded in Fortran90. The current version is written for a single processor platform. The parallel processing alternative should become available in the near future.

The code consists of 59 modules, plus a *Makefile* routine. All modules (and *Makefile*) are archived into a *tarfile*. Once the *tarfile* is extracted, Fortran modules are compiled into an executable following the instructions provided in the *Makefile*. For example, on an SGI platform

```
make build_sgi
```

creates the executable `jeno_2d`.

The "*.o" and "*.mod" files created during the compilation may be removed using command

```
make clean
```

1.2.3 Obtaining the Wind Code and Tools

Wind is distributed by the NPARC Alliance. Information about obtaining the Wind Code is provided from the Wind website http://www.grc.nasa.gov/WWW/winddocs/install/index.html

The Wind code homepage is: *http://www.grc.nasa.gov/WWW/winddocs/index.html*

1.2.4 Data-Format Issues

The unformatted CFD solution files need to meet the machine requirements. Situations may require a conversion of unformatted data between the so-called `big-endian` (64 bit architectures) and the `little-endian` (32 bit architectures).

1.3 Mean Flow Computation Details

It is recognized that significant effort may be spent to obtain mean flow solutions for any given jet prior to generating the acoustic predictions from JeNo. A number of factors should be kept in mind when calculating the mean flow solution. This may simplify the preparation of the JeNo input files significantly. General recommendations are given here, and more specific details are discussed in the two Tutorial cases. JeNo expects to read three files from the mean flow calculation: a grid file, a solution file, and a turbulence file.

1.3.1 Grid File Recommendations

Currently, JeNo is customized to read a single-block structured H-grid originating at the nozzle exit plane(s), Figure 1. It should be a Plot3D, unformatted, 2D, multiblock file (with the number of grid blocks equal to 1). Ideally axial gridlines should be normal to the flow direction. By constructing the grid so that there is a block boundary at the nozzle exit plane, and ensuring that each of the blocks downstream of the nozzle are point-to-point matched without overlap, multiblock grids created to accelerate convergence of the mean flow solution can be combined into single blocks. Currently, the user must create the single block grid by either using utilities that may accompany their Reynolds-Averaged Navier-Stokes solver or by writing a stand-alone program.

The grid created for the 2 inch Acoustic Reference Nozzle subsonic validation case extended 4 nozzle diameter upstream of the nozzle exit plane, 25 diameters radially outward, and 40 diameters downstream. For the Mach 1.5 single stream validation case, the computational grid extended 5 diameters upstream of the nozzle exit plane, 20 diameters radially outward, and 50 diameters downstream. While grid is needed upstream of the nozzle exit plane for the mean flow calculation, only the portion of the RANS solution downstream of the nozzle exit plane is used for the JeNo noise calculations. It must also be noted that there must not be any solid surface obstructions in the jet plume grid used for JeNo noise calculations. These grid requirements are imposed since the Green's Function calculations assume that there are no physical barriers separating the source and the observer.

For dual stream nozzles with staggered exit planes and centerbodies, such as the one described in the second Tutorial (Figure 11), creation of the single block grid file is more complicated. It is still recommended that the block boundaries be coincident with the nozzle exit planes, and that the blocks downstream of the nozzles be point-to-point matched without overlap. However, the user must also create fictitious "ghost points" in order to form a rectangular domain. The user must also modify the JeNo subroutine "CENTER_BODY" to indicate which "ghost points" should be omitted from the sound pressure level calculations.

1.3.2 Solution File Recommendations

JeNo expects to read the mean flow solution as a single block of data in a 2D, unformatted, multiblock Plot3D format (with the number of blocks equal to 1). For an axisymmetric case, the solution file contains four variables: ($\rho, \rho u, \rho v, E$). JeNo assumes that the values of the variables in the solution file have been normalized by the reference values given in Table 1. The code segment "SUBROUTIND INPUT" reads the three RANS files as shown below.

The solution file prepared for JeNo must match the grid file prepared for JeNo. That is, the solution data should be presented as a single block of data beginning at the nozzle exit plane. Again, if the problem used multiple blocks to accelerate convergence of the mean flow solution, the blocks downstream of the nozzle exit must be combined and exported as a single block. This can often be done with utilities supplied with your CFD code or by writing a stand-alone program.

Table 1.—Normalizing factors

Property	Notation	Normalizing Parameter	JeNo Variable
Coordinates	X, Y, r	L_r	`Lref`
Temperature	T	T_r	`Tinf`
Velocity Component	u, v	a_r	`Aref`
Pressure	p	γp_r	`Gamma*Pinf`
Density	ρ	ρ_r	`Rhoref`
Time	t	L_r/a_r	
Total Internal Energy/unit volume	E	$\rho_r\ a_r^2$	
Turbulent Kinetic Energy	k	a_r^2	
Turbulent Dissipation Rate	ε	a_r^3/L_r	

Since most RANS solution files output turbulent kinetin energy k and its dissipation rate ε as dimensional, JeNo performs the required normalization internally within module *input.f90*.

Assuming an ideal gas law with specific heat ratio γ and gas constant R, the normalizing parameters are defined using the reference values for length, temperature and pressure (L_r, T_r, p_r) = (`Lref, Tinf, Pinf`)

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

1.3.2.1 Segments of Module *input.f90*

```
! -------------------------------------------------------------------
SUBROUTINE INPUT
! -------------------------------------------------------------------
!
USE Ambient
USE Centerbody
USE Free_Stream
USE Gas_Constants
USE Jet_Exit
USE MeanFlow
USE Nozzle_Exit
USE Radial_Start
USE RANS
USE RANS_Files
USE Reference
!
IMPLICIT DOUBLE PRECISION   (a-h,o-z)
!
REAL              XMACH,ALPHA,RE,DT
DOUBLE PRECISION :: Mexit
!
! open RANS Solution files
!
open (27, file=GFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
open (28, file=QFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
```

```
open (29, file=TFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
.
.
.
!
!  Reads radial dimensionless mean flow profiles
!
READ(27) NBLK
READ(27) JD, KD
!
!  CHECK DIMENSIONS
!
IF(NBLK.NE.1)THEN
   WRITE( 6,*)' Error - Number of blocks (NBLK) in grid file must be 1'
   WRITE( 6,*)' Program Terminated in routine INPUT.'
   STOP
ENDIF
.
.

JMAX= JD
kmax= KD
.
.
CALL ALLOCATE

READ(27) (( X(J,K),J=1,JMAX),k=1,kmax) &
&       ,(( Y(J,K),J=1,JMAX),k=1,kmax)
!
! WIND Q and ke files:
! (Qi , i=1,2,3,4  are non-dimensional)
! (Qi , i=5, 6 are dimensional ; i.e., ft^2/s^2 & ft^2/s^3)
!
!  Q1    : Density
!  Q2    : X momentum
!  Q3    : Y momentum
!  Q4    : Internal energy/unit mass
!  Q5    : k
!  Q6    : epsilon
!
! READ Qi  i=1,2,3,4
READ(28) NBLK
READ(28) JL, KL
READ(28)XMACH,ALPHA,RE,DT
READ(28)((( Q(J,K,N),J=1,JMAX),k=1,kmax),n=1,4)
!
! READ Qi  i=5,6   (k & epsilon)
READ(29) NBLK
READ(29) JL, KL
READ(29)XMACH,ALPHA,RE,DT
READ(29)((( Q(J,K,N),J=1,JMAX),k=1,kmax),n=5,6)
!
CLOSE(27)
CLOSE(28)
CLOSE(29)

write(*,*) 'Done reading RANS files'
```

```
.
.
.
! Important Note:
!
! WIND normalization for Q5 and Q6
!
!   In routine SPECTRAL_DENS, calculation of
!   parameters source strength DS(m), and time-scale FS(m),
!   assumes that that Q5 and Q6 are normalized as done below.
!   If Q5 and Q6 are already in normalized form, then
!   the following 6 lines are not required and should be commented out.
!
do j = 1, jmax
do k = 1, kmax
Q(j,k,5) = Q(j,k,5)/ Aref/Aref
Q(j,k,6) = Q(j,k,6)*Lref/Aref/Aref/Aref
enddo
enddo
.
.
.


RETURN
END
```

1.3.3 Turbulence File Recommendations

JeNo expects to read the turbulent kinetic energy and its dissipation rate from a turbulence file consisting of a single block of data in a 2D, unformatted, multiblock Plot3D format (with the number of blocks equal to 1). For a 2D or axisymmetric case, this file could hold up to four variables such as ($k, \varepsilon, k, \varepsilon$). As seen above, *SUBROUTINE INPUT* only reads the first two variables as k and ε respectively, although the turbulence file contains four variables.

In addition, JeNo source spectral density calculations assume that the variables in the turbulence files are already normalized with respect to their reference values. Since most RANS codes output the values of (k, ε) as dimensional, such as (ft^2/sec^2) and (ft^2/sec^3), it was determined to input parameters (k, ε) as dimensional and have their required normalization be performed within JeNo in module *input.f90*. In the event that these two parameters are already normalized prior to input to JeNo, several lines in the code need to be commented out as highlighted in module *input.f90*. This will be examined in the tutorial example that follows.

At NASA Glenn, the Shear Stress Transport (SST) turbulence model available in the Wind code [5] has often been used to obtain the mean flow solutions for a number of jets, which is a k-ω model. In these cases, we first calculated the value of epsilon as:

$$\varepsilon = 0.09 \times k \times \omega \tag{2}$$

The turbulence file prepared for JeNo must match the grid file prepared for JeNo. That is, the turbulence data should be presented as a single block of data beginning at the exit plane of the nozzle. Again, if the problem used multiple blocks to accelerate convergence of the mean flow solution, the blocks downstream of the nozzle exit must be combined and exported as a single block. This can often be done with utilities supplied with your CFD code or by writing a stand-alone program.

1.4 JeNo Computation Details

The JeNo code is developed around Lilley's form of the Acoustic Analogy [4,6]. A linearized form of Lilley's equation governs generation and propagation of sound. The governing equation is linearized about a unidirectional, transversely sheared mean flow and terms that are second-order in fluctuating variables are identified as the *equivalent* sources of sound and placed on the right hand side of the equation [7,8]. The propagation Green's Function is solved numerically in a frequency domain using an adjoint form of the equation. This propagation filter, also known as a non-causal Green's function, is responsible for the zone of silence that forms at small angles near the jet axis.

Upon reading the RANS solution grid, solution file, turbulence quantities, as well as additional parameters supplied in a *noise.inp* file, JeNo calculates the far-field sound pressure levels produced by axisymmetric jets along an arc or sideline for a range of frequencies. As pointed out earlier, the solutions files should be expressed on a properly prepared computational grid. Jet outputs the jet mixing noise as well as its two elementary components, designated as self- and shear-noise, in tabular format. In addition to the lossless spectra, tables are also provided after the application of the atmospheric attenuation routine that attenuates the high frequency sound for temperature, humidity and distance.

A pseudo-code outline of the JeNo 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 propagation Green's Function (assuming a locally parallel flow)

            3) calculate the sound pressure level at the observer location by performing the source/Green's function convolution integral

        Repeat each source element

    Repeat each frequency

Repeat each observer location

Observer location, represented in Figure 1, is calculated using parameters specified in the *noise.inp* file. The user chooses to calculate sound pressure levels along a sideline or arc using the `N_Arc` keyword. The user must also specify a radial location (`R_Obs`), number of angles relative to the downstream jet axis (`Nang`), and the individual observer angular locations (`Thetd`) relative to the downstream jet axis.

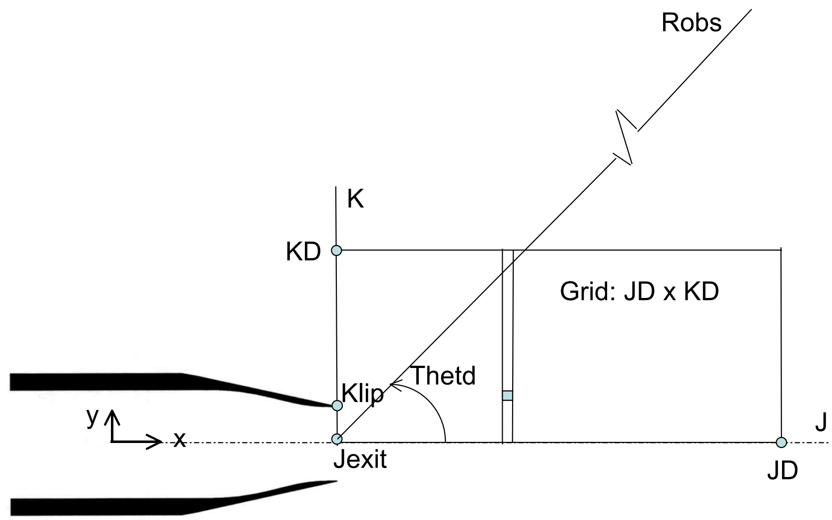


Figure 1.—JeNo expects a single block domain with the axial datum located at the nozzle exit plane.

Frequency range is also calculated by JeNo using parameters specified in the *noise.inp* file. Frequency range is limited by user-defined values for the minimum and maximum Strouhal number:

$$St = \frac{fD_J}{U_J}, \tag{3}$$

where f denotes the observer frequency in Hz, D_J is the jet exit diameter and U_J is the jet exit velocity as calculated from the mean flow solution using the value of `Jexit` specified in the JeNo input file. In dual-flow jets where the core and fan streams may exit at different axial locations, parameter `Jexit` should be selected to best represent a nominal exit plane.

Parameters `St_min, St_max` combined with Eq. (2) define a frequency range from the following band of 1/3-Octave center frequencies, in Hertz (`Fcen`) : 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300, 8000, 10000, 12500, 16000, 20000, 25000, 31500, 40000, 50000, 63000, 80000, 100000. Note that the frequency-range is confined to (`50 to 100,000` Hz), or at most 34 bands.

Sound pressure level (SPL) can be calculated in either narrow-band or 1/3-Octave band, and the *noise.inp* keyword `I_band` must be set accordingly. The narrow-band calculations are performed per Strouhal number

$$10Log10\left(U_J D_J^{-1}\,\overline{p^2}\big/p_o^2\right), \tag{4}$$

while the 1/3-Octave predictions use

$$10Log10\left(BW \times \overline{p^2}\big/p_o^2\right). \tag{5}$$

The band-width at a center-frequency `Fcen` is

$$BW = Fcen \times (2^{1/6} - 2^{-1/6})\,. \tag{6}$$

$\overline{p^2}$ is the mean-square pressure at the observer locations and the acoustic reference pressure is $p_o = 0.0002\ \mu bar$ (i.e. 4.17×10^{-7} psf). In either case, the Overall Sound Pressure Level (OASPL) is calculated by integrating the SPL on a 1/3-Octave basis.

The current version of JeNo works in the British system of units. Appropriate statements are also provided within the code that may be un-commented if one desires to switch to the SI units. Ideally one may customize the code with an input flag to select units. However, when the RANS solution files are provided in the SI units, a more convenient way for conversion to FPSR units would be to simply convert the reference values:

Table 2.—Conversion from SI units

Quantity SI Units	Multiply by	To obtain FPSR Units
Length L_r (m)	3.28	ft
Temperature T_r (°K)	1.8	°R
Pressure p_r (Pa)	1/47.88	lb/ft^2

In addition, assuming that variables k and **ε** were dimensional, each variable should now be multiplied by 3.28^2 in order to convert from (m^2/sec^2) and (m^2/sec^3) to (ft^2/sec^2) and (ft^2/sec^3) respectively, prior to input to JeNo. Since all calculations are now performed in the PFSR units, the observer distance `Robs` should also be provided in feet.

Grid elements are defined according to the computational grid used for the mean flow calculation. The user may choose to accelerate JeNo convergence by skipping axial slices when performing the source/Green's function convolution integral. Parameters `j_start`, `j_end` and `j_inc` determine the range and spatial density of slices to be integrated. When the increment in axial slice location `j_inc` is larger than 1, several slices are skipped in between two subsequent calculations. The Green's function, in effect, is treated as a constant between slices `j` and `j+ j_inc`. If the axial clustering of the grid is such that changes in the mean flow are rather insignificant between these slices, the predicted SPL would differ only by a slight margin from the more demanding calculation with `j_inc = 1`. Calculations of the Green's function would increase in direct proportion to the number of slices, frequency bands, and observer angles integrated**.** If the grid blocks were not a point-to-point match, it is recommended to integrate with `j_inc =1`.

Far-field sound spectral density is calculated from the source/Green's function convolution integral at all source volume elements that comprise a turbulent jet. The assumption is made that each correlation volume element is radiating noise to the far field independent of the adjacent elements. Source spectral intensity at each element is calculated using a physics-based modeling approach that models the two-point space-time correlation between the turbulent velocity fluctuations. The length- and time-scales required to calculate each second order velocity covariance are obtained from the local values of k and ε.

Once the sound is emitted, it goes through refraction as it propagates through the shear layer. Various frequency components refract differently before they reach a far field observer. This effect is captured by the propagation Green's function. In a locally parallel flow, the mean profiles (i.e., mean axial velocity component and temperature) are used to integrate the second order compressible Rayleigh operator. The Green's function is thus stored at all source locations on a jet slice. Numerical calculation of the Green's function is carried out at a specified frequency and observer angle as shown in the following `Loop` structure.

```
  slice_integration: DO j_loc =
&   (j_start+j_inc), (j_end-j_inc), j_inc
```

```
      CALL SLICE
      :
      freq_integration:  DO J_freq = J_FMIN, J_FMAX
      St = OBSTN (J_freq)
      :
      observer_angle:    DO I_Theta= 1, nang
      Theta = Thetd(I_Theta)*pi/180.
      :
c
c  Calculate parallel Green's function at this slice and at this angle and frequency
c
      CALL PARALLEL_GREEN(I_Theta)
      :
      ENDDO observer_angle
      :
      ENDDO freq_integration
      :
      ENDDO slice_integration
```

1.5 JeNo File Summary

1.5.1 Input Files

Unit	Description
10	Namelist file *noise.inp* – defines input parameters
27	Unformatted grid file – specify file name in *noise.inp*
28	Unformatted Q file – specify file name in *noise.inp*
29	Unformatted turbulence file – specify file name in *noise.inp*
53	Restart file *fort.53* (see output unit 54)

1.5.2 Output Files

Unit	Description
6	Formatted output – shows calculation progress
19	Formatted *fort.19* – lists flow profiles at selective axial locations when `NPRINT` is not 0.
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

1.5.3 Primary Input Parameters

Parameter	Description
`GFILE:`	`Grid File`
`QFILE:`	`CFD-predicted Q file`
`TFILE:`	`CFD-predicted Turbulence file`
`Jexit:`	`Identifies the jet exit plane (where exit velocity` U_J `is calculated)`
`Klip:`	`Identifies the jet exit diameter,` D_J `= 2Y(Jexit, Klip)`
`J_start, J_end, J_inc:`	`Integration limits of axial jet slices`

Pinf:	Reference pressure - ambient pressure, psf (2116.8)*
Tinf:	Reference temperature - ambient static temperature, °R (520.0)*
h_r:	Percentage relative humidity (70.0)*
Rgas:	Gas constant, ft^2/sec^2 °R (1716.0)*
Gamma:	Specific heat ratio (1.4)*
Lref:	Reference length used in CFD normalization, ft (1.0)*
Ljet:	A factor to modify jet exit diameter (defaults to Lref)*
Robs:	radial observer location in the far field, ft
N_Arc:	1* spectra is calculated on Arc = Robs else spectra is calculated on sideline = Robs
St_min, St_max	Range of Strouhal number St= fD_J/U_J, (5.0d-2, 1.0d1)*
NPRINT	n Prints flow profiles on the integrated slices at every nth slice (file fort.19) 0* No flow profiles are printed
I_CB:	0* No center body exists else Center body geometry is specified in routine "Center_body"
I_band:	3 Spectral-density is calculated in 3rd-Octave band else* Spectral-density is calculated in narrow-band
I_restart:	0* No restart 1 Restart – Read restart information from file fort.53 and continue calculation
Nang:	Number of polar angles
Thetd:	Angles (in degrees from down-stream jet axis) Thetd(i), i=1, Nang
Errel, Errabs:	Relative and absolute error tolerances in solving the ODE's (1.0d-6, 1.0d-6)*

* Indicates a default value

1.5.4 Sample Input File

An example of the JeNo input file is given below, accompanied by a description of the variables that must be specified. This example presents the required input for a 2-inch diameter jet operating at Mach 0.5. The input file "*noise.inp*" defines the *Namelist* parameters and provides a link to the CFD files. Case title information should be provided on the first line of the *noise.inp* file.

1.5.4.1 Filename: noise.inp

```
ARN2 – SP03, (Arc=16.6667ft= 100D)
&CFD_FILES
 GFILE = './sp03.x'
 QFILE = './sp03.q'
 TFILE = './sp03.t'
&END
&JET_DATA
 Jexit = 1, Klip = 81, j_start= 1, j_end= 241, j_inc= 5,
 Pinf = 2059.2 Tinf = 530.0, h_r = 70.0,
```

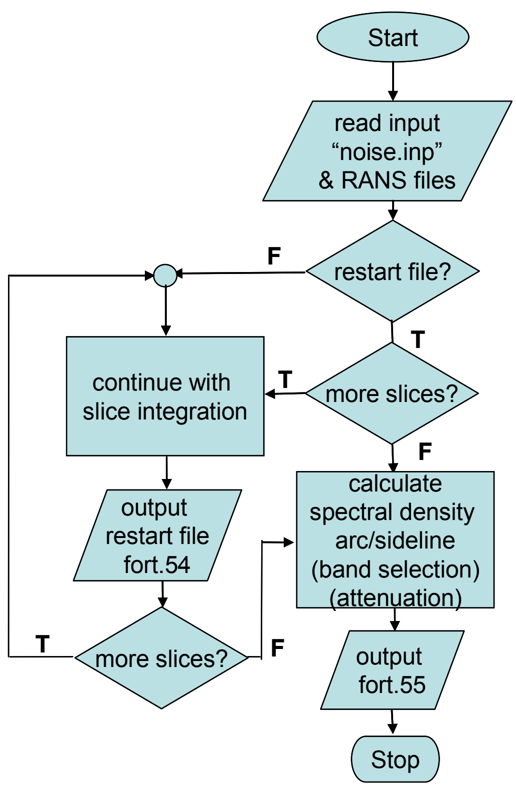
```
  Rgas=1716.0, Gamma=1.40, Lref=1.0, Ljet = 1.0,
  Robs = 16.6667, N_Arc=1, St_min =0.02, St_max= 18.,
  I_restart = 0, I_CB = 0, I_band=0,
  Nang= 10, Thetd=
  20.,30.,40.,50.,60.,70.,80.,90.1,120.,140.
 &END
```

1.5.5 Restart File

Data required for SPL calculation (up to the current jet segment) are written to a restart file, `fort.54`, following each slice `j_loc`. The restart information is updated continuously. When initiating jet volume integration, one may wish to read in the partial results from a previous run, and continue with the integration of the remaining jet volume. JeNo saves restart information to the file fort.54. By copying this file to fort.53 and setting flag `I_restart = 1`, one can instruct JeNo to restart the integration.

After reading a restart file, JeNo determines the slices that have been integrated previously. There is no need to change any of the parameters `j_start`, `j_inc, and j_end` in the input file. The integration should continue in the same sequence as before.

The restart file also provides a quick turn-around for sound calculation at a new distance (same angles as before), or under different atmospheric conditions. One may simply change parameters `Robs`, `N_Arc` and `h_r` as required prior to a new run with `I_restart = 1`. In addition, the restart file could also be used as a utility to convert the spectra from narrow-band to 1/3-Octave band, or vice versa, by selecting the flag parameter `I_band`.



Parameter Ljet is used to size the jet diameter. A default value of Lref calculates the exit diameter as D_J=2Y(Jexit, Klip)xLref (ft). Otherwise, D_J is sized as D_J = 2Y(Jexit, Klip)xLjet (ft). Obviously, the existing CFD solution is treated as suitable for the resized jet (i.e., Reynolds number effect is absent). When Robs/D_J is kept constant, the sizing of the jet diameter should simply shift the spectrum due to the Strouhal scaling.

2.0 Tutorial I—Single Stream Axiysmmetric Jet

2.1 Prepare CFD Input

To begin a JeNo calculation one must prepare the computational grid file, mean flow solution file, and turbulence quantity file. As an example, we will study the 2 inch diameter Acoustic Reference Nozzle (ARN2) shown in Figure 2. The CFD grid consisted of 3 blocks; block#1 (121x81) shown in red; block#2 (81x81) in green; and block#3 (241x181) in blue.

In this case, the grid used for the mean flow solution very closely matches the grid needed for the noise calculations. It is a structured H-grid, with block boundaries at the nozzle exit plane. Axial gridlines in the block downstream of the nozzle exit plane are perpendicular with the direction of flow, and there are no solid surface obstructions in the jet plume. The single block, unformatted, Plot3D grid, solution, and turbulence files can be exported directly from the RANS solver utilities or could be extracted using the Fortran code below. Since the turbulence kinetic energy and dissipation rate were provided in their *preferred* dimensional form, they were normalized within module *input.f90* as explained earlier. The RANS files for this example have been named `arn.sp03.x, arn.sp03.q, and arn.sp03.t` for the grid, solution, and turbulence data, respectively.

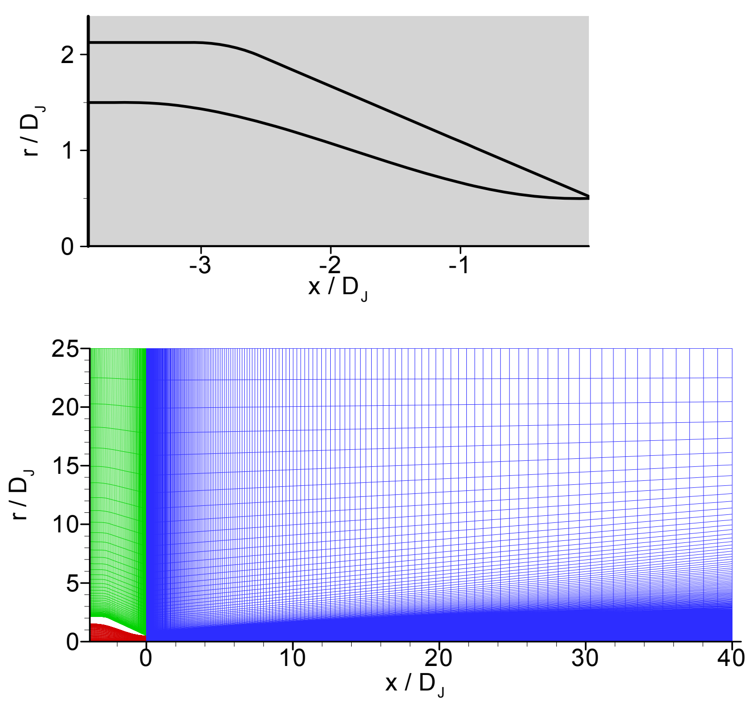


Figure 2.—Geometry for ARN2 convergent nozzle (top). Multiblock grid used for mean flow solution of a single stream nozzle (bottom). Single block grid for JeNo solution is shown in blue.

```
cccccccccccccccccccccccccccccccccccccccc
c ARN2 nozzle
c Reads 3 blocks and outputs block#3 - Wind RANS ( k-epsilon solution )
ccccccccccccccccccccccccccccccccccccccccc
c Mach 0.51 and 0.98, 3 blocks: (121x81), (81x81), (241x181)
c
c (wrt block3, jexit =1, Klip= 81, Dj/2=1" )
c
      PARAMETER (JD=241, KD=181, nb = 3)
      REAL               X(JD,KD,nb),Y(JD,KD,nb),Q(JD,KD,8,nb)
      INTEGER            JL(nb), KL(nb)
      REAL               XMACH,ALPHA,RE,DT
      REAL               Tref, Lref
      CHARACTER(len=100)  GFILE, QFILE, TFILE
c
c assign input files (multi-block)
c
      GFILE = '../arn.sp03.x'
      QFILE = '../arn.sp03.q'
      TFILE = '../arn.sp03.t'
c
c reference values (lb – ft- s)
c
      Pinf = 14.3*144.
      Tinf = 530.
      Lref = 1.0
      Rgas = 1716.
      Gamma= 1.4
      Aref = sqrt(Gamma*Rgas*Tinf)
c
c assign output files to a single block
c
      open (27, file='sp03.x',    form='unformatted')
      open (28, file='sp03.q',    form='unformatted')
      open (29, file='sp03.t',    form='unformatted')
c
c RANS Solution files
c
      open (37, file=GFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (38, file=QFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (39, file=TFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
c
c read grid for all blocks
c
      READ(37) NBLK
      READ(37) (JL(i_block), KL(i_block), i_block = 1, nb)
C
      do i_block = 1, nb
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(37) (( X(J,K,i_block),J=1,JMAX),k=1,kmax)
     &        ,(( Y(J,K,i_block),J=1,JMAX),k=1,kmax)
      enddo
c
c read Q file in its normalized form
c
C  Q1    : Density
c  Q2    : X momentum
c  Q3    : Y momentum
C  Q4    : Internal energy/unit mass
c
      READ(38) NBLK
      READ(38) (JL(i_block), KL(i_block), i_block = 1, nb)
```

```
      do i_block = 1, nb
      READ(38)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(38)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=1,4)
      enddo
c
c read ke file
c
C  Q5    : k (ft2/s2)
c  Q6    : epsilon (ft2/s3)
c  Q7    : mut/muref
C  Q8    : U fps
c
      READ(39) NBLK
      READ(39) (JL(i_block), KL(i_block), i_block = 1, nb)
      do i_block = 1, nb
      READ(39)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(39)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=5,8)
      enddo
c
c output block#3 (single block- unformatted)
c
      i_block = 3
      jmax = JL(i_block)
      kmax = KL(i_block)
      WRITE(27) 1
      WRITE(27) jmax, kmax
      WRITE(27) (( X(J,K,i_block),J=1,JMAX),k=1,kmax)
     &          ,(( Y(J,K,i_block),J=1,JMAX),k=1,kmax)
c
      WRITE(28) 1
      WRITE(28) jmax, kmax
      WRITE(28) XMACH,ALPHA,RE,DT
      WRITE(28)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=1,4)
c
      WRITE(29) 1
      WRITE(29) jmax, kmax
      WRITE(29) XMACH,ALPHA,RE,DT
c
c output k,e,k,e
c
      WRITE(29)  (( Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
     &          ,(( Q(J,K,6,i_block),J=1,JMAX),k=1,kmax)
     &          ,(( Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
     &          ,(( Q(J,K,6,i_block),J=1,JMAX),k=1,kmax)
c
      CLOSE(27)
      CLOSE(28)
      CLOSE(29)
      STOP
      END
```

2.2 Prepare JeNo Input

Once the CFD files have been prepared, the user must then focus on collecting the proper information needed to create the *noise.inp* file for JeNo. The *noise.inp* file for the 2 inch diameter Acoustic Reference Nozzle (ARN2) at the Set Point 03 (SP03) Mach 0.51 unheated jet condition is reprinted and examined below.

2.2.1 JeNo Input filename, *noise.inp*

```
ARN2 - SP03, (Arc=16.6667ft= 100D)
&CFD_FILES
 GFILE = './sp03.x'
 QFILE = './sp03.q'
 TFILE = './sp03.t'
&END
&JET_DATA
 Jexit = 1, Klip = 81, j_start= 1, j_end= 241, j_inc= 5,
 Pinf = 2059.2 Tinf = 530.0, h_r = 70.0,
 Rgas=1716.0, Gamma=1.40, Lref=1.0,
 Robs = 16.6667, N_Arc=1, St_min =0.02, St_max= 18., NPRINT = 10,
 I_restart = 0, I_CB = 0, I_band=0,
 Nang= 10, Thetd=
 20.,30.,40.,50.,60.,70.,80.,90.1,120.,140.
&END
```

After providing the filenames for the grid, solution, and turbulence quantity data, the user must examine the original grid used for the mean flow calculation in order to provide the proper values for `Klip` and `Jexit`, indicated on Figure 3. In this case, the nozzle inner diameter corresponds to `Klip = 81` and the jet exit plane corresponds to `Jexit = 1`. JeNo will use these values to set U_J to the maximum axial velocity at the nozzle exit plane. In this example, calculation was accelerated by evaluating the source/Green's Function convolution integral at every fifth gridline, as indicated by the values for `j_start`, `j_end`, and `j_inc`.

Default values for air are provided for freestream static pressure (`Pinf`) and temperature (`Tinf`), humidity (`h_r`), gas constant `Rgas`, and ratio of specific heats (`Gamma`) unless otherwise specified by the user. While `Lref` and `Ljet` default to 1.0, users should take particular care that these values are set appropriately for the modeled nozzle. Actual mesh units, when multiplied by the value of `Ljet` should result in physical lengths expressed in feet. In this example, the computational mesh was exported with coordinates expressed in feet. The value of the y coordinate at the nozzle exit (`Jexit` = 1, `Klip` = 81) was 0.08333 ft. Therefore, for the 2 inch (0.1666 ft) Acoustic Reference Nozzle:

`Ljet` = exit diameter in mesh units/exit diameter in feet

`Ljet` = (2*0.0833 ft)/(0.1667 ft) = 1.0

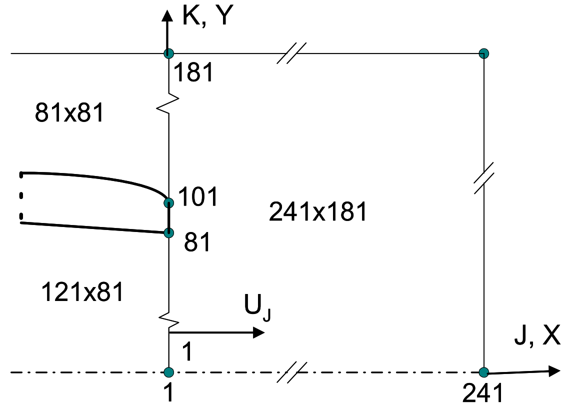


Figure 3.—Sketch of the nozzle exit.

When the user specifies values for `Robs, N_Arc, Nang,` and `Thetd`, observer locations are defined. While this example will calculate sound pressure levels for a range of 10 observer angles, it is recommended that a single observer angle should be specified for troubleshooting new cases (`Nang` = 1 and `Thetd` = 90.). The output file `fort.55` should be examined for possible errors in the import/reading of the CFD files. At 90° a robust density-scaled Green's function is applied. Once satisfactory results are obtained at 90° relative to the downstream jet axis for the case under study, it is recommended that the user change the single angle slightly (by specifying something like `Thetd` = 90.001°) so that more demanding numerical integration of the Green's function propagation equation can be exercised. Again, once the user obtains satisfactory results from these two points, a wider range of observer angles can be specified.

```
IF(Thetd(I_Theta) .ne. 90.0)CALL PARALLEL_GREEN(I_Theta).
```

2.3 Run the JeNo Code

The standard input and standard output files are directed at runtime using standard UNIX redirection syntax as:

JeNo_executable_name < noise.inp

If a restart run is desired, the user must move the most current output restart from:

Case.restart.new

to the default input restart file name:

Case.restart.old

each time the code is restarted.

2.4 Examine the Output

JeNo writes to file *fort.55* as its primary output file. It echoes a listing of input parameters defined in *noise.inp* and/or their default values – followed by parameters calculated at the nozzle exit plane and the ambient.

Sound spectral density is tabulated as a function of angle and frequency. Jet mixing noise as well as its two elementary components, designated as self- and shear-noise, are listed separately. In this example, after echoing the input file parameters for the ARN2 nozzle, the first table lists the lossless spectral density in narrow-band, and on the 16.7 feet arc. The second column in the table is the frequency band number

$$Band = 10Log10(f).$$

A separate table highlights the effect of atmospheric loss on high frequency sound as it propagates the required distance ($100D_J$ in the example), at specified relative humidity and ambient temperature. Here a frequency range (63 – 63000 *Hz*) was required to span the specified Strouhal numbers selected in the input file.

The atmospheric attenuation module is named *Atmos_Loss.f90*, and is activated from within the module *Output_Spectra.f90* using the following call statement

CALL Atmos_Loss(Tinf, h_r, AA).

2.4.1 Primary Output

2.4.1.1 Filename: *fort.55*

```
******************************
*  JeNo_2D version beta3.1   *
******************************
------------------------ input --------------------
ARN - SP03, (Arc = 16.6667 ft; 100D)

Grid file: ./sp03.x
Q    file: ./sp03.q
Tke  file: ./sp03.t
     Jexit =  1
      Klip = 81
   j_start =  1
     j_end =241
     j_inc =  5
      C_el =  0.29431E+01
     C_tau =  0.33000E+00
       A_m =  0.17638E+00
      Pinf =  2059.20
      Tinf =   530.00
       h_r =    70.00
      Rgas =  1716.00
     Gamma =   1.40
      Lref =   1.000000
      Ljet =   1.000000
      Robs =  16.67
     N_Arc = 1
    St_min =   0.02
    St_max =  18.00
    NPRINT =  0
 I_restart =  0
      I_CB =  0
    I_band =  0
      Nang = 10
     Thetd =
  20.0   30.0   40.0   50.0   60.0   70.0   80.0   90.1  120.0  140.0
 ------------------------------------
```

```
GFILE was opened successfully.
QFILE was opened successfully.
TFILE was opened successfully.
Aref=    1128.393548368653      fps,  Rhoref=   2.2641509433962259E-003
lbm/cft
------------------------------------
Exit values the point of Max U,
  (at J =           1  and K =           41 )

   Velocity =    564.9538936843832       fps
    Density =   2.3832156523218688E-003  lbm/cft
   Pressure =    2058.792411694222       psf
Static temp =    503.4217010568919       R
Sound speed =    1099.736465985864       fps
   Mach No. =   0.5137175233867758
   Diameter =   0.1666599810123444       ft
Temp. ratio =   0.9999865504125639
------------------------------------
Calculated AMBIENT values (from CFD)

   Velocity =    9.996653602157636       fps
    Density =   2.2646454145323553E-003  lbm/cft
   Pressure =    2059.123534560568       psf
Static temp =    529.8646013280622       R
Sound speed =    1128.249404267752       fps
   Mach No. =   8.8603225176490046E-003
------------------------------------
Strouhal number (fD/U) calculated based on:

 o Freq Range    (f)=           63        63000  (Hz)
 o Exit Diameter (D)=   0.1666599810123444       ft
 o Exit Velocity (U)=    564.9538936843832       fps
 o Strouhal Range   =   1.8584841915689820E-002    18.58484191568982
------------------------------------

Vol. integration continues with j_start=            1  to j_end=          241
```

Total jet slices integrated are from j= 1 to j =236 with j_inc= 5
Spectral density is calculated in Narrow Band

***MIXING (SELF+SHEAR) NOISE Pressure Level Directivity ***
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Unattenuated spectra / Angle from down-stream axis

Freq	Band	St	20	30	40	50	60	70	80	90	120	140
63	18	0.019	69.25	67.83	65.96	63.82	61.66	59.84	58.61	58.01	57.15	56.73
80	19	0.024	71.18	69.78	67.95	65.88	63.83	62.13	60.99	60.41	59.51	59.07
100	20	0.029	72.90	71.53	69.73	67.69	65.71	64.09	63.01	62.44	61.48	61.02
125	21	0.037	74.55	73.20	71.41	69.40	67.46	65.89	64.84	64.27	63.27	62.80
160	22	0.047	76.28	74.94	73.15	71.16	69.25	67.72	66.69	66.12	65.08	64.58
200	23	0.059	77.75	76.40	74.61	72.63	70.74	69.23	68.22	67.63	66.55	66.05
250	24	0.074	79.09	77.72	75.94	73.98	72.11	70.61	69.60	69.01	67.88	67.39
315	25	0.093	80.28	78.91	77.19	75.24	73.37	71.88	70.88	70.27	69.10	68.61
400	26	0.118	81.22	79.99	78.31	76.35	74.50	73.02	72.01	71.39	70.18	69.69
500	27	0.147	81.83	80.83	79.15	77.23	75.36	73.88	72.87	72.25	71.02	70.54
630	28	0.186	82.30	81.36	79.82	77.91	76.04	74.55	73.54	72.91	71.67	71.21
800	29	0.236	82.41	81.70	80.25	78.36	76.48	74.99	73.98	73.36	72.14	71.69
1000	30	0.295	81.94	81.65	80.39	78.54	76.65	75.14	74.13	73.53	72.36	71.93
1250	31	0.369	81.24	81.27	80.27	78.48	76.56	75.04	74.05	73.48	72.39	71.96
1600	32	0.472	79.77	80.46	79.82	78.14	76.19	74.65	73.69	73.16	72.17	71.71
2000	33	0.590	77.99	79.28	79.16	77.59	75.62	74.08	73.14	72.64	71.72	71.24
2500	34	0.737	75.75	77.76	78.26	76.86	74.86	73.31	72.39	71.91	71.03	70.55
3150	35	0.929	73.12	75.79	77.07	75.92	73.90	72.36	71.45	70.96	70.04	69.60

4000	36	1.180	70.28	73.48	75.60	74.81	72.77	71.23	70.30	69.79	68.82	68.37
5000	37	1.475	67.66	71.19	74.03	73.65	71.60	70.04	69.07	68.55	67.62	67.11
6300	38	1.858	64.97	68.75	72.22	72.34	70.24	68.63	67.65	67.15	66.18	65.74
8000	39	2.360	62.28	66.27	70.22	70.87	68.68	67.04	66.09	65.57	64.62	64.21
10000	40	2.950	59.87	63.99	68.27	69.37	67.09	65.50	64.53	64.02	63.04	62.57
12500	41	3.687	57.49	61.74	66.27	67.73	65.46	63.85	62.91	62.39	61.41	61.09
16000	42	4.720	54.93	59.30	64.05	65.75	63.54	61.98	61.04	60.53	59.55	58.62
20000	43	5.900	52.65	57.11	62.04	63.96	61.79	60.23	59.31	58.80	57.82	56.91
25000	44	7.375	50.44	54.97	60.03	62.21	59.98	58.44	57.53	57.02	56.06	54.78
31500	45	9.292	48.19	52.78	57.95	60.21	58.08	56.57	55.66	55.15	54.12	52.79
40000	46	11.800	45.95	50.57	55.80	58.19	56.08	54.59	53.69	53.19	51.98	50.61
50000	47	14.750	43.85	48.53	53.81	56.33	54.19	52.72	51.83	51.33	49.93	48.66
63000	48	18.585	41.78	46.45	51.75	54.35	52.23	50.76	49.88	49.38	49.53	46.56
OASPL DIRECTIVITY			79.66	80.44	81.08	80.49	78.44	76.89	75.94	75.41	74.42	73.86

***MIXING (SELF+SHEAR) NOISE Pressure Level Directivity ***
16.7 FT. ARC

Attenuated spectra at 70.00000000000000 % Rel. Humidity and
530.0000000000000 deg. R

			Angle from down-stream axis									
Freq	Band	St	20	30	40	50	60	70	80	90	120	140
63	18	0.019	69.25	67.83	65.96	63.82	61.66	59.84	58.61	58.01	57.15	56.73
80	19	0.024	71.17	69.78	67.95	65.88	63.83	62.13	60.99	60.41	59.51	59.07
100	20	0.029	72.90	71.53	69.73	67.69	65.71	64.09	63.01	62.44	61.48	61.02
125	21	0.037	74.55	73.20	71.41	69.40	67.46	65.89	64.84	64.27	63.27	62.80
160	22	0.047	76.28	74.94	73.15	71.16	69.25	67.72	66.69	66.12	65.08	64.58
200	23	0.059	77.75	76.40	74.61	72.62	70.74	69.23	68.22	67.63	66.55	66.05
250	24	0.074	79.09	77.72	75.94	73.97	72.11	70.61	69.60	69.01	67.88	67.39
315	25	0.093	80.28	78.91	77.19	75.24	73.37	71.88	70.88	70.27	69.10	68.61
400	26	0.118	81.22	79.99	78.31	76.35	74.50	73.02	72.01	71.39	70.18	69.69
500	27	0.147	81.83	80.82	79.14	77.22	75.36	73.88	72.87	72.24	71.01	70.54
630	28	0.186	82.30	81.36	79.82	77.90	76.04	74.55	73.54	72.91	71.67	71.21
800	29	0.236	82.41	81.69	80.25	78.36	76.48	74.98	73.97	73.35	72.13	71.69
1000	30	0.295	81.94	81.64	80.38	78.54	76.64	75.13	74.13	73.53	72.36	71.93
1250	31	0.369	81.23	81.27	80.26	78.47	76.55	75.03	74.04	73.47	72.38	71.96
1600	32	0.472	79.76	80.44	79.81	78.12	76.17	74.64	73.67	73.14	72.15	71.70
2000	33	0.590	77.97	79.26	79.14	77.57	75.60	74.05	73.11	72.61	71.70	71.22
2500	34	0.737	75.72	77.73	78.22	76.82	74.82	73.28	72.36	71.88	70.99	70.51
3150	35	0.929	73.06	75.73	77.02	75.87	73.85	72.31	71.39	70.91	69.98	69.54
4000	36	1.180	70.19	73.39	75.51	74.72	72.68	71.14	70.21	69.70	68.74	68.28
5000	37	1.475	67.52	71.05	73.89	73.51	71.46	69.90	68.93	68.41	67.48	66.97
6300	38	1.858	64.75	68.53	72.00	72.12	70.03	68.41	67.43	66.93	65.96	65.52
8000	39	2.360	61.93	65.92	69.87	70.52	68.32	66.69	65.74	65.22	64.27	63.86
10000	40	2.950	59.33	63.45	67.73	68.83	66.54	64.96	63.98	63.48	62.50	62.03
12500	41	3.687	56.65	60.90	65.43	66.90	64.62	63.01	62.07	61.56	60.58	60.26
16000	42	4.720	53.60	57.96	62.71	64.41	62.21	60.64	59.70	59.19	58.22	57.28
20000	43	5.900	50.62	55.09	60.02	61.94	59.76	58.21	57.28	56.77	55.79	54.89
25000	44	7.375	47.43	51.95	57.01	59.19	56.97	55.43	54.51	54.01	53.05	51.76
31500	45	9.292	43.73	48.33	53.49	55.76	53.62	52.11	51.20	50.70	49.67	48.34
40000	46	11.800	39.48	44.10	49.33	51.72	49.61	48.12	47.22	46.72	45.51	44.14
50000	47	14.750	34.97	39.65	44.93	47.45	45.31	43.84	42.95	42.45	41.05	39.78
63000	48	18.585	29.84	34.51	39.82	42.42	40.29	38.83	37.94	37.45	37.59	34.62
OASPL DIRECTIVITY			79.60	80.32	80.79	79.99	77.95	76.40	75.44	74.92	73.92	73.42

It is informative to compare the above result with one obtained using the axial slice increment `j_inc = 1`. In this case there are five-times as many axial slices to integrate compared to `j_inc = 5` described above, which clearly prolongs the computation by nearly five-times. The difference between the two results is practically insignificant as seen below.

Total jet slices integrated are from j= 1 to j =240 with j_inc= 1

Spectral density is calculated in   Narrow Band

***MIXING (SELF+SHEAR) NOISE Pressure Level Directivity ***
16.7 FT. ARC

Attenuated spectra at   70.00000000000000   % Rel. Humidity and
530.0000000000000   deg. R

			Angle from down-stream axis									
Freq	Band	St	20	30	40	50	60	70	80	90	120	140
63	18	0.019	69.27	67.86	66.00	63.88	61.75	59.96	58.75	58.16	57.30	56.87
80	19	0.024	71.19	69.80	67.98	65.91	63.88	62.20	61.08	60.50	59.59	59.15
100	20	0.029	72.91	71.54	69.74	67.71	65.74	64.13	63.05	62.48	61.53	61.07
125	21	0.037	74.55	73.20	71.41	69.41	67.47	65.91	64.86	64.29	63.29	62.82
160	22	0.047	76.28	74.93	73.15	71.16	69.25	67.72	66.69	66.12	65.08	64.58
200	23	0.059	77.74	76.39	74.60	72.62	70.73	69.22	68.21	67.63	66.55	66.05
250	24	0.074	79.08	77.71	75.93	73.97	72.10	70.60	69.59	69.00	67.87	67.38
315	25	0.093	80.27	78.90	77.18	75.23	73.36	71.87	70.87	70.26	69.09	68.60
400	26	0.118	81.21	79.98	78.30	76.34	74.49	73.01	72.00	71.38	70.17	69.68
500	27	0.147	81.82	80.81	79.13	77.21	75.34	73.87	72.86	72.23	71.00	70.53
630	28	0.186	82.29	81.35	79.81	77.89	76.03	74.54	73.53	72.90	71.66	71.20
800	29	0.236	82.40	81.68	80.24	78.34	76.47	74.97	73.96	73.34	72.12	71.68
1000	30	0.295	81.93	81.63	80.37	78.53	76.63	75.12	74.12	73.52	72.35	71.91
1250	31	0.369	81.22	81.25	80.25	78.46	76.54	75.02	74.03	73.46	72.37	71.94
1600	32	0.472	79.75	80.43	79.80	78.11	76.16	74.63	73.66	73.13	72.14	71.69
2000	33	0.590	77.96	79.25	79.12	77.55	75.59	74.04	73.10	72.60	71.69	71.21
2500	34	0.737	75.71	77.72	78.21	76.81	74.81	73.27	72.35	71.87	70.98	70.50
3150	35	0.929	73.05	75.72	77.01	75.86	73.84	72.30	71.38	70.90	69.97	69.53
4000	36	1.180	70.18	73.38	75.50	74.71	72.67	71.13	70.20	69.69	68.72	68.27
5000	37	1.475	67.51	71.04	73.88	73.50	71.45	69.89	68.92	68.40	67.47	66.96
6300	38	1.858	64.74	68.52	71.99	72.11	70.01	68.40	67.42	66.92	65.95	65.51
8000	39	2.360	61.92	65.91	69.86	70.51	68.31	66.68	65.73	65.21	64.26	63.84
10000	40	2.950	59.32	63.44	67.72	68.82	66.53	64.95	63.97	63.47	62.49	62.02
12500	41	3.687	56.64	60.89	65.42	66.88	64.61	63.00	62.06	61.55	60.57	60.25
16000	42	4.720	53.58	57.95	62.70	64.40	62.19	60.63	59.69	59.18	58.20	57.27
20000	43	5.900	50.61	55.07	60.01	61.93	59.75	58.19	57.27	56.76	55.78	54.88
25000	44	7.375	47.42	51.94	57.00	59.18	56.96	55.41	54.50	54.00	53.03	51.75
31500	45	9.292	43.72	48.32	53.48	55.75	53.61	52.10	51.19	50.69	49.66	48.32
40000	46	11.800	39.47	44.09	49.32	51.71	49.59	48.10	47.21	46.71	45.50	44.13
50000	47	14.750	34.96	39.64	44.92	47.44	45.30	43.83	42.94	42.44	41.03	39.80
63000	48	18.585	29.83	34.50	39.81	42.41	40.28	38.81	37.93	37.43	37.58	34.70
OASPL DIRECTIVITY			79.59	80.31	80.78	79.98	77.94	76.39	75.43	74.91	73.91	73.41

2.5 Validation Cases

Since sound pressure levels from JeNo are based on mean flow calculations, both the aerodynamic and acoustic predictions must be validated against experiment. The mean flow predictions from Wind for the ARN2 nozzle at the conditions of Set Point 3 (SP03), i.e., Mach 0.51 unheated jet, are shown in Figure 4. Normalized length- and time-scales are $k^{1.5}/(\varepsilon D_J)$ and $kU_J/(\varepsilon D_J)$ respectively, where k and ε are the turbulent kinetic energy and its dissipation rate. The time-scale could potentially become very large within the laminar core due to the small dissipation factor appearing in the denominator. However, since the turbulent kinetic energy is also quite small in that region, the contours are masked out. A comparison of turbulent kinetic energy with the Particle Image Velocimetry (PIV) measurements [9] is shown in Figure 5. JeNo narrow-band sound spectral density and comparison with lossless data on a $100D_J$ arc is shown in Figure 6. All measured data presented for comparison have been collected at the Small Hot Jet Acoustic Rig (SHJAR) at the NASA Glenn Research Center [9]

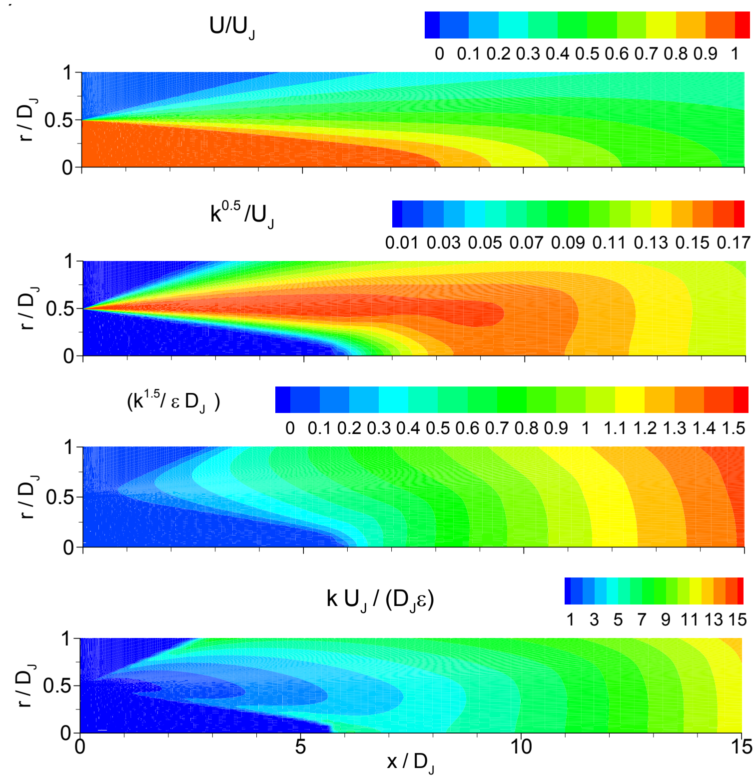


Figure 4.—Wind CFD solution.
Mach 0.51, unheated jet (ARN2–SP03).

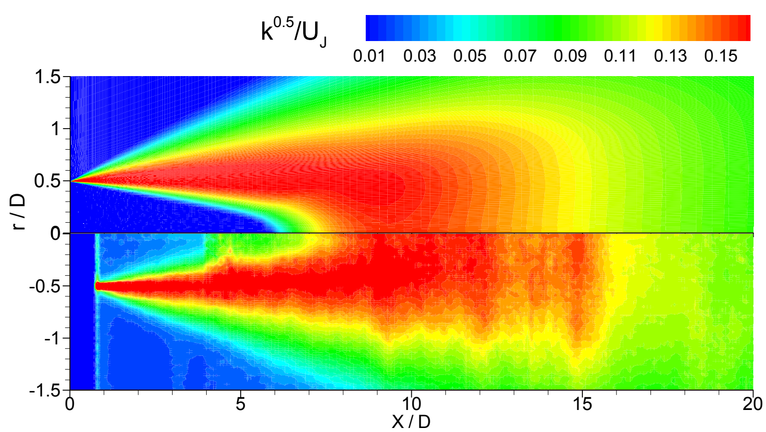


Figure 5.—Turbulent kinetic energy (ARN2–SP03).
Top half, Wind solution; bottom half, PIV data.

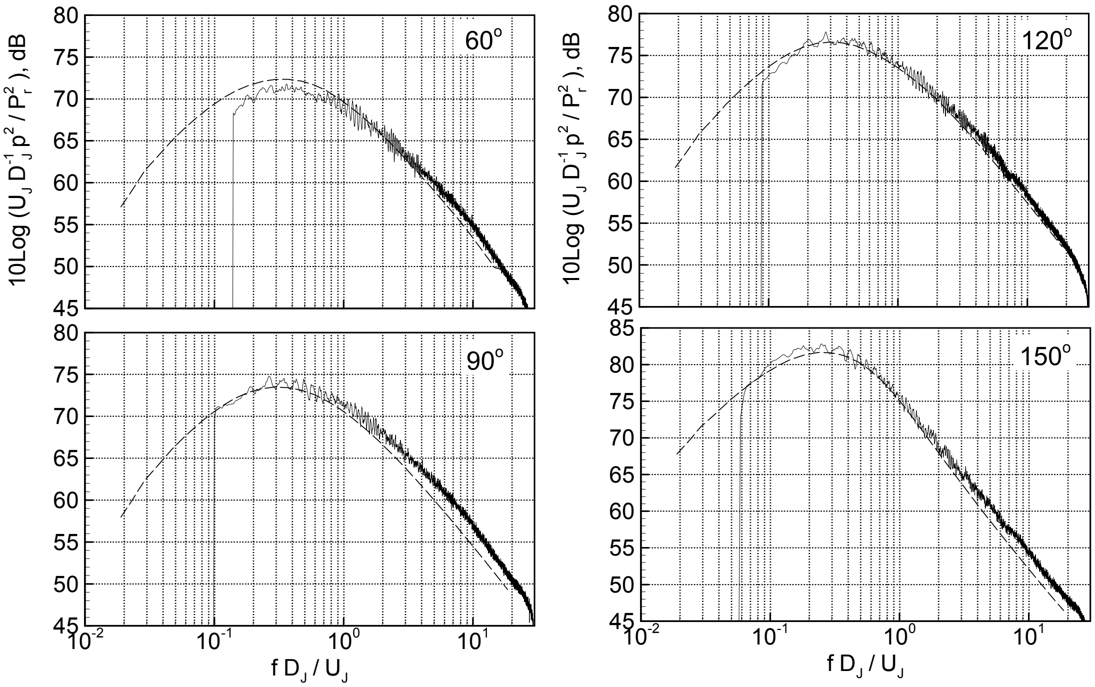


Figure 6.—Spectrum at indicated inlet angles and comparison with data. Mach 0.51 unheated jet (ARN2-SP03)

The case presented in the first tutorial is only one of a total of seven unheated single stream validation cases presented here. Both subsonic and supersonic single stream validation cases are listed in Table 3. All nozzles have a 2 inch exit diameter. The first two set points are subsonic—and utilize the 2-inch Acoustic Reference Nozzle (ARN2) as shown in Figure 2. Figure 7 shows the lossless spectrum in a Mach 0.98 unheated jet (i.e., SP07) on a 100D_J arc, and using the ARN2 nozzle geometry of Figure 2. The remaining supersonic jets require properly designed shock-free Convergent-Divergent (CD) nozzles to obtain a fully expanded flow at each design condition.

Table 3.—Unheated jet cases ($T_o/T_\infty = 1$)

Nozzle	Condition	Mach No.	U_J/a_∞
ARN 2	SP03	0.51	0.50
ARN 2	SP07	0.98	0.90
CD 1.18	M1.18	1.185	1.047
CD 1.4	M1.40	1.40	1.186
CD 1.5	M1.50	1.50	1.245
CD 1.66	M1.66	1.66	1.33
CD 1.8	M1.80	1.80	1.40

The Mach 1.50 CD nozzle geometry and grid are illustrated in Figure 8. In practice, a slight deviation from the design conditions generated shock-associated noise (and possibly screech) that contaminated the jet mixing noise at up-stream, and to a lesser extent near the mid-angles. This is usually noticed as an anomaly in noise data at mid to higher frequency or possibly as screech-related spikes.

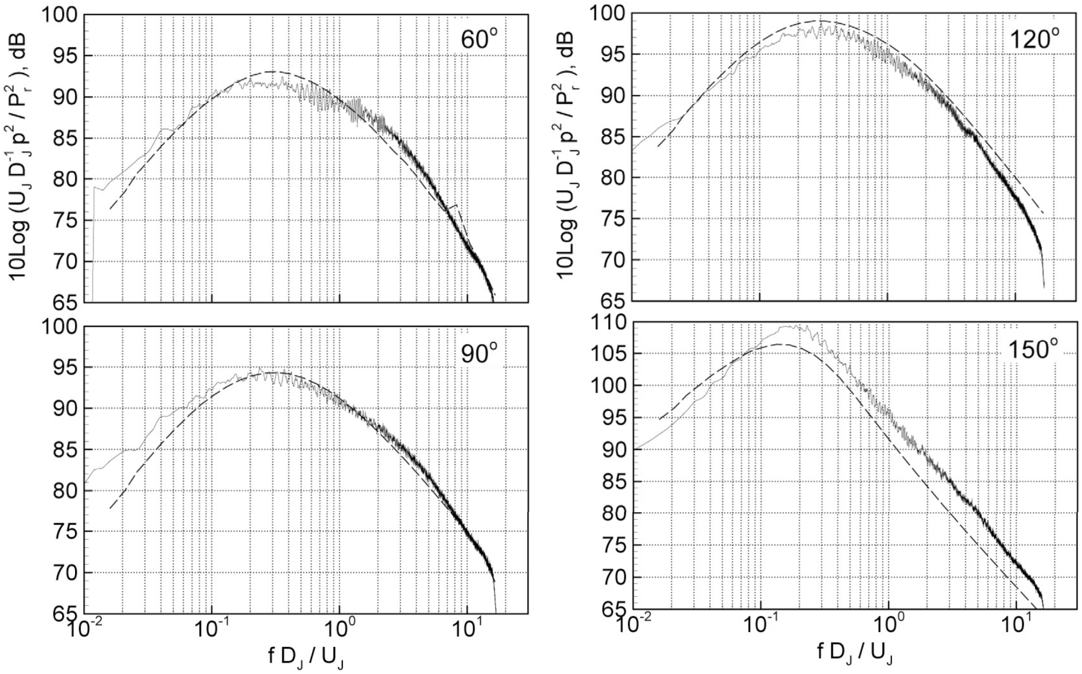


Figure 7.—Spectra at indicated inlet angles and comparison with data. Mach 0.98 unheated jet (ARN2–SP07).

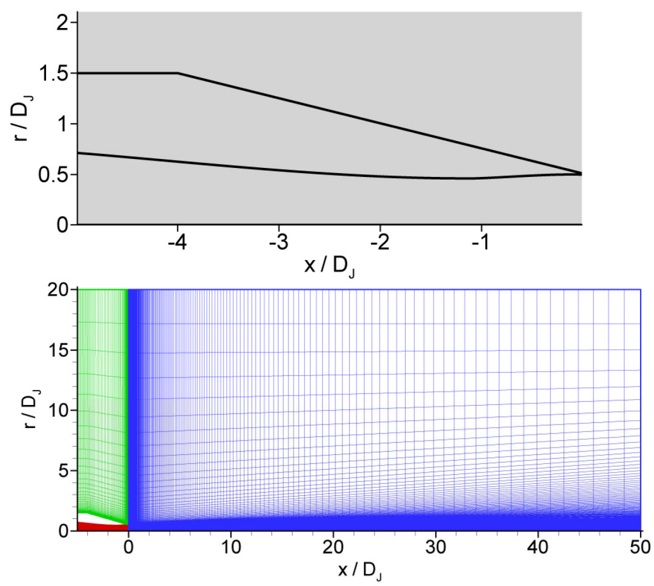


Figure 8.—Geometry and grid—Mach 1.50 convergent-divergent nozzle.

From a theoretical point of view, the mechanism describing the generation of a shock-associated noise is entirely different from that of the jet mixing noise. Semi-empirical models are available in the literature that estimate this noise component from parameters such as deviation from the design point, shock-cell spacing, shock intensity, and so on. JeNo predictions are currently limited to the jet mixing noise, although a shock module could readily be incorporated into the code.

Narrow-band spectra were calculated for all five CD nozzles of Table 3 and compared with lossless data from the NASA Glenn Small Hot Jet Acoustic Test Rig (SHJAR) along a $100D_J$ arc, as seen in Figure 9. Since the CFD solutions were generated with a k-Ω turbulence model available in the Wind code on the 3-block grid as seen in Figure 8, additional pre-processing was needed before running JeNo. An external code is provided below that calculates k and ε from the supplied k and Ω turbulent variables. The code writes out a single block solution (i.e., block 3) suitable for JeNo calculations. As in the first tutorial example, the normalization of k and ε are done within JeNo.

```
cccccccccccccccccccccccccccccccccccccccc
c CD Nozzles
c Reads 3 blocks and outputs block#3 - Wind RANS ( k-Omega solution )
ccccccccccccccccccccccccccccccccccccccccc
c Mach 1.40, 1.50, 1.66, 1.80; 3 blocks: (201x101), (61x61), (201x181)
c Mach 1.185;                  3 blocks: (201x101), (61x61), (201x171)
c
c (wrt block3, jexit =1, Klip= 101, Dj/2=1" )
c
      PARAMETER (JD=201, KD=181, nb = 3)
      REAL              X(JD,KD,nb),Y(JD,KD,nb),Q(JD,KD,8,nb)
      INTEGER           JL(nb), KL(nb)
      REAL              XMACH,ALPHA,RE,DT
      REAL              Tref, Lref
      CHARACTER(len=100)  GFILE, QFILE, TFILE
      GFILE = './mach.1.40.x'
      QFILE = './mach.1.40.q'
      TFILE = './mach.1.40.t'
c
c reference values (lb – ft- s)
c
      Pinf = 14.3*144.
      Tinf = 530.
      Lref = 1.0
      Rgas = 1716.
      Gamma= 1.4
      Aref = sqrt(Gamma*Rgas*Tinf)
c
c assign output files to a single block
c
      open (27, file='mach1.40_1b.x',form='unformatted')
      open (28, file='mach1.40_1b.q',form='unformatted')
      open (29, file='mach1.40_1b.t',form='unformatted')
c
c RANS Solution files
c
      open (37, file=GFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (38, file=QFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (39, file=TFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
c
c read grid for all blocks
c
      READ(37) NBLK
      READ(37) (JL(i_block), KL(i_block), i_block = 1, nb)
C
      do i_block = 1, nb
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(37) (( X(J,K,i_block),J=1,JMAX),k=1,kmax)
     &        ,(( Y(J,K,i_block),J=1,JMAX),k=1,kmax)
      enddo
c
c read Q file in its normalized form
```

```
c
C  Q1    : Density
c  Q2    : X momentum
c  Q3    : Y momentum
C  Q4    : Internal energy/unit mass
c
      READ(38) NBLK
      READ(38) (JL(i_block), KL(i_block), i_block = 1, nb)
      do i_block = 1, nb
      READ(38)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(38)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=1,4)
      Enddo
c
c read turbulence file
c
C  Q5    : k (ft2/s2)
c  Q6    : mut/muref
c  Q7    : Omega (1/s)
C  Q8    : U (ft/s)
c
      READ(39) NBLK
      READ(39) (JL(i_block), KL(i_block), i_block = 1, nb)
      do i_block = 1, nb
      READ(39)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(39)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=5,8)
      enddo
c
c output block#3 (single block- unformatted)
c
      i_block = 3
      jmax = JL(i_block)
      kmax = KL(i_block)
      WRITE(27) 1
      WRITE(27) jmax, kmax
      WRITE(27) (( X(J,K,i_block),J=1,JMAX),k=1,kmax)
     &         ,(( Y(J,K,i_block),J=1,JMAX),k=1,kmax)
c
      WRITE(28) 1
      WRITE(28) jmax, kmax
      WRITE(28) XMACH,ALPHA,RE,DT
      WRITE(28)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=1,4)
c
      WRITE(29) 1
      WRITE(29) jmax, kmax
      WRITE(29) XMACH,ALPHA,RE,DT
C
C output k,e,k,e
c Convert Omega into epsilon (epsilon = 0.09*Omega*k)
c
      WRITE(29)               (( Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
     & ,(( 0.09*Q(J,K,7,i_block)*Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
     &                        ,(( Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
     & ,(( 0.09*Q(J,K,7,i_block)*Q(J,K,5,i_block),J=1,JMAX),k=1,kmax)
c
      stop
      end
```

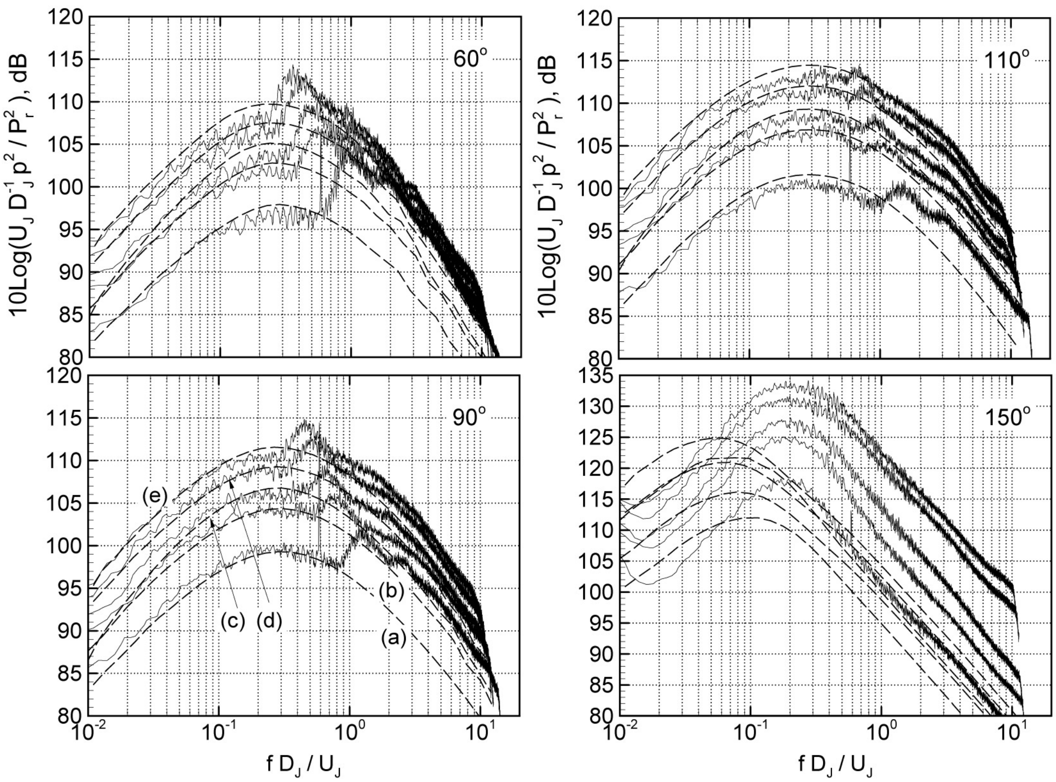


Figure 9.—Comparison between calculated spectra (dashed lines) and data at indicated inlet angles. (a) M_J=1.185, (b) M_J=1.40, (c) M_J=1.50, (d) M_J=1.66, (e) M_J=1.80.

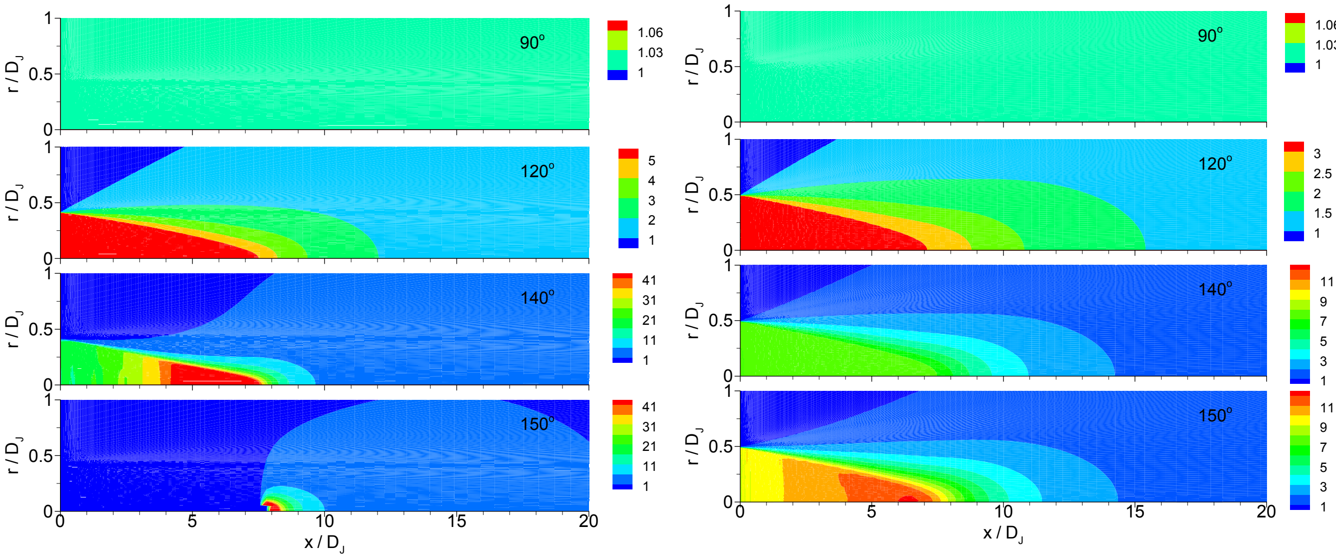
2.5.1 Small Angle Predictions

It was pointed out earlier that the instability-associated noise enters the noise spectrum at small angles when the acoustic Mach number exceeds the sonic point. Supersonic calculations of Figure 9 exhibit a gradual deterioration at shallow angles. The predicted spectrum peaks at a lower frequency compared to data. This was also noticeable, although to a lesser degree, at the 150° spectral peak in Mach 0.98 jet (Figure 7).

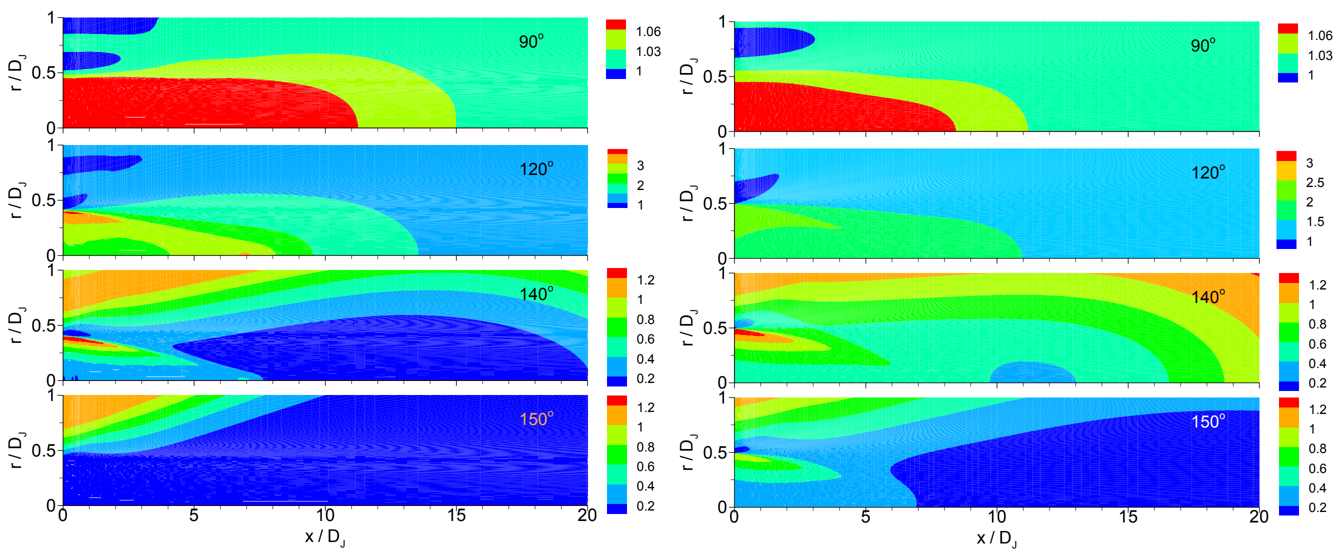
It is conceivable that, in addition to the instability-related noise, jet spread could also play a role at small angles and near the zone of *relative* silence. A parallel flow model is known to exaggerate the High Frequency (HF) refraction. The actual decay rate into the cone of silence is relatively less steep when the HF-GF is calculated in a truly spreading jet. The effect of jet divergence on the Low Frequency (LF) noise is less clear and yet to be determined. For long waves, the "*locally parallel flow*" assumption is more likely to deteriorate when the mean flow is not slowly varying on a wavelength scale. On the other hand, one could also argue that refraction is relatively weak at low frequencies.

Figure 10 shows the Green's function for the M1.50 jet. Similar figures are also shown for Mach 0.98 jet, side-by-side, for comparison. Local jet profiles at each source location were utilized to solve the propagation equation. Using a stationary Monopole-type source, the Green's function was calculated for a unit volume ring at radius *r*—and mapped throughout the jet as a function of the observer polar angle and frequency. JeNo code may easily be customized to store the Green's function at selective angles and frequencies.

The M1.50 jet shows strong HF attenuation at small angles, i.e., less than 40° to the axis. More importantly, the relative amplification of the LF noise due sources *near the centerline* and/or close to the ending of the potential core cannot go un-noticed. Fortunately, turbulence level remains very small within the laminar core. Given the amplifying effect of the Green's function at low frequency (and small angles), and the high-intensity sources near the core ending, both factors compound and radiate strong low frequency noise originating from this vicinity.



(a)



(b)

Figure 10.—Green's function due a monopole-type stationary ring source at indicated inlet angles at (a) *St* = 0.10. Left Mach 1.50 (M1.50); right Mach 0.98 (SP07) jet. (b) *St* = 1.0. Left Mach 1.50 (M1.50); right Mach 0.98 (SP07) jet.

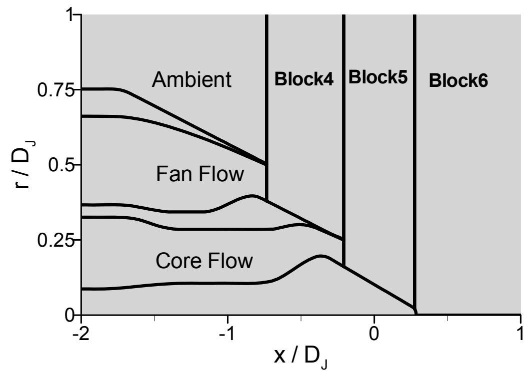
3.0 Tutorial II—Dual Stream Nozzle

3.1 Prepare CFD Input

When the jet flow consists of multiple streams and/or a centerbody, CFD solution files need to be restructured into a single block for export to JeNo. As before, a single-block rectangular grid with dimensions (JD x KD) describes the jet segment to be integrated. Rather than using I-blanked nodes to exclude portions of the flow that do not enter noise calculations, these segments are excluded from the slice integration by calling module `Center_Body` within JeNo. The module should be customized to define the starting radial location for noise work at each jet slices.

In practice, it should not be a difficult task to modify the JeNo code slightly in order to manage the multi-grid solutions directly, provided that all blocks are *stacked in a stream-wise direction*, as seen in Figure 11.

As an example, let's consider a dual flow nozzle (configuration 3BB) shown in Figure 11. It consists of a primary core flow, a secondary fan flow and the ambient. A center body extends out of the core stream. While the original grid used for the mean flow solution consisted of more than 6 blocks, Wind utilities were used to merge some together to form a six block grid. Block 6 extends nearly 15 fan diameter downstream from the fan exit, but only a small segment of the grid is highlighted for clarity. The following code prepares the JeNo grid by creating "ghost points" toward the centerline for blocks 4 and 5, and combines blocks 4, 5 and 6 into a single rectangular grid (361×301). The blocks representing the Core Flow (1), Fan Flow (2) and Ambient Flow (3) are not used in the JeNo calculation.



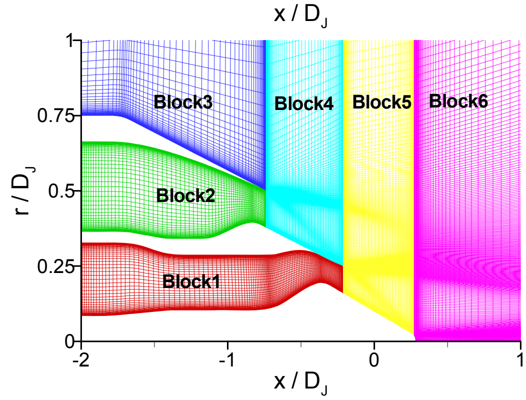


Figure 11.—Dual flow nozzle (3BB) with a center body. (a) Multiblock grid used for mean flow solution of a dual stream nozzle with centerbody. (b) Single block grid for JeNo solution of a dual stream nozzle with centerbody.

```
cccccccccccccccccccccccccccccccccccccccc
c 3bb Nozzles
c Reads 6 blocks and combines blocks 4 through 6 into a single block size (361 x 301)
c Wind RANS ( k-Omega solution )
ccccccccccccccccccccccccccccccccccccccccc
c block1 (141 x 81)  core flow prior to exit
c block2 ( 81 x 81)  fan flow prior to exit
c block3 ( 81 x 81)  ambient flow prior to fan exit
c block4 ( 81 x161)  fan and ambient flow from fan exit to core exit
c block5 ( 81 x261)  fan, core and ambient flow from core exit to neat the plug tip
c block6 (201 x301)  fan, core and ambient from near plug tip to final down-stream
c                    location.
c
      PARAMETER (JD=201, KD=321, nb = 6, jm = 81+81+201-2)
      REAL              X(JD,KD,nb),Y(JD,KD,nb),Q(JD,KD,8,nb)
      REAL              XX(jm,KD),YY(jm,KD),QQ(jm,KD,6)
      INTEGER           JL(nb), KL(nb)
      REAL              XMACH,ALPHA,RE,DT
      REAL              Tref, Lref
      CHARACTER(len=100)  GFILE, QFILE, TFILE
      GFILE = './3bb.x'
      QFILE = './3bb.q'
      TFILE = './3bb.k'
c
c reference values (lb - ft- s)
c
      Pinf = 14.3*144.
      Tinf = 529.67
      Lref = 1.0
      Rgas = 1716.
      Gamma= 1.4
      Aref = sqrt(Gamma*Rgas*Tinf)
c
c assign output files to a single block
c
      open (27, file='3bb_1b.x',form='unformatted')
      open (28, file='3bb_1b.q',form='unformatted')
      open (29, file='3bb_1b.t',form='unformatted')
c
      open (37, file=GFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (38, file=QFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
      open (39, file=TFILE,form='unformatted',STATUS='OLD',IOSTAT=istat)
c
c read grid for all blocks
c
      READ(37) NBLK
      READ(37) (JL(i_block), KL(i_block), i_block = 1, nb)
      do i_block = 1, nb
      JMAX = JL(i_block)
      kmax = KL(i_block)
      READ(37) (( X(J,K,i_block),J=1,JMAX),k=1,kmax)
     &        ,(( Y(J,K,i_block),J=1,JMAX),k=1,kmax)
      enddo
c
c read 2D Q file
c
C  Q1    : Density
c  Q2    : X momentum
c  Q3    : Y momentum
C  Q4    : Internal energy/unit mass
c
      READ(38) NBLK
      READ(38) (JL(i_block), KL(i_block), i_block = 1, nb)
```

```
      do i_block = 1, nb
      READ(38)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(38)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=1,4)
      enddo
c
c read ke file
c
C  Q5    : k (ft2/s2)
c  Q6    : Omega (1/s)
C  Q7    : k (ft2/s2)
c  Q8    : Omega (1/s)
c
c
      READ(39) NBLK
      READ(39) (JL(i_block), KL(i_block), i_block = 1, nb)
      do i_block = 1, nb
      READ(39)XMACH,ALPHA,RE,DT
      jmax = JL(i_block)
      kmax = KL(i_block)
      READ(39)((( Q(J,K,n,i_block),J=1,JMAX),k=1,kmax),n=5,8)
      enddo
c
c combine blocks 4, 5 and 6
c
      j_start = 0
      do i_block = 4,6
         if(i_block .eq. 4) then
        j_start=0
        else
        j_start = j_start + JL(i_block-1)-1
        endif
c
      kk = KL(6) - KL(i_block)
      do j = 1, JL(i_block)
      do k = 1, KL(6)
       if( k .LE. kk) THEN
       xx(j+j_start,k) = x(j, 1, i_block)
       yy(j+j_start,k) = y(j, 1, i_block)
       do n = 1,6
       qq(j+j_start,k,n) = q(j, 1, n, i_block)
       enddo
       else
       xx(j+j_start,k) = x(j, k-kk, i_block)
       yy(j+j_start,k) = y(j, k-kk, i_block)
       do n = 1,6
       qq(j+j_start,k,n) = q(j, k-kk, n, i_block)
       enddo
       endif
c
      enddo
      enddo
c
      enddo
      write(6,*) ' Final j = ',j+j_start -1
c
c output blocks 4, 5 and 6 as a single block (unformatted)
c
      jmax = JL(4)+ JL(5) + JL(6) -2
      kmax = KL(6)
      WRITE(27) 1
      WRITE(27) jmax, kmax
```

```
      WRITE(27) (( XX(J,K),J=1,JMAX),k=1,kmax)
     &         ,(( YY(J,K),J=1,JMAX),k=1,kmax)
c
      WRITE(28) 1
      WRITE(28) jmax, kmax
      WRITE(28) XMACH,ALPHA,RE,DT
      WRITE(28)((( QQ(J,K,n),J=1,JMAX),k=1,kmax),n=1,4)
c
      WRITE(29) 1
      WRITE(29) jmax, kmax
      WRITE(29) XMACH,ALPHA,RE,DT
c
c Convert Omega into epsilon (Epsilon = 0.09*Omega*k)
c
      WRITE(29)                (( QQ(J,K,5),J=1,JMAX),k=1,kmax)
     & ,(( 0.09*QQ(J,K,6)*QQ(J,K,5),J=1,JMAX),k=1,kmax)
     &                         ,(( QQ(J,K,5),J=1,JMAX),k=1,kmax)
     & ,(( 0.09*QQ(J,K,6)*QQ(J,K,5),J=1,JMAX),k=1,kmax)
c
     write(*,*) ' Single block now has dimension:', jmax,' x',kmax
c
      CLOSE(27)
      CLOSE(28)
      CLOSE(29)
      stop
      end
```

3.2 Prepare JeNo Input

As is done here, one may choose to define the exit conditions at the fan exit. Thus the maximum axial velocity component and the jet diameter at the fan exit plane would be utilized to normalize the frequency as shown in the "***noise.inp***" file.

3.2.1 3BB Input File

```
3BB Nozzle (Lref=1 -> Dj=0.80238ft)
&CFD_FILES
GFILE = './3bb_1b.x'
QFILE = './3bb_1b.q'
TFILE = './3bb_1b.t'
&END
&JET_DATA
Jexit = 1, Klip = 221, j_start= 1, j_end= 361, j_inc= 5,
Pinf = 2073.6, Tinf = 529.67, h_r = 70.0,
Rgas=1716.0, Gamma=1.4, Lref=1.0,
Robs = 80.238, N_Arc=1, St_min =.020, St_max= 14.0, NPRINT = 0,
I_restart = 0, I_CB = 1, I_band=0,
Nang= 9, Thetd=
20.,30.,40.,50.,60.,70.,90.0,110.,120.
&END
```

Flag `I_CB = 1` points to an existing module within JeNo (listed subsequently) that sets the initial radial node for each slice integrated. A default value of `I_CB = 0` selects the first radial point as the starting node.

The following code segment shows the calling statement when `I_CB` is not zero.

```
c
c determine starting radial count at each slice location J
c
      IF( I_CB .EQ. 0) THEN
         DO J = 1, JMAX
         Kstart(J) = 1
         ENDDO
      ELSE
         CALL Center_Body
      ENDIF
```

Module `Center_Body`, as tailored for the 3BB nozzle geometry (single-block grid structure) is listed here.

```
c ------------------------------------------------------------------
      SUBROUTINE Center_Body
c ------------------------------------------------------------------
c
      INCLUDE 'dimensions.i'
      INTEGER       Kstart(JD)
      COMMON / Radial_start/Kstart
      CHARACTER*30 IDENT
c
c 3BB geometry
c
      IDENT = '3BB_NOZZLE CONFIGURATION'
      JMAX = JD
      DO J = 1, JMAX
                    IF (J .LE. 81) THEN
                    Kstart(J) = 141
                    ELSEIF( J. LE. 161) THEN
                    Kstart(J) = 41
                    ELSE
                    Kstart(J) = 1
                    ENDIF
      ENDDO
      WRITE(6,*)'  '
      WRITE(6,*) ' Center body geometry was read for ', IDENT
      WRITE(55,*)' Center body geometry was read for ', IDENT
c
      RETURN
      END SUBROUTINE Center_Body
```

The parameter `Kstart(J)` is defined at each axial slice `J`, and works to I-blank cell nodes that should not appear in noise calculations. This parameter is not necessary tied to the presence of a center body in the flow. The above 3BB nozzle requires I-blanked cells to exclude a segment of the primary jet between fan and core exit planes, regardless of the presence of a plug.

3.3 Run the JeNo Code

The standard input and standard output files are directed at runtime using standard UNIX redirection syntax as:

JeNo_executable_name < noise.inp

If a restart run is desired, the user must move the most current output restart from:

Case.restart.new

to the default input restart file name:

Case.restart.old

each time the code is restarted.

Appendix A

A.1 Summary of JeNo Modules

The following is a summary of JeNo modules and their tasks. JeNo makes use of scientific subroutines from the SLATEC Mathematical Library. The SLATEC routines have been modified slightly to conform to Fortran90 conventions, exclude obsolescent constructs, and take advantage of new Fortran90 intrinsic functions. Only the top–level SLATEC routines are described here. JeNo uses the following SLATEC routines which are included in the JeNo distribution: BEJ, BESJ, BJ0, BJ1, D1MACH, D9LGMC, DBINT4, DBNFAC, DBVALU, DBSPEV, DBSPVD, DBSPVN, DCSEVL, DGAMLM, DGAMMA, DINTRV, HAN, HAN0, HAN1, HANN, I1MACH, INITDS, J4SAVE, XERCNT, XERHLT, XERMSG, XERPRN, and XGETUA. The original subroutines are available on the Web at www.netlib.org.

JENO_2D – Main Program, reads input parameters, forms required loops for slice integration of the jet				
	INPUT – Reads CFD files, calculates exit and ambient parameters, performs normalization of k and ε (if necessary)			
		CENTER_BODY – Determines the starting radial node in jet slice integration (should be customized for the particular jet)		
	STROUHAL – Determines the dimensionless frequency at each 1/3–Octave center frequency			
	READ_RESTART – Reads restart file `fort.53` when flag is on			
	SLICE – Stores mean flow profiles and calculates the spline interpolation coefficients			
		DBINT4 – (SLATEC) Compute the B–representation of a cubic spline which interpolates given data.		
		DBSPDR – (SLATEC) Use the B–representation to construct a divided difference table preparatory to a (right) derivative calculation.		
		FIND_EPSILON – Determines the proper radius in contour deformation around a singularity		
	SPECTRAL_DENS – Calculates the source strength and frequency scales			
	NUMBER_OF_MODES – Determines the number of azimuthal modes to be summed at each frequency			
	PARALLEL_GREEN – Initiates the calculation of the GF for a locally parallel flow			
		CRITICAL_POINT – Locates and stores all critical points related to singularities of the propagation equation on a jet slice		
			INTMEAN – Interpolates on the mean flow	
				DBSPEV – (SLATEC) Calculates the value of the spline and its derivatives from the B–representation
		EPSILON_TO_FCM – Integrates the propagation equation in an appropriate range		
			DE – Integrates a system of up to 20 first order ordinary differential equations	
				INTRP –
				STEP –
			FDERIV_REAL – Calculates the mean flow derivatives in a real plane	
				INTMEAN (see above)
		DIRECT_EPSILON_TO_FCM – Integrates the propagation equation in an appropriate range		
			DE (see above)	
			FDERIV_REAL (see above)	
		CIRCLE_THE_ARC – Integrates the propagation equation in an appropriate range		
			DE (see above)	

			FDERIV_ARC – Calculates the mean flow derivatives in a complex plane	
				INTMEAN (see above)
		NEXT_CRITICAL – Integrates the propagation equation in an appropriate range		
			DE (see above)	
			FDERIV_REAL (see above)	
		TO_JET_BOUNDARY – Integrates the propagation equation in an appropriate range		
			DE (see above)	
			FDERIV_REAL (see above)	
		NO_CRITICAL_POINT – Integrates the propagation equation in an appropriate range		
			DE (see above)	
			FDERIV_REAL (see above)	
		INTMEAN (see above)		
		BESJ – (SLATEC) Computes the complex Bessel function of order N with argument Z		
		HANN – (SLATEC) Computes the Hankel function of the first kind of order N with argument Z		
		RING_GREEN – Calculates the ring source GF in an axisymmetric jet		
	CONVOLUTION – Performs the source/Green's function convolution integral			
		INTMEAN (see above)		
	OUTPUT_RESTART – Writes a restart file `fort.54`			
	OUTPUT_SPECTRA – Outputs tables of sound spectral density to `fort.55`			
		ATMOS_LOSS – Attenuates the spectra for atmospheric loss		
MODULES – Declares shared variables				

References

1. Khavaran, A., Bridges, J., and Georgiadis, N., “Prediction of Turbulence-Generated Noise in Unheated Jets—Part 1: JeNo Technical Manual (Version 1.0),” NASA/TM–2005-213827.
2. Khavaran, A., and Bridges, J., “Modeling of Turbulence Generated Noise in Jets,” AIAA Paper 2004–2983, May 2004.
3. Khavaran, A., Georgiadis, N.J., Bridges, J., and Dippold, V.F., “Effect of Free Jet on Refraction and Noise,” AIAA Paper 2005–2941, May 2005. (Also NASA/TM—2005-213821).
4. Lilley, G.M., “The Radiated Noise from Isotropic Turbulence with Application to the Theory of Jet Noise,” J. Sound and Vibration, **190(3**), 1996, pp. 463–476.
5. Nelson, C.C., and Power, G.D., CHSSI Project CFD-7: The NPARC Alliance Flow Simulation System, AIAA Paper 2001–0594, Jan. 2001
6. Lilley, G.M., “On the Noise from Jets, Noise Mechanisms,” AGARD–CP–131, 1974, pp. 13.1–13.12.
7. Goldstein, M.E., *Aeroacoustics*, 1976, New York, NY, McGraw-Hill.
8. Goldstein, M.E., “A Generalized Acoustic Analogy,” J. Fluid Mechanics, **488**, pp. 315–333, 2003.
9. Bridges, J., and Wernet, M. P., “Measurements of the Aeroacoustic Sound Source in Hot Jets” AIAA Paper 2003–3130, May 2003.

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14. ABSTRACT
JeNo (Version 1.0) is a Fortran90 computer code that calculates the far-field sound spectral density produced by axisymmetric, unheated jets at a user specified observer location and frequency range. The user must provide a structured computational grid and a mean flow solution from a Reynolds-Averaged Navier Stokes (RANS) code as input. Turbulence kinetic energy and its dissipation rate from a k-ε or k-Ω turbulence model must also be provided. JeNo is a research code, and as such, its development is ongoing. The goal is to create a code that is able to accurately compute far-field sound pressure levels for jets at all observer angles and all operating conditions. In order to achieve this goal, current theories must be combined with the best practices in numerical modeling, all of which must be validated by experiment. Since the acoustic predictions from JeNo are based on the mean flow solutions from a RANS code, quality predictions depend on accurate aerodynamic input.This is why acoustic source modeling, turbulence modeling, together with the development of advanced measurement systems are the leading areas of research in jet noise research at NASA Glenn Research Center.

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