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# Fast Scattering Code (FSC) User’s Manual

## *Version 2.0*

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# CHAPTER 1 Introduction

## 1.1 FSC DESCRIPTION AND FEATURES

The Fast Scattering Code (version 2.0) is a computer program for predicting the three-dimensional scattered acoustic field produced by the interaction of known, time-harmonic, incident sound with aerostructures in the presence of potential background flow. The FSC has been developed for use as an aeroacoustic analysis tool for assessing global effects on noise radiation and scattering caused by changes in configuration (geometry, component placement) and operating conditions (background flow, excitation frequency).

The code is written in the FORTRAN programming language, and can be operated in batch mode or driven by a graphical user interface (GUI) written in C++ and developed using WXWidgets. Although the FSC was developed for the UNIX and LINUX operating systems, it can be adapted for Windows and Macintosh environments as well. FSC v2.0 can be requested through the NASA Langley Research Center Geometry Laboratory web page (http://geolab.larc.nasa.gov).

Upgrades featured in Version 2.0 of the FSC include the effects of a non-uniform background flow, full scale prediction capability for axi-symmetric configurations (e.g., engine nacelles represented by a body of revolution), and liner treatment capabilities. The code has been modularized to facilitate future upgrades and ported to FORTRAN 90 to take advantage of dynamic memory allocation. The GUI includes a viewer for examining and manipulating graphical images of the input geometry and FSC discretization schemes, facilitating proper program usage.

The FSC has been applied to various aeroacoustic scattering simulations involving full-scale GE90-like engines, and scale models of a commercial transport similar to the Boeing 777, and Blended Wing Body (BWB) configurations (see references 1 through 4). Many of the code features, including input/output options, are illustrated in the reference papers and summarized below in section 1.2. Brief discussions on the FSC theoretical formulation and numerical solution strategy are presented in sections 1.3 and 1.4. Detailed derivations can be found in references 1 and 2. In section 1.5, computer resource requirements due to the linear algebra algorithms used in the FSC are discussed and related to aeroacoustic predictions using 2005 computer workstation technology.

## 1.2 INPUT AND OUTPUT

The physical and computational details for each input and output variable are described in chapters 2 and 3. They are summarized here for clarity. Input to the FSC can be divided into five categories:

1) Fundamental constants: excitation frequency, freestream thermodynamic variables, and duct mode parameters;
2) Numerical parameters for determining the appropriate grid generation and solution strategies;
3) Data structures defining the scattering surface geometries (wings, fuselages, nacelles) and liner admittances;
4) Local flow variables (density, speed of sound, and Mach number vector) - code options include a) no flow, b) uniform flow, c) FSC generated small perturbation compressible flow, and d) user-supplied flow;
5) Complex values of incident acoustic pressure and acoustic velocity at FSC requested locations in space and time - code options include a) simple point monopole(s) and dipole(s), b) FSC generated engine noise from nacelle alone run, and c) results from external noise codes capable of producing FSC type inputs.

Output from the FSC includes complex values of instantaneous acoustic pressure, velocity and intensity at user prescribed locations in space and time. Users have the option to specify their own observer points or to request field calculations on spheres, cylinders, rectangular volumes surrounding the scattering geometries, or on the aerosurfaces. There is also an option for producing take-off or flyover footprints. The flow of I/O for the FSC is shown schematically in Figure 1.1.

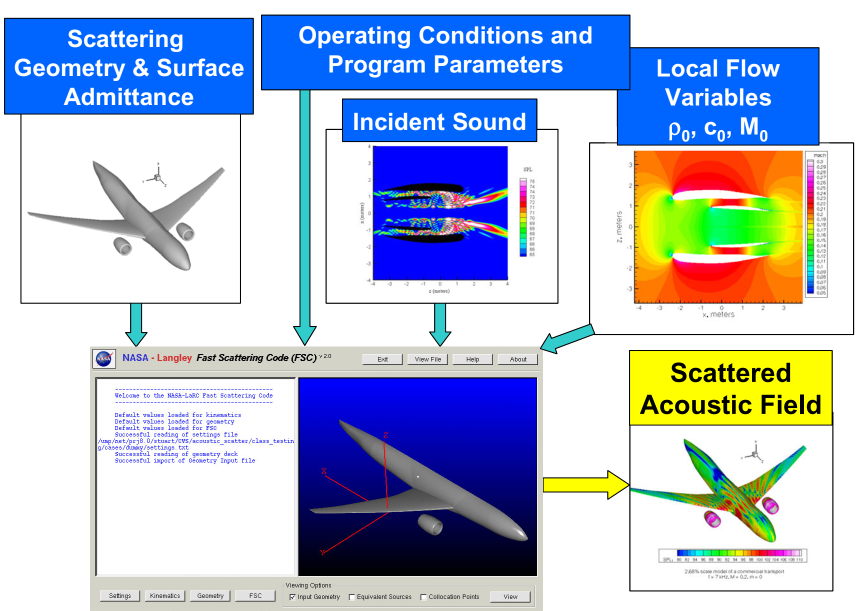



Figure 1.1 - Schematic diagram of FSC input/output.

## 1.3 THEORETICAL FORMULATION

The low speed, steady motion of a thin aerodynamic body through air with an attached time-harmonic ($e^{i\omega t}$) sound source is considered (see Figure 1.2). The resulting flow is assumed to be inviscid and irrotational. The governing acoustical differential equations for the FSC are obtained from a small perturbation analysis of the inviscid flow equations yielding the mass and momentum conservation equations:

$$ik_0 p' + c_0 \nabla \cdot \left(\frac{1}{c_0} p' \vec{M}_0 + \rho_0 \vec{v}'\right) = 0, \; \vec{x} \in S^+ \tag{1.1}$$

$$ik_0 \vec{v}' + \frac{1}{c_0} \nabla\left(\frac{p'}{\rho_0} + c_0 \vec{M}_0 \cdot \vec{v}'\right) = 0, \; \vec{x} \in S^+ \tag{1.2}$$

Where,

$p'$ = acoustic pressure

$v'$ = acoustic velocity

$\rho_0$ = local density

$c_0$ = local speed of sound

$\vec{M}_0$ = local Mach number vector

$k_0 = \frac{\omega}{c_0}$ = local wave number

$\omega$ = excitation frequency

$i$ = $\sqrt{-1}$

On the scattering surfaces, the acoustic pressure and velocity satisfy an impedance boundary condition (see reference 5) given by:

$$\vec{v}' \cdot \hat{n} = Ap'\left[\frac{1}{ic_0 k_0} \hat{n} \cdot (\hat{n} \cdot \nabla c_0 \vec{M}_0) - 1\right] - \left(\frac{1}{ik_0} \vec{M}_0 \cdot \nabla Ap'\right), \; \vec{x} \in S \tag{1.3}$$

Where,

$A = \frac{1}{Z}$ = acoustic admittance

$Z$ = complex normal impedance

$\hat{n}$ = unit surface normal

In the farfield, Sommerfeld's radiation condition is applied:

$$\lim_{R = |\vec{x}| \to \infty} R\left(\frac{\partial}{\partial R} p' + ik_0 p'\right) = 0 \tag{1.4}$$

The known incident sound field is independent of the scattering surfaces and satisfies equations 1.1, 1.2, and 1.4. Thus, the acoustic pressure and velocity can be split into a sum of known incident and unknown scattered parts. For scattering geometries without edges, equations (1.1) through (1.4) comprise a uniquely solvable, exterior boundary value problem (BVP) for the scattered components of acoustic pressure and velocity with source terms provided by the incident sound field. If the geometry contains edges, then equations (1.1) through (1.4) must be augmented by Kutta's edge condition. Edge conditions are not presently available in the FSC, but will be included in future upgrades.

The FSC solves the BVP given by equations (1.1) through (1.4) assuming uniform flow conditions. When the non-uniform flow option is selected an explicit correction involving the local flow variables is applied to the uniform flow field. The conditions under which the uniform flow assumption is valid and the mathematical formulation describing the flow non-uniformity correction are given in reference 2. Calculations for M = 0.2 show little difference between corrected and uniform flow results. Users are warned that the effectiveness of the correction requires further study and will be addressed in future upgrades.

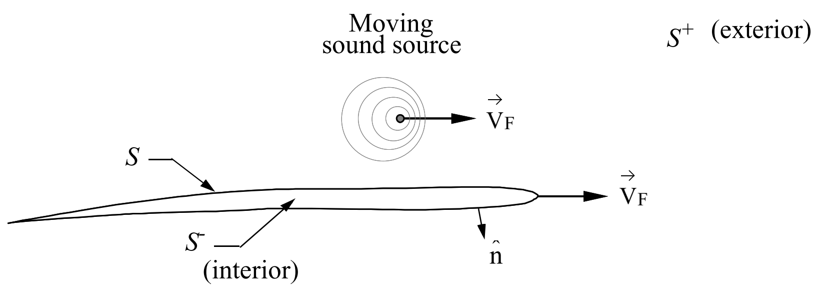



Figure 1.2 - Diagram showing FSC theoretical configuration. *S* denotes scattering surface, $V_F$ is the constant speed of the aerobody and acoustic source.

## 1.4 NUMERICAL SOLUTION

The BVP given by equations (1.1) through (1.4) is solved by the equivalent source method (ESM). A numerical analysis of the solution methodology is given in reference 1. The features of the ESM important to FSC usage are outlined in this section and presented in greater detail in Chapter 2 where ESM discretization parameters are discussed.

The central idea of the ESM is to approximate the solution to the BVP with a superposition of simple sources, such as point monopoles, dipoles, or any multipole combination and determine the strengths of the sources so that the acoustic boundary condition, equation (1.3), is satisfied in the least squares sense. The equivalent sources are located interior to the scattering surfaces and satisfy the partial differential equations (1.1) and (1.2) and the radiation condition, equation (1.4). After selecting the type of equivalent sources for a particular problem, the ESM solution strategy has four steps.

### 1.4.1 Step 1 - Collocation Point Generation

The scattering surfaces are covered with enough grid points (called the collocation points) to capture the incident noise fluctuations (see Figure 1.3). Users control the fineness of the grid with various program parameters. For general three-dimensional scattering problems, the number of collocation points, $N_c$, is given by:

$$N_c = \left(\frac{N_w}{2\pi}\sqrt{S}\frac{\omega}{\beta_\infty c_\infty}\right)^2 \tag{1.5}$$

Where,

| | |
|---|---|
| S | = surface area |
| $N_W$ | = points per wavelength |
| $c_\infty$ | = freestream speed of sound |
| $\beta_\infty$ | $= \sqrt{1 - M_\infty^2}$ |

For axi-symmetric scattering problems, the number of collocation points is given by the square root of equation (1.5) and the numerical complexity of the ESM is reduced substantially.

### 1.4.2 Step 2 - Equivalent Source Generation

Source surfaces, which are smaller replicas of the scattering surfaces, are constructed. These source surfaces are contained entirely inside the scattering surfaces. The source surfaces are discretized in a similar manner as the actual (scattering) surfaces, but are coarser and the selected equivalent source surface distributions are placed at the resulting source points (see figure 1.3). Users control the number of source points, $N_S$, with program parameters. It is computationally advantageous to minimize the number of source points. Numerical evidence suggests that values of $N_s = 0.33 N_c$ give results with acceptable accuracy.

### 1.4.3 Step 3 - Equivalent Source Matrix Solution

A complex matrix equation for the unknown equivalent source strengths is built by evaluating the acoustic boundary condition, equation (1.3), at each of the $N_c$ collocation points and for each of the $N_S$ equivalent sources. After a preconditioning step, the matrix equation is solved using LU decomposition[1]. The numerical linear algebra step is the most computationally intensive of the solution process, and is discussed more thoroughly in the next section.

### 1.4.4 Step 4 - Acoustic Field Computation

The acoustic field is obtained by evaluating the equivalent source distribution at the user specified field locations.

It is noted that users may create their own collocation and equivalent source grids external to the FSC, thus bypassing the geometry module. As long as the information required by the ESM module of the FSC is provided in a suitable format, any grid generation program can be used. Users of this option are advised to maintain similar fineness requirements as expressed in steps 2 and 3.

[1] The linear algebra subroutines used by the FSC (LAPACK/BLAS) can be obtained from the NETLIB repository, which can be found online at http://www.netlib.org/lapack. Usage of versions of the package that have been optimized for the operating system under consideration is strongly recommended.

### 1.4.5 ESM Advantages and Disadvantages

Relative to other boundary solution techniques, the ESM is numerically less accurate, but much simpler to implement, requiring approximately 1/9 the computer memory and 1/27 the computational time. In addition, field calculations are highly amenable to multiprocessor computing. The major disadvantage of the ESM is in the construction of the source surfaces. The process is computationally difficult and there is not much theory to guide the type, location, and number of equivalent sources. Source surface characteristics are problem dependent and discussed in more detail in chapters 2 and 3. Recommended ranges for source surface parameters are based on computational experience.

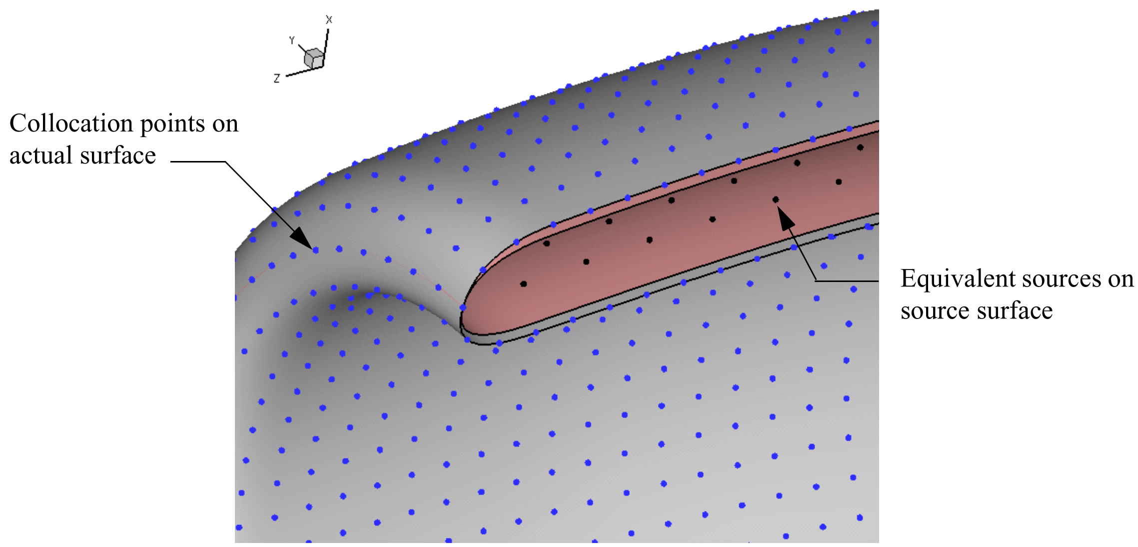



Figure 1.3 - Sample grid for scattering and source surfaces.

## 1.5 LINEAR ALGEBRA CONSIDERATIONS

Computer memory requirements and total execution time for the FSC are strongly dependent on the number of collocation and source points. In the first phase of the linear algebra portion of the ESM solution process (see section 1.4.3), a complex non-square matrix of size $N_c$ x $N_s$ is generated by evaluating the boundary condition $N_cN_s$ times. The preconditioning phase involves premultiplication of the previous matrix by its complex conjugate, requiring $O(N_s^2)$ memory and $O(N_c^2N_s)$ scalar multiplications. LU decomposition requires $O(N_s^2)$ memory and $O(N_s^3)$ scalar multiplications.

In terms of excitation frequency (see equation 1.5), the total memory needed by the FSC is proportional to $\omega^4$ and computational time is proportional to $\omega^6$. The proportionality constants are highly dependent on the scattering surface area. In Figure 1.4, FSC memory is plotted as a function of frequency for several configurations of practical interest. The upper memory limit on the graph (5.0 GB) corresponds approximately to the limitations of 2005 computer workstation technology such as that used to generate the results presented in chapter 3. It is evident from this chart that full-scale, high-frequency scattering predictions for a helicopter geometry ($\omega < 30$ x BPF), non-symmetric nacelles ($\omega < 3$ x BPF), and axi-symmetric nacelles ($\omega < 6$ x BPF) are achievable with 2005 workstation technology. Memory required for large-scale commercial transport simulations at 1 x BPF far exceeds workstation limits. Sample calculations to date have not surpassed 0.3 x BPF for large-scale configurations.

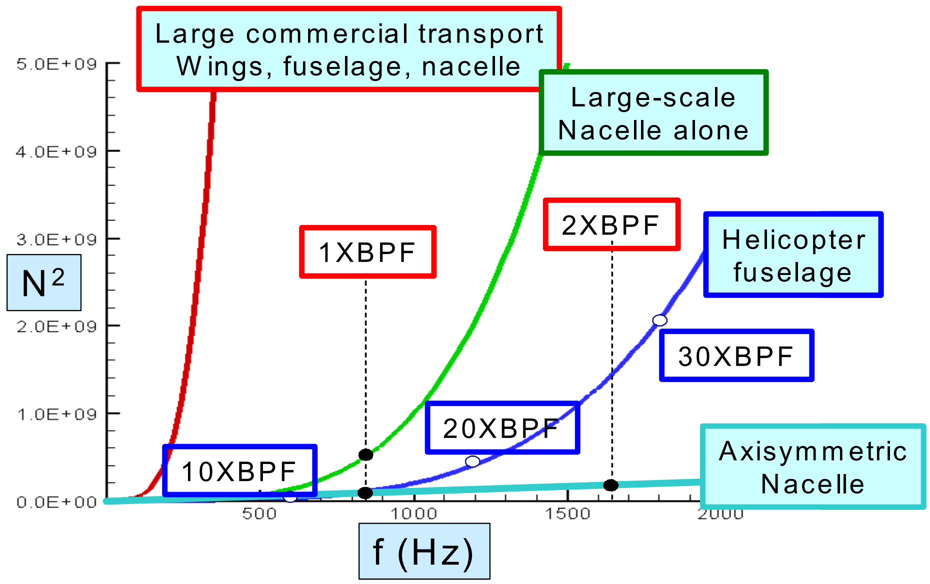



Figure 1.4 - Chart of FSC memory as function of excitation frequency for a) commercial transport (red), b) commercial transport nacelle (green), c) MD-50 type helicopter fuselage (blue), and d) axi-symmetric nacelle (cyan).

CHAPTER 2

# Program Usage

## 2.1 INTRODUCTION

The FSC is composed of two main modules: a geometry module for the generation/placement of collocation points and equivalent sources, and an ESM module for the calculation of acoustic parameters at user-defined observer locations. A preprocessor to the ESM module that tailors the executable file to user selected options for incident/scattered field generation is also included. Input/output and modules can be controlled in two ways: 1) through the use of a graphical user interface (GUI), which includes on-line help and a viewer to facilitate configuration/equivalent source placement evaluation, and 2) batch mode, under which the user manually creates/modifies input files and executes the modules. Note that the FSC is a dimensional code -- all input variables are converted to the SI system of units prior to execution; all output is given in this system as well.

The contents of this chapter are organized as follows: 1) general descriptions of the main components of the FSC (sections 2.1.1 through 2.1.3); 2) information on GUI structure and usage, with detailed descriptions of the various data fields and program options (section 2.2); and 3) information on input file structure and line-by-line descriptions of all input parameters for batch mode execution (section 2.3). Because the GUI has been designed as a facilitator for data collection and code execution, sections 2.2 and 2.3 contain essentially the same information. Thus, the users may choose their preferred approach, and refer only to the corresponding section to learn about running the FSC.

### 2.1.1 Geometry Module

The main function of the geometry module is to generate the required number of collocation points and equivalent sources. The first set of points is distributed on the scattering surface, and the second, on the source surface. The process is as follows:

1) The user input geometry is read in and a two-dimensional fit of each surface is generated.

2) Each splined surface is divided into evenly spaced $N_i$-1 and $N_j$-1 segments of equal arc length, where i and j denote two coordinate directions. The number of segments is determined by Nyquist frequency limitations, i.e., it is dependent on excitation frequency and reference length. The number of collocation points is thus $N_c = (N_i-1).(N_j-1)$

3) Surface normals (to be used by the ESM module) are calculated for every $N_c$.

4) Location of collocation points and their unit normals are written to output.

The procedure to obtain $N_s$ equivalent sources ($N_S \approx 0.333 N_C$) is similar, except that the input surfaces are arbitrarily scaled down prior to being fitted.

### 2.1.2 ESM Module

The ESM module utilizes the output from the geometry module to solve an exterior Helmholtz BVP at each observer location (see reference 1). SI units are assumed throughout the module. The process is as follows:

1) Output from the geometry module (coordinates and surface unit normals for collocation points and equivalent sources) is read in.

2) The acoustic boundary condition at every surface (collocation) point is calculated for each incident source and equivalent source.

3) The equivalent source coefficients are obtained. This is done by minimizing the boundary condition residual matrix using least squares approximation techniques.

4) The coefficients are used to calculate the scattered acoustic variables (pressure, velocity, SPL, intensity) at the chosen observer locations. The total acoustic field is thus given by the sum of the incident and scattered components at every observer. Note that, for constant aerodynamic (geometry, background flow density and velocity) and acoustic (excitation frequency) operating conditions the same set of coefficients can be used for different sets of observers.

### 2.1.3 ESM Module Preprocessor

The preprocessor allows the ESM module to be case specific: the subroutines to be included in the executable file depend on the choices specified by the user in the input deck. Determination of the needed routines is guided by a dependencies file, which communicates to the preprocessor the relationships between the user parameters and the subroutines that go into constructing the executable file (see section 2.3.3).

## 2.2 GRAPHICAL USER INTERFACE

Input/output and code execution can be easily managed through a graphical user interface (GUI). The purpose of the interface is threefold: 1) to provide the means for specifying the quantities necessary for code execution; 2) to provide a vehicle for viewing various geometry files required by, or output from, the code; and 3) to provide a help facility for explanation of the code's functionality and operation. The GUI consists of a task selection area, a viewer, and a messaging area. The arrangement of these primary components is depicted in Figure 2.1. The information submitted through the GUI is written to text files prior to code execution. Thus the code can be run with or without the assistance of the interface. In the latter case, the user must modify the files manually.

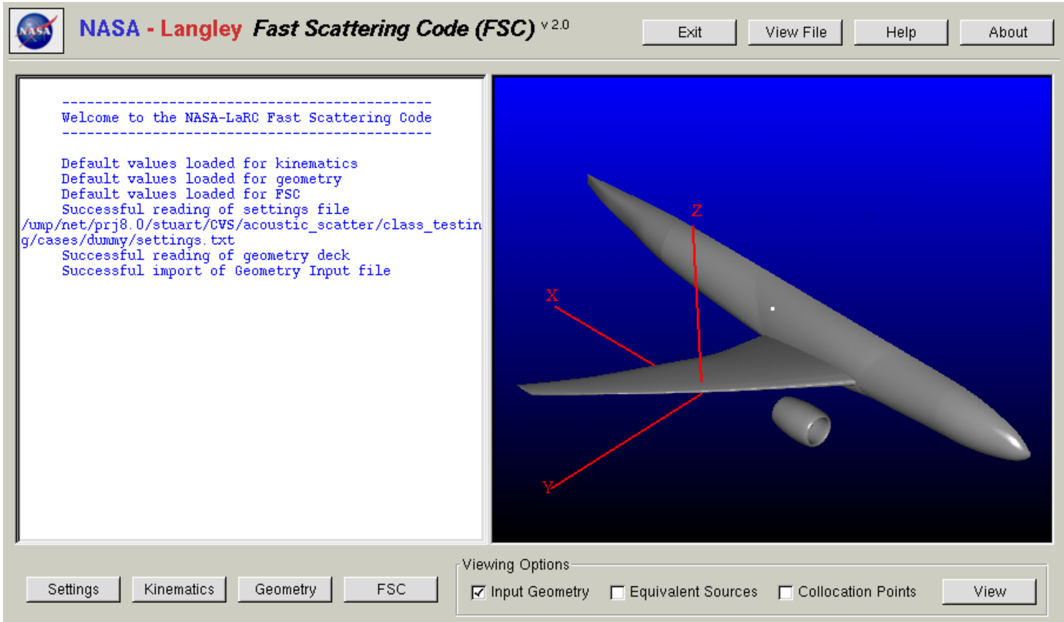



Figure 2.1 - Graphical User Interface - Main dialog.

### 2.2.1 Task Selection

Task selection refers to the various buttons found on the main panel. Most input/output information for a given case is entered via these controls, which activate dialogs that contain text fields and additional buttons used to specify the various quantities needed for code execution. These dialogs perform four basic functions: specification of directory paths and locations of executable files called by the FSC, specification of units and run conditions, execution of the geometry module, and execution of the ESM module.

As the user supplies information, the options applicable to the current specification are sensitized/desensitized accordingly. All fields are initially displayed with default values. Where applicable, these defaults represent recommended parameter values. Defaults can be chosen by clicking the *Load Defaults* button; alternatively, they may be re-specified either by manual entry of a specific quantity, or by reading an appropriate geometry or FSC input deck named in the input deck selection area. Clicking the *Clear Fields* button removes all selections and displays blank fields. When the user is required to specify a file name, it may be entered either by typing it in the text field or by using the file selection dialog activated by clicking the browser button located to the right of the field. **Note: any blank field in a dialog will prevent module execution.**

#### 2.2.1.1 Settings

The GUI is simply a “front end” that accomplishes FSC computations by calling other standalone codes. These codes must be specified by entering their locations in the *Settings* dialog shown in Figure 2.2. In addition to specifying the geometry module and ESM module executable locations, the location of the ESM preprocessor executable is also required. These paths and file names may be saved for subsequent use by writing the settings file from the dialog. Filling in the Settings dialog is a prerequisite to any geometry or ESM calculation, since without specifications, the GUI cannot know where to find the necessary executable and object files.

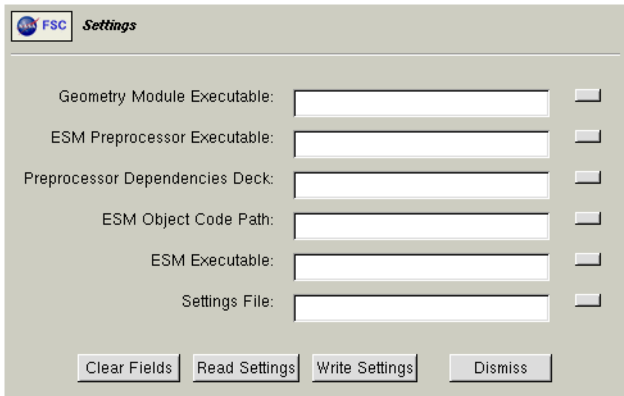



Figure 2.2 - Settings dialog.

### 2.2.1.2 Kinematics

Parameters common to both the geometry and ESM modules are entered through the kinematics tab (see Figure 2.3). These parameters are:

- *Title*: One line describing the case to be calculated.
- *Frequency*: Value of excitation frequency, in Hz.
- *Ambient density*: Value of freestream density, in kg/m$^3$ (default = 1.22 kg/m$^3$).
- *Freestream Speed of sound*: Freestream speed of sound, in m/s (default = 340 m/s).
- *Scale Factor*: Scale factor for input geometry. Usually 1.0.
- *Mach*: Mach number of background flow (default = 0.2).

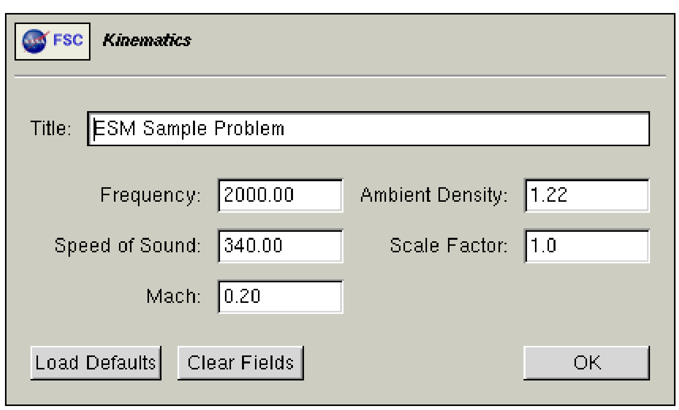



Figure 2.3 - Kinematics dialog.

### 2.2.1.3 Geometry

Geometry units, surface parameters, and names for required input and output files to be used by the geometry module are entered through this dialog (see Figure 2.4). The parameters required to fit the input surfaces and generate the equivalent sources are specified in this dialog.

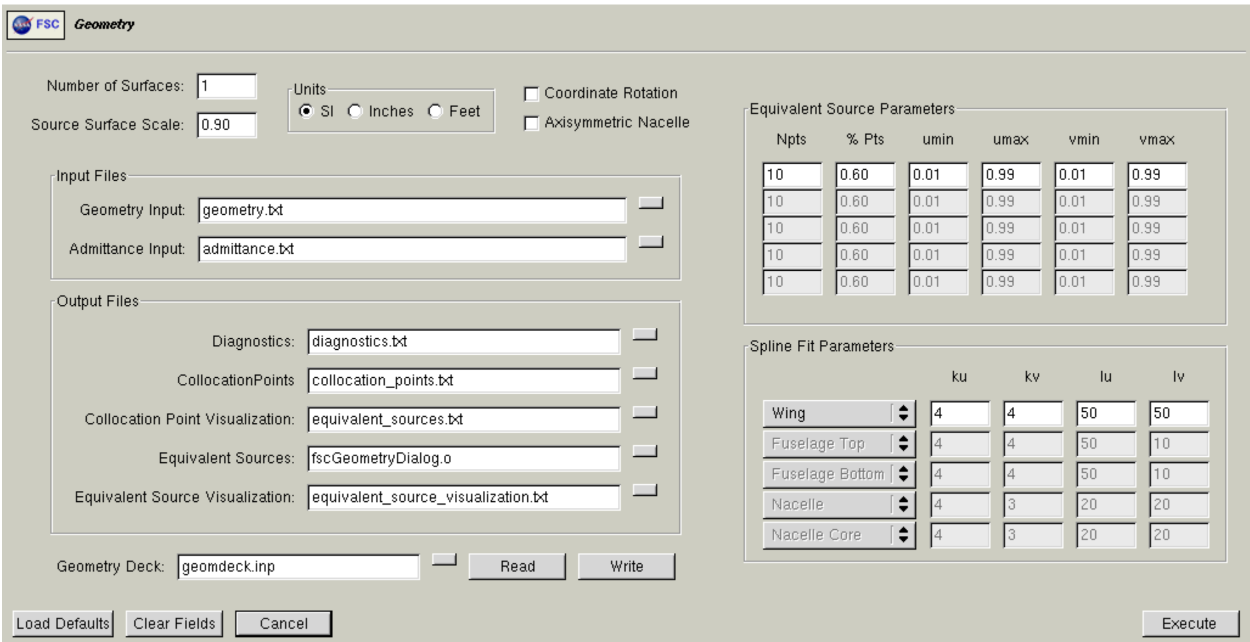



Figure 2.4 - Geometry dialog.

- *Number of Surfaces*: Number of surfaces to be fitted. At present, the code accepts wings, fuselages (must be given as two separate surfaces, top and bottom), nacelles, and engine cores.
- *Source Surface Scale*: Scale of the source surface, referenced to input scattering surface, where the equivalent sources are to be placed. Note that the source surface must be contained within the scattering surface; thus, the scale will always be less than unity. For thick geometries like fuselages, a value between 0.85 and 0.95 is adequate; for thin geometries like nacelles, smaller values should be used.
- *Units*: Dimensional units of input surfaces. Default is meters.
- *Coordinate Rotation*: Coordinate directions can be specified in one of two ways:
  - x increases downstream, y increases spanwise, z increases "up"
  - z increases upstream, y increases spanwise, x increases "up"

  Acoustic calculations use the second orientation (body motion in the +z direction). It is assumed that the input surface follows the first orientation; thus, a coordinate rotation will be performed (default). However, if the input surface follows the second orientation (specified by preceding *number of surfaces* with a negative sign), then the user must deselect the *Coordinate Rotation* button.

- *Axisymmetric Nacelle*: Single input surface is an axisymmetric nacelle. In this case, collocation points and equivalent sources will be generated ONLY for the first airfoil defining the geometry. Output from this choice is to be used with the spinning monopole option for both incident and equivalent sources (see section 2.2.1.4, Acoustic Source Characteristics) to simulate scattered fields for full scale nacelles.

Input Files: File names can be input through the keyboard or selected from the current directory by using the browser, which is activated by clicking the button located at the right of each name field.

- *Geometry Input*: Input file containing the geometric description of the scattering surfaces. The data must be presented as an ordered collection of (x,y,z) single precision points. In order for the code to properly read the geometry, the data must be written in the format below (plot3d). The number of surfaces to be read is indicated by `nsurf` and `id,jd,kd` are the number of points to be read on each surface. Note that for surfaces, `kd` = 1.

```
write (iunit,*) nsurf
write (iunit,*) (id(n),jd(n),kd(n),n=1,nsurf)
do n=1,nsurf
   write (iunit,*) (((x(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                  (((y(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                  (((z(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n))
end do
```

  The geometry must also conform with the following requirements:

  - For wings, the i index increases spanwise from root to tip; the j index increases chordwise from upper trailing edge to lower trailing edge. The same convention applies to nacelles and engine cores, which are considered “wrapped” wings.
  - For fuselages, the i index increases axially from nose to tail; the j index increases circumferentially from top to bottom.

- *Admittance Input*: File containing the surface admittance at every point in the input geometry file. In order for the code to properly read the admittance, the values must be written as a plot3d function file. The format is as follows:

```
write (iunit,*) nsurf
write (iunit,*) (id(n),jd(n),kd(n),nvar(n),n=1,nsurf)
do n=1,nsurf
   write (iunit,*) (((adm1(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                  (((adm2(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n))
end do
```

  The number of surfaces to be written is indicated by `nsurf` and `id,jd,kd` are the number of values to be written for each surface (`kd` = 1); `nvar` is the number of variables to be written. The variables, `adm1` and `adm2`, correspond to the real and imaginary components of admittance, respectively. Units for admittance are MKS $rayl^{-1}$.

  The input surfaces and admittances are spline fitted in a similar manner. Thus, the resulting admittances will differ slightly form the original values, and discontinuities between regions of different admittance will be smoothed out. If this is not acceptable, then the user must supply the desired admittances at every collocation point.

Output Files

- *Diagnostics*: Output file containing spline parameters and interpolation values. Used for debugging purposes only.
- *Collocation Points*: Output file containing the location and unit surface normals of the collocation points. Required input by ESM module.
- *Collocation Visualization*: Output file containing the geometry and unit surface normals of the fitted scattering surface, and the location and unit surface normals of the calculated collocation points. The same information is written to two different files. The contents of the file specified in this field can be visualized through viewer; a secondary file, in Tecplot format (the suffix ".dat" is appended to the given name) can be used to view the information outside the GUI.
- *Equivalent Sources*: Output file containing the location and unit surface normals of the equivalent sources. Required input by ESM module.
- *Equivalent Source Visualization*: Same as above, for source surface and equivalent sources.

Equivalent Source Parameters: The parameters in these lines are used to generate the appropriate number/location of equivalent sources. Note that only *Number of Surfaces* lines are activated, one per surface. The recommended (default) values have been found to yield the best combination of collocation points/equivalent sources for the chosen surfaces. Thus, in the vast majority of cases, **the user does not need to change these values**.

- *Npts*: Number of grid points per wavelength for scattering surface (recommended = 10. Can vary between 8 and 12 depending on excitation frequency. For lower frequencies, use higher value).
- *% Pts*: Number of equivalent sources, referenced to number of collocation points. The relationship is not linear, so that the recommended value (0.6) will result in $N_s \approx 0.333N$.
- *umin, umax, vmin, vmax*: The scattering surfaces are parameterized (u,v) during the spline fitting process. Minimum and maximum values for these parameters are provided here.

| | |
|---|---|
| `umin` | Minimum value for u. For wing-like surfaces, umin corresponds to the root; for fuselages, umin corresponds to the nose. For the vast majority of cases, `umin` = 0.0. However, `umin` > 0.0 (`umin` = 0.01 recommended) when entire nacelles are provided (i.e., when the first and last airfoils are identical) to avoid overlapping of collocation points and equivalent sources. |
| `umax` | Maximum value for u. For wing-like surfaces, `umax` corresponds to the tip; for fuselages, `umax` corresponds to the end of the tail. For the vast majority of cases, `umax` = 1.0. However, `umax` < 1.0 (`umax` = 0.99 recommended) when entire nacelles are provided (i.e., when the first and last airfoils are identical) to avoid overlapping of collocation points and equivalent sources. |

`vmin` Minimum value for v. For wing-like surfaces, `vmin` corresponds to the upper trailing edge; for fuselages, `vmin` corresponds to the line defining the top most boundary. For wing-like surfaces with sharp trailing edges, it is recommended that `vmin` > 0.0 (`vmin` = 0.02 recommended), to prevent overlapping of equivalent sources.

`vmax` Maximum value for v. For wing-like surfaces, `vmax` corresponds to the lower trailing edge; for fuselages, `vmax` corresponds to the line defining the bottom most boundary. For wing-like surfaces with sharp trailing edges, it is recommended that `vmax` < 1.0 (`vmax` = 0.98 recommended), to prevent overlapping of equivalent sources.

Spline Fit Parameters: The parameters in these lines are used to generate the fitted representations of the input and source surfaces. Note that only *Number of Surfaces* lines are activated, one per surface. The recommended (default) values have been found to yield the best fit for the chosen surfaces. Thus, in the vast majority of cases, **the user does not need to change these values.**

- *Surface type*: Choose one among the list provided. Currently, the code supports wings, fuselages (specified separately as fuselage top and fuselage bottom), nacelles, and engine cores.
- *ku, kv*: Order of the spline in u and v directions. k should be the smallest value that can accurately represent the original surface. Too high an order will introduce oscillations in areas with sharp corners or rapidly changing derivatives; too low an order may not accurately represent smooth functions (surfaces). In general, cubic splines (*ku* = *kv* = 4) provide acceptable results.
- *lu, lv*: Number of break point intervals in u and v directions. These values should be proportional to the length and width of the surface, and their number at most half of the number of planes in the i (u) and j (v) directions defining the input grid.

After all the parameters in the Kinematics and Geometry dialogs have been selected, they **must be written to a file prior to module execution**. The name of the file to be generated (or read in) is specified in the *Geometry Deck* area. Writing the input information to a file can be done by the user, or automatically by the GUI by clicking the *Execute* button.

#### 2.2.1.4 ESM

Run parameters and names for required input and output files to be used by the ESM module are entered through this dialog (see Figure 2.5). Depending on the user's choices, some output files may be empty at the end of execution. The following parameters are written to output: observer location (x,y,z), real and imaginary components of incident pressure, real and imaginary components of total (incident plus scattered) pressure, incident and total SPL (in dB, referenced to 20μPa). All data are output in Tecplot format.

Input Files

- *Collocation Points*: Input file (generated by geometry module) containing the location and unit surface normals of the collocation points.
- *Equivalent Sources*: Same as above, for equivalent sources.

- *Incident Noise*: Input file containing equivalent source coefficients from a previous FSC run of an engine only (nacelle with/without core) configuration. The contents of this file are added to the incident field calculated for the current simulation. This feature is very useful during multi-component configuration runs - in cases with at least two components, one of them being the engine, noticeable savings in computational resources can be obtained.

- *Collocation Point Acoustics*: Input file containing acoustic data information at each collocation point. Each line in the file (one line per point) contains the following 11 fields: (x, y, z) coordinates, real and imaginary components of incident acoustic pressure, real and imaginary components of incident acoustic velocity in the x, y, and z directions, respectively.

- *Observer Field Acoustics*: Same as above for an arbitrary, user-supplied observer field.

- *Surface Geometry*: Input file, in plot3d format, containing the geometry definition of the surfaces upon which the acoustic field variables will be calculated. Usually, it is the same file as that specified in *Geometry Input* (see section 2.2.1.3).

- *Arbitrary Observer Field*: (x, y, z) coordinates of observer field supplied by the user. Data to be written in plot3d grid file format (see section 2.2.1.3, *Geometry Input*).

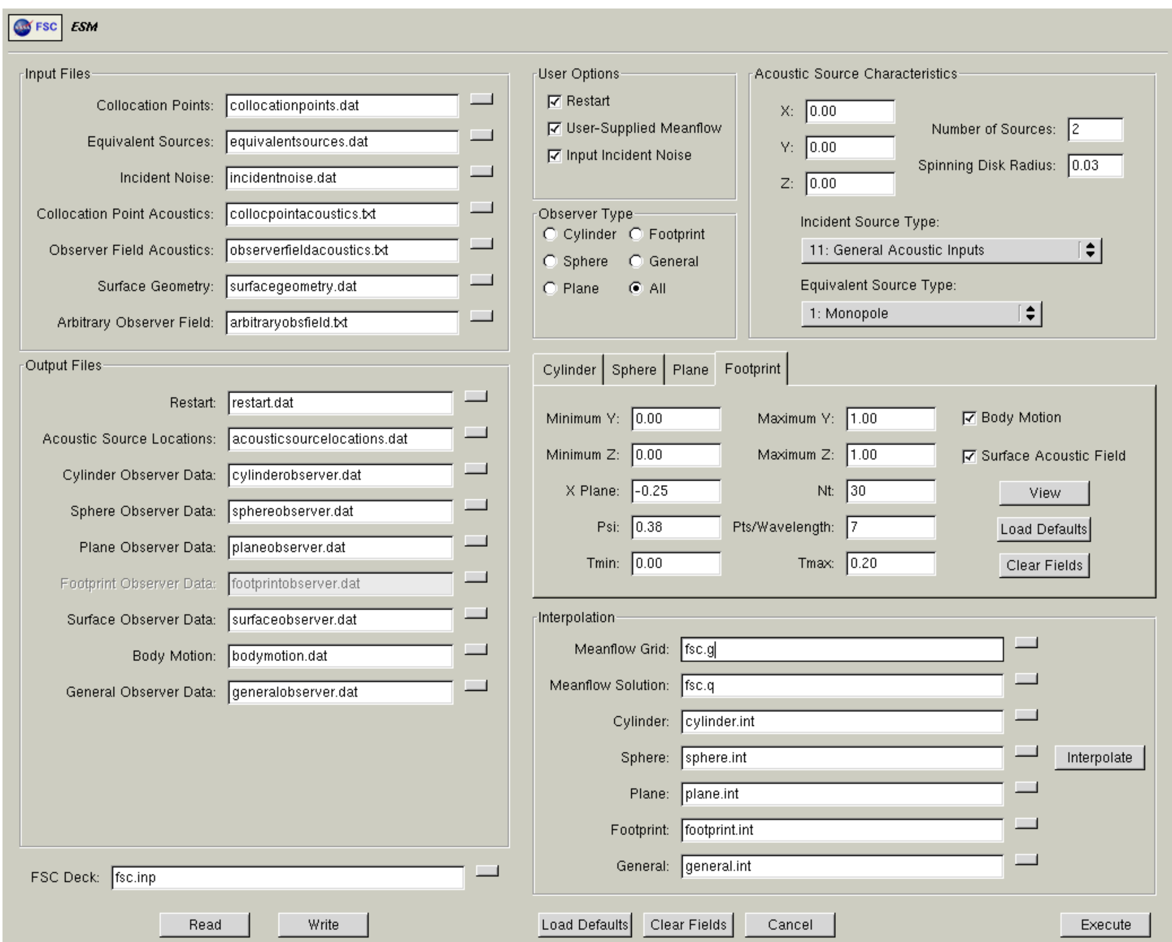



Figure 2.5 - ESM dialog.

Output Files

- *Restart*: Input/output file containing the equivalent source coefficients, which are used to calculate the scattered component of pressure. See FSC tab for file usage.
- *Incident Source Locations*: Output file containing the location of the incident acoustic source. This file is for visualization purposes only. For stationary monopole sources, a small-radius sphere is generated around the source; for spinning sources, a small-radius sphere is generated around the origin of the spinning disk.
- *Cylinder Observer Data*: Output file containing the acoustic field for a collection of observers uniformly distributed on a cylinder surrounding the scattering surfaces. The dimensions/location of the cylinder are specified via the FSC tab.
- *Sphere Observer Data*: Output file containing the acoustic field for a collection of observers uniformly distributed on a hemisphere surrounding the scattering surfaces. The dimensions/location of the hemisphere are specified in the FSC dialog.
- *Plane Observer Data*: Output file containing the acoustic field for a collection of observers uniformly distributed within a rectangular volume (or plane) surrounding the scattering surfaces. The dimensions/location of the volume/plane are specified in the FSC dialog.
- *Surface Observer Data*: Output file containing the acoustic field for a collection of observers placed on the user-supplied scattering surfaces. Observer locations coincide with input geometry points.
- *Footprint Observer Data*: Output file containing the acoustic field for a collection of observers uniformly distributed on a plane below the scattering surfaces. Time dependency is incorporated into the calculations. The dimensions/location of the plane are specified in the FSC dialog.
- *Body Motion*: Output file containing time dependent locations of the scattering surfaces. This file is for visualization purposes only, to be used in conjunction with the F*ootprint Observer Data* file.
- *General Observer Field*: Output file containing acoustic data for a user-supplied collection of observers.

Values for the parameters required to run the ESM module and obtain a solution are also specified through this dialog. All dimensional quantities must be given in SI units, and where applicable, must conform with the coordinate system used by the ESM module (see *Coordinate Rotation*, section 2.2.1.3). The parameters are grouped in several categories to facilitate input.

User Options - these options are not exclusive, so the user can select any that may apply.

- *Restart*: The code reads equivalent source coefficients stored in file *restart.dat*. The file must be available at the start of module execution. This option should be used when the configuration and case conditions are unchanged (i.e., a pre-existing solution is available for the same geometry, excitation frequency, and background flow parameters), and the acoustic field is desired for a different set of observers.

- *User-Supplied Mean Flow*: The code reads interpolated background flow parameters - local values of density, speed of sound, and (x,y,z) components of Mach number. These values are stored in one or more files whose names are specified in the Interpolation section. File format is the same as that for the geometry input file, i.e., text files with single precision data written in plot3d format. The file(s) must be available at the start of module execution.

- *Input Incident Noise*: The code reads equivalent source coefficients, obtained from a previous nacelle-only run[2], stored in file *Incident Noise*. The file must be available at the start of module execution.

<u>Acoustic Source Characteristics</u>

- *X, Y, Z*: Location of incident acoustic source.

  *Number of sources*: Number of spinning acoustic sources to be used (equal to the circumferential mode number under study). These sources are evenly distributed on the perimeter of a disk whose center is located at the coordinates specified above.

- *Spinning Disk Radius*: Radius of disk where the spinning sources are located.

- *Incident Source Type*:
  1 - Monopole
  2 - Two monopoles symmetric about y = 0
  3 - Dipole
  4 - Two dipoles symmetric about y = 0
  5 - Small perturbation background flow
  6 - Spinning monopole
  7 - Two spinning monopoles symmetric about y = 0, rotating in opposite directions.
  8 - Two spinning monopoles symmetric about y = 0, rotating in the same direction.
  9 - Axi-symmetric nacelle noise feedback. Proper use of this selection requires *Equivalent Source Type* = 5.
  10- Engine noise feedback. This option can be used with *Equivalent Source Type*s = 1 and 2.
  11- General acoustic inputs. This selection uses the data contained in files *Collocation Point Acoustics* and *Observer Field Acoustics.* Output information is written to file *General Observer Field*.

- *Equivalent Source Type*:
  1 - Monopole
  2 - Monopoles symmetric about y = 0
  3 - Dipole
  4 - Dipoles symmetric about y = 0
  5 - Spinning monopoles

---

2 For version 2.0, only engine noise results generated with *Incident Source Type* = 6 and *Equivalent Source Types* = 1 and 5 can be used in the feedback option.

Observer Type: These selections determine how the collection of observers, at which the acoustic field is to be calculated, are placed with respect to the scattering surfaces. The number of observers is proportional to excitation frequency, points per wavelength, and observer field dimensions. Thus, for large configurations at high frequencies, the number of observers could be prohibitive. The number of observers in any given direction (cartesian or polar) has been limited to 250.

- *Cylinder*: The observers are evenly distributed on a cylinder surrounding the configuration. Required parameters are (see *Cylinder* sub-dialog):
  - *Minimum and maximum Z*: length of observer field, measured in the axial direction.
  - *Offset*: distance by which the cylinder will be displaced from the given range in the direction of motion (z-axis). Recommended value = 0.0 (default).
  - *Shift*: increment in azimuthal direction. Recommended value = 0.0 (default).
  - *Radius*: cylinder radius.
  - *Points Per Wavelength*: recommended value = 5 to 10.
- *Sphere*: The observers are evenly distributed on a hemisphere surrounding the configuration. Required parameters are (see *Sphere* sub-dialog):
  - *X, Y, Z offset*: distance by which the observer field will be displaced. Recommended value = 0.0 (default).
  - *Radius*: hemisphere radius.
  - *Points Per Wavelength*: recommended value = 5 to 10.
- *Plane*: The observers are evenly distributed on a rectangular volume, composed of planes in the three coordinate directions, surrounding the configuration. Single planes can also be specified. Required parameters are (see *Plane* sub-dialog):
  - *Minimum and Maximum X, Y, Z*: these values determine the outer bounds of the "box" surrounding the geometry.
  - *Points Per Wavelength*: recommended value = 5 to 10.
  - *Nacelle only*: assumes the input geometry consists of a nacelle only, or a nacelle plus core. In this case, the observers are distributed on a cylindrical volume surrounding the nacelle. Relevant parameters are as follows:
    - *Nacelle radius*: outer radius of nacelle.
    - *Max Radius*: used to define the outer boundary of the observer field. Given in multiples of nacelle radius.
    - *Azimuth Increment*: determines the number of azimuthal planes contained in the volume.
- *Footprint*: The observers are evenly distributed on a (ground) plane below the scattering surfaces. The acoustic field, as a function of time, is calculated for the same set of observers, for a specified period. Required parameters are (see *Footprint* sub-dialog):

- *Minimum and Maximum Y, Z*: these values determine the bounds of the ground plane.
- *X Plane*: location of plane below scattering surfaces.
- *Tmin, Tmax*: bounds of time segment to be considered.
- *Nt*: number of intervals within time segment.
- *Psi*: climb angle for scattering surfaces.
- *Points Per Wavelength*: recommended value = 5 to 10.
- *Body Motion*: in addition to calculating the time-dependent acoustic field, a file containing the scattering surfaces at the corresponding locations is generated.
- *Surface Acoustic Field*: instead of generating footprints, the code will use a grid defining the scattering surfaces as the set of observers. This grid is specified in the *Surface Geometry* input file.

• *General Field*: The observers are supplied by the user.

• *All*: Acoustic data are generated for all of the above observer distributions.

The acoustic grids generated from the *observer type* dialogs can be checked for desirability by using the *view* button. Doing so will display the grid(s) on the Viewer area of the GUI.

Interpolation: This sub-dialog is activated when the *User-Supplied Mean Flow* option is selected. The GUI will use grid and solution files, which have been previously obtained from a CFD run of the scattering surfaces, to interpolate the given solution to the acoustic grid(s) selected via the Observer Type buttons. The process is executed by clicking the *interpolate* button. **Note: the solution must conform to the limitations of the FSC code - steady, inviscid, irrotational flow**.

• *Mean Flow Grid*: file containing a grid, in plot3d format (see Geometry section).

• *Mean Flow Solution*: file containing a solution (array of primitive variables in conservation form). The GUI will read the file as follows (plot3d format):

```
read (iunit,*) nsurf
read (iunit,*) (id(n),jd(n),kd(n),n=1,nsurf)
do n=1,nsurf
   read (iunit,*) xmach,alpha,rey,time
   read (iunit,*) (((rho (i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                 (((rhou(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                 (((rhov(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                 (((rhow(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
.                 (((e(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n))
end do
```

• *Cylinder*: name of file containing the given solution interpolated on the cylinder grid specified via the Observer Type buttons/dialogs.

• *Sphere*: name of file containing the given solution interpolated on the hemispherical grid specified via the Observer Type buttons/dialogs.

• *Plane*: name of file containing the given solution interpolated on the plane/volume grid specified via the Observer Type buttons/sub-dialogs.

- *Footprint*: name of file containing the given solution interpolated on the footprint plane specified via the Observer Type buttons/sub-dialogs.
- *General*: name of file containing the given solution interpolated on a user-supplied observer field, specified via the Observer Type buttons/sub-dialogs.

After all the parameters in the FSC dialog have been specified, they **must be written to a file prior to module execution**. The name of the file to be generated (or read in) is specified in the *FSC Deck* area. Writing the input information to a file can be done by the user, or automatically by the GUI when the *Execute* button is clicked.

### 2.2.2 Viewer

The Viewer is used in conjunction with the Task Selection dialog to ensure that 1) the input geometry has been properly discretized; 2) the collocation points and equivalent sources are properly distributed on their corresponding surfaces; and 3) the desired input decks have been read/written.

The input geometry and/or output from the geometry module can be examined via the Viewing Options on the main dialog. Once displayed, geometry manipulation is controlled through combinations of the mouse button and the keyboard Shift as shown in Table 2.1.

Table 2.1. - Viewer manipulation.

| **Mouse button** | **Modifier key** | **Function** |
|---|---|---|
| Middle | | Zoom in/out |
| Right | | Translation |
| Right | Shift | Rotation |

Currently, seven classes of viewing objects are supported, three of which are available as toggle buttons in the main dialog (see Figure 2.6). Pressing the *view* button causes loading and display of the file(s) corresponding to the toggled choice(s). If no such file can be found, a diagnostic message is written in the message area informing the user. In addition to these three choices, *View* buttons on the observer sub-dialogs (FSC dialog) can be used to display the observer grids. Presently, default renderings are assigned to viewable objects as shown in Table 2.2.

Table 2.2. - Default renderings.

| **Object** | **Rendering** |
|---|---|
| Geometry Viewing | Gray shaded surface |
| Equivalent Source Viewing | Yellow square points |
| Collocation Point Viewing | Pink square points |
| Cylinder Observer Grid | Green wireframe surface |
| Sphere Observer Grid | Cyan wireframe surface |
| Plane Observer Grid | Salmon wireframe surface |
| Footprint Observer Grid | Orange wireframe surface |


Figure 2.6 - Object viewing options.

### 2.2.3 Messaging Area and Help

The messaging area displays various runtime information to aid the user during input preparation/ execution process. A help window is available by pressing the Help button. Doing so invokes Acrobat reader displaying a PDF file with information about the code and its operation (this document). The window may be scrolled both horizontally and vertically, resized in either direction, or dismissed.

## 2.3 BATCH MODE EXECUTION

Descriptions of input files or decks for batch mode usage of the geometry and ESM modules, and the ESM module preprocessor, are provided in this section. Note that, for the ESM input file, not all of the lines of information will be required for every application. Sample input files for a model commercial transport (wing, fuselage, nacelle) similar to the Boeing 777, will be used to describe the parameters.

### 2.3.1 Geometry Module

```
1)  Geometry calculation for 3% scale 777 wing/fuselage/nacelle combination
    input geometry file
2)  777_geo-fuswn.p3d
3)  777_geo-fuswn_adm.p3d
    output geometry files
4)  777_geo.out
5)  777wfn_M0.0-c2k.vis
6)  777wfn_M0.0-s2k.vis
7)  777wfn_M0.0-cesm2k.fil
8)  777wfn_M0.0-sesm2k.fil
    grid parameters
          nsurf       iunit    srcalph       iaxi
9)           4           1       0.85           0
            Nw      srcpct       umin       umax       vmin        vmax
10)         10        0.60       0.00       1.00       0.02        0.98
            10        0.60       0.00       1.00       0.01        0.99
            10        0.60       0.00       1.00       0.01        0.99
            10        0.60       0.01       0.99       0.02        0.98
    spline fit parameters
         itype          ku         kv         lu          lv
11)          1           4          4         50          50
             2           4          4         50          20
             3           4          4         50          20
```

```
          4           3          3         20          20
   kinematic parameters
          freq       mach        cc      factsz
12)      2000.        0.0      340.         1.0
```

### 2.3.1.1 Line 1 - Case Title

Title describing case

### 2.3.1.2 Line 2 - Input Geometry File

*Input_geometry*: File containing the geometric description of the scattering surfaces. The data must be presented as an ordered collection of (x,y,z) single precision points. In order for the code to properly read the geometry, the data must be written in the format below (plot3d, single precision text files). The number of surfaces to be read is indicated by `nsurf` and `id,jd,kd` are the number of points to be read, in each coordinate direction, on each surface. Note that for surfaces, `kd` = 1.

```
      write (iunit,*) nsurf
      write (iunit,*) (id(n),jd(n),kd(n),n=1,nsurf)
      do n=1,nsurf
         write (iunit,*) (((x(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
     .                   (((y(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
     .                   (((z(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n))
      end do
```

The geometry must also conform with the following requirements:

- For wings, the i index increases spanwise from root to tip; the j index increases chordwise from upper trailing edge to lower trailing edge. The same convention applies to nacelles and engine cores, which are considered “wrapped” wings.
- For fuselages, the i index increases axially from nose to tail; the j index increases circumferentially from top to bottom.

### 2.3.1.3 Line 3 - Admittance File

*Input_admittance*: File containing the surface admittance at every point in the input geometry file. In order for the code to properly read the admittance, the values must be written as a plot3d function file. The format is as follows:

```
      write (iunit,*) nsurf
      write (iunit,*) (id(n),jd(n),kd(n),nvar(n),n=1,nsurf)
      do n=1,nsurf
         write (iunit,*) (((adm1(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n)),
     .                   (((adm2(i,j,k,n),i=1,id(n)),j=1,jd(n)),k=1,kd(n))
      end do
```

As before, the number of surfaces to be written is indicated by `nsurf` and `id,jd,kd` are the number of values to be written for each surface (`kd` = 1); `nvar` is the number of variables to be written. The variables, `adm1` and `adm2`, correspond to the real and imaginary components of admittance, respectively. These components are dimensional, with units MKS $rayl^{-1}$.

The input surfaces and admittances are spline fitted in a similar manner. Thus, the resulting admittances will differ slightly form the original values, and discontinuities between regions of different admittance will be smoothed out. If this is not acceptable, then the user must supply the desired admittances at every collocation point.

#### 2.3.1.4 Lines 4 through 8 - Output Files

*Diagnostics*: File containing information about the collocation points and equivalent sources. The first value corresponds to the wave number corrected for forward motion ($k_0/\beta_0$). For each component, the following are listed, first for the scattering surface, and then for the equivalent source surface: surface area ($m^2$), reference length (m), number of intervals on reference curve, Nuu (u direction), number of points on each u-interval, Nvv (v direction).

*Collocation_point_visualization*: File containing the location of the collocation points, to be used by the GUI. A file containing the same information, plus the unit normals at each point, is also written in Tecplot format (a "*.dat*" suffix is appended to the visualization file name).

*Equivalent_source_visualization*: File containing the location of the equivalent sources, to be used by the GUI. A file containing the same information, plus the unit normals for each source, is also written in Tecplot format (a "*.dat*" suffix is appended to the visualization file name).

*Collocation_points*: File containing a one-dimensional array of collocation points and their unit normals, one array per component. Required input by ESM module.

*Equivalent_sources*: File containing a one-dimensional array of equivalent sources and their unit normals, one array per component. Required input by ESM module.

#### 2.3.1.5 Line 9 - Input Grid Parameters

`nsurf` Number of surfaces in input geometry file. At present, the code accepts wings, fuselages (must be given as two separate surfaces, top and bottom), nacelles, and engine cores. Coordinate directions can be specified in one of two ways:

- x increases downstream, y increases spanwise, z increases "up"
- z increases upstream, y increases spanwise, x increases "up"

Acoustic calculations use the second orientation (body motion in the +z direction). If `nsurf` > 0, the input surfaces follow the first orientation; thus, a coordinate rotation/transformation will be performed (default). However, if `nsurf` < 0, the input surfaces follow the second orientation, and a coordinate rotation/transformation will not be performed.

`iunit` Input surface units: 0 - meters (default)
1 - feet
2 - inches

srcalph Scale of source surface, referenced to input scattering surface, where the equivalent sources are to be placed. Note that the source surface must be contained within the scattering surface; thus, the scale will always be less than unity. The proper choice for this value depends on surface size and frequency; for thick surfaces like fuselages, 0.85 < srcalph < 0.95 gives adequate results; for thin surfaces like nacelles, a smaller value should be used.

iaxi Axisymmetric nacelle: 0 - Do not use axisymmetric nacelle option
1 - Single input surface is an axisymmetric nacelle. In this case, collocation points and equivalent sources will be generated ONLY for the first airfoil defining the geometry. Output from this choice is to be used with the spinning monopole option for both incident and equivalent sources (see section 2.3.2.6) to simulate scattered fields for full scale nacelles.

#### 2.3.1.6 Line 10 - Collocation Point and Equivalent Source Parameters

The parameters in this line are used to generate the appropriate number/location of collocation points and equivalent sources. The recommended values have been found to yield the best combination of points and sources for the chosen surfaces. This line should be repeated nsurf times.

nw Number of points per wavelength for scattering surface (recommended = 10. Can vary between 8 and 12, depending on excitation frequency. For lower frequencies, use higher value).

srcpct Number of equivalent sources, referenced to number of collocation points. The relationship is not linear, so that the recommended value (0.6) will result in $N_S \approx 0.333 N_C$.

umin Minimum value for u. The scattering surfaces are parameterized (u,v) during the spline fitting process. For wing-like surfaces, umin corresponds to the root; for fuselages, umin corresponds to the nose. For the vast majority of cases, umin = 0.0. However, umin > 0.0 (umin = 0.01 recommended) when entire nacelles are provided (i.e., when the first and last airfoils are identical) to avoid overlapping of collocation points and equivalent sources.

umax Maximum value for u. For wing-like surfaces, umax corresponds to the tip; for fuselages, umax corresponds to the end of the tail. For the vast majority of cases, umax = 1.0. However, umax < 1.0 (umax = 0.99 recommended) when entire nacelles are provided (i.e., when the first and last airfoils are identical) to avoid overlapping of collocation points and equivalent sources.

vmin Minimum value for v. For wing-like surfaces, vmin corresponds to the upper trailing edge; for fuselages, vmin corresponds to the line defining the top most boundary. For wing-like surfaces with sharp trailing edges, it is recommended that vmin > 0.0 (vmin = 0.02 is recommended), to prevent overlapping of equivalent sources.

vmax Maximum value for v. For wing-like surfaces, vmax corresponds to the lower trailing edge; for fuselages, vmax corresponds to the line defining the bottom most boundary.

For wing-like surfaces with sharp trailing edges, it is recommended that `vmax` < 1.0 (`vmax` = 0.98 is recommended), to prevent overlapping of equivalent sources.

2.3.1.7 Line 11 - Spline Fit Parameters

The parameters in this line are used to generate the fitted representations of the scattering and source surfaces. The recommended values have been found to yield the best fit for the chosen surfaces. Thus, in the vast majority of cases, **the user does not need to change these values**. This line should be repeated `nsurf` times.

`itype` Type of surface to be read in/fitted:
1 - wing
2 - top fuselage
3 - bottom fuselage
4 - nacelle
5 - engine core

`ku,kv` Order of spline in u and v directions. k should be the smallest value that can accurately represent the original surface. Too high an order will introduce oscillations in areas with sharp corners or rapidly changing derivatives; too low an order may not accurately represent smooth functions (surfaces). In general, cubic splines ($ku = kv = 4$) provide acceptable results.

`lu,lv` Number of break point intervals in u and v directions. These values should be proportional to the length and width of the surface, and their number should be at most half of the number of planes in the i (u) and j (v) directions defining the input grid.

2.3.1.8 Line 12 - Kinematic Parameters

`freq` Excitation frequency, Hz.
`mach` Freestream Mach number
`cc` Freestream speed of sound, m/s
`factsz` Scale factor for output geometry. Usually 1.0.

### 2.3.2 ESM Module

```
1)  ESM calculation for 3% scale 777 fuselage/wing/nacelle combination
    input files
2)  777wfn_M0.0-cesm2k.fil
3)  777wfn_M0.0-sesm2k.fil
4)  flowin-cyl.p3d
5)  flowin-sph.p3d
6)  flowin-plane.p3d
7)  flowin-foot.p3d
8)  flowin-general.p3d
9)  cnac_M0.0-2k.rst
10) colloc
11) field
    output files
12) 777wfn_M0.0-2k_cyl.dat
```

```
13) sphere.dat
14) plane.dat
15) fprint.dat
16) 777wfn_M0.0-2k_surf.dat
17) general.dat
18) source.dat
    restart file
19) 777wfn_M0.0-2k.rst
    kinematic parameters
       freq     mach      cc      rho0
20)    2000.     0.0     340.     1.22
    $BEGIN_PARAMETERS   -----   restart and inflow parameters
     ifield   inflow    incp    isctp  inoise
21)       0        0      10        2       1
    source location coordinates
       X10      X20     X30    mpole    drad
22)   0.077    0.258   -0.65        2   0.033
    observer locations
       iobs
23)       1
    periodc   offset   zminc    zmaxc  cylrad   shift
24)       8      0.0   -2.25     0.25    1.25     0.0
    periods    x-off   y-off    z-off  sphrad
25)       7      0.0     0.0      0.0     2.0
    periodp    xminp   xmaxp    yminp   ymaxp   zminp   zmaxp  inac    rad
rmax    thinc
26)      8    -0.1   0.35     0.0    1.0    -2.0   0.20    0   0.05     2.0
10.0
    periodf    ypmin   ypmax    zpmin   zpmax      tmin    tmax    nt     psi
xplane   isurf   ibmot  iunit   icoord
27)       8      0.0     2.4      5.5     9.5       0.0     0.2    40   0.38  -
0.25         1       0      1        1
    $END_PARAMETERS     -----   body motion files
28) 777_geo-fuswn.p3d
29) geo-time.dat
    user supplied field
30) usr_field.dat
```

### 2.3.2.1 Line 1 - Case Title

Title describing case.

### 2.3.2.2 Lines 2 through 11 - Input Files

Depending on the user's choices, some input files may not be required. If so, they will be empty at the conclusion of a given run.

*Collocation_points*: Input file (generated by the geometry module) containing the location and unit surface normals of the collocation points.

*Equivalent_sources*: Input file (generated by the geometry module) containing the location and unit surface normals of the equivalent sources.

*Cylinder_interpolation*: File containing a pre-existing CFD solution interpolated to a cylinder grid specified by the user. Used with the user-supplied mean flow option (`inflow` = 1). The file contains local values of density, speed of sound, and (x,y,z) components of Mach number. File format is the same as that for the geometry input file, i.e., text files with single precision data written in plot3d format. The file(s) must be available at the start of module execution. The interpolation can be performed through the GUI.

*Sphere_interpolation*: File containing a pre-existing CFD solution interpolated on a semi-spherical grid specified by the user. File format same as above.

*Plane_interpolation*: File containing a pre-existing CFD solution interpolated on a plane or box grid specified by the user. File format same as above.

*Footprint_interpolation*: File containing a pre-existing CFD solution interpolated on a footprint plane specified by the user. File format same as above.

*General_field_interpolation*: File containing a pre-existing CFD solution interpolated on a user-supplied observer field. File format same as above.

*Input_incident_engine_noise*: File containing equivalent source coefficients from a previous FSC run of an engine only (nacelle with/without core) configuration. The contents of the file are added to the incident field calculated for the current simulation.

*Input_collocation_data*: File containing acoustic variable information at each collocation point. Each line in the file (one line per point) contains the following 11 fields: (x, y, z) coordinates, real and imaginary components of incident acoustic pressure, real and imaginary components of incident acoustic velocity in the x, y, and z directions, respectively.

*Input_observer_data*: Same as above for an arbitrary, user-defined field of observers.

#### 2.3.2.3 Lines 12 through 18 - Output Files

Depending on the user's choices, some output files may not be required. If so, they will be empty at the conclusion of a given run. The following parameters are written to output: observer location (x,y,z), real and imaginary components of incident pressure, real and imaginary components of total (incident plus scattered) pressure, incident and total SPL (in dB, referenced to 20μPa). All data are output in Tecplot format.

*Cylinder_observer*: File containing the acoustic field for a collection of observers uniformly distributed on a cylinder surrounding the scattering surfaces. The dimensions/location of the cylinder are specified by the user.

*Sphere_observer*: name of file containing the acoustic field for a collection of observers uniformly distributed on a hemisphere surrounding the scattering surfaces. The dimensions/location of the hemisphere are specified by the user.

*Plane_observer*: File containing the acoustic field for a collection of observers uniformly distributed within a plane, or rectangular volume surrounding the scattering surfaces. The dimensions/location of the plane/volume are specified by the user.

*Footprint_observer*: File containing the acoustic field for a collection of observers uniformly distributed on a plane below the scattering surfaces. Time dependency is incorporated into the calculations. The dimensions/location of the plane are specified by the user.

*Surface_observer*: File containing the acoustic field for a collection of observers placed on the user-supplied scattering surfaces. Observer locations coincide with input geometry points.

*General_observer*: File containing the acoustic field for a user-supplied collection of observers.

*Acoustic_source*: Name of file containing the location of the incident acoustic source. This file is for visualization purposes only. For stationary monopole sources (see section 2.3.2.6 for source definition), a small-radius sphere is generated around the source; for spinning sources, a small-radius sphere is generated around the origin of the spinning disk.

#### 2.3.2.4 Line 19 - Restart File

*Restart*: Name of input/output file containing the location and values for the equivalent source coefficients, which are used to calculate the scattered component of acoustic pressure and acoustic velocity.

#### 2.3.2.5 Line 20 - Kinematic Parameters

| | |
|---|---|
| `freq` | Excitation frequency, Hz. |
| `mach` | Freestream Mach number |
| `cc` | Freestream speed of sound, m/s |
| `rho0` | Ambient density, kg/m$^3$ |

#### 2.3.2.6 Line 21 - Restart and Inflow Parameters

Information between the tag line pair `$BEGIN_PARAMETERS` and `$END_PARAMETERS` constitutes a complete list of all user-specified parameters that will be considered by the ESM module preprocessor when determining which subroutine will be used in construction of the executable file. Note that **the parameter names must be as shown in the example for proper preprocessor performance**.

| | | |
|---|---|---|
| `ifield` | Restart: | 0 - Calculate equivalent source coefficients.<br>1 - Read equivalent source coefficients stored in the *Restart* file. This option should be used when the configuration and case conditions are unchanged (i.e., a pre-existing solution is available for the same geometry, excitation frequency, and background flow parameters), and the acoustic field is desired for a different set of observers. |
| `inflow` | Background flow: | 0 - Do not use externally calculated (user-supplied) background flow.<br>1 - The code reads interpolated background flow parameters stored in *Cylinder_interpolation* and similar files. |

`incp` Incident source:

1 - Monopole
2 - Two monopoles symmetric about y = 0
3 - Dipole
4 - Two dipoles symmetric about y = 0
5 - Small perturbation background flow
6 - Spinning monopole
7 - Two spinning monopoles symmetric about y = 0, rotating in opposite directions.
8 - Two spinning monopoles symmetric about y = 0, rotating in the same direction.
9 - Axi-symmetric nacelle noise feedback. Proper use of this selectiion requires `isctp` = 5.
10- Engine noise feedback. This option can be used with `isctp` = 1 and 2.
11- General acoustic inputs. This selection uses the data contained in files *Input_collocation_data* and *Input_observer_data.* Output information is written to file *General_observer* (see `iobs` = 5, section 2.3.2.8).

`isctp` Equivalent sources:

1 - Monopoles
2 - Monopoles symmetric about y = 0
3 - Dipoles
4 - Dipoles symmetric about y = 0
5 - Spinning monopoles

`inoise` Noise feedback:

0 - Do not use engine noise feedback option
1 - The code reads equivalent source coefficients, obtained from a previous nacelle run[3], stored in *Input_incident_engine_noise*. Used with `incp` = 10. This feature is very useful during multi-component runs, because it 1) permits a better definition of the incident field, and 2) may result in considerable resource savings.

2.3.2.7 Line 22 - Incident Sound Source Coordinates and Parameters

`x10,x20,x30` Location of incident sound source (x, y, z), meters.

`mpole` Number of spinning sources (circumferential modes) to be used. These sources are evenly distributed on the perimeter of a spinning disk centered at the point (x10, x20, x30).

`drad` Radius of spinning disk, measured from (x10, x20, x30). If placed inside a nacelle, it should always be smaller than the nacelle inner radius.

3 For version 2.0, only results generated with `incp` = 6 and `isctp` = 1 and 5 can be used in the engine noise feedback option.

#### 2.3.2.8 Lines 23 through 27 - Observer Locations

These selections determine how the collection of observers, at which the acoustic field variables are to be calculated, are placed with respect to the scattering surfaces. The number of observers is proportional to excitation frequency, points per wavelength, and observer field dimensions. Thus, for large configurations at high frequencies, the number of observers could be prohibitive. The number of observers in any given direction (cartesian or polar) has been limited to 250.

`iobs` 1 - Cylinder: The observers are evenly distributed on a cylinder surrounding the configuration. The size/location of the cylinder is controlled with the following parameters:

- `periodc`: Points per wavelength. Recommended value = 5 to 10.
- `offset`: Distance by which the cylinder will be displaced from the given range in the direction of motion (z-axis). Recommended value = 0.0 (default).
- `zminc,zmaxc`: Minimum and maximum values of z, which define the length of the observer field in the axial direction.
- `cylrad`: Cylinder radius.
- `shift`: Increment in azimuthal direction. Recommended value = 0.0 (default).

2 - Sphere: The observers are evenly distributed on a hemisphere surrounding the configuration.The size/location of the hemisphere is controlled with the following parameters:

- `periods`: Points per wavelength. Recommended value = 5 to 10.
- `x-off,y-off,z-off`: Distance by which the observer field will be displaced. Recommended value = 0.0.
- `sphrad`: Hemisphere radius.

3 - Plane: The observers are evenly distributed on a volume, composed of planes in the three coordinate directions, surrounding the configuration; alternately, single planes can also be specified by setting the length in any given direction to zero (*min* = *max*). The size/location of the volume is controlled with the following parameters:

- `periodp`: Points per wavelength. Recommended value = 5 to 10.
- `xminp,xmaxp`: Minimum and maximum values of x, which define the height of the observer field.
- `yminp,ymaxp`: Minimum and maximum values of y, which define the width of the observer field.
- `zminp,zmaxp`: Minimum and maximum values of z, which define the length of the observer field.
- `inac` 0 - General plane calculation

  1 - Calculations for nacelle-alone configurations. In this case, the observer field around the nacelle is defined by a series of azimuthal planes centered at the nacelle axis, and determined by the following parameters:

  `rad` Nacelle radius, measured from the nacelle axis

  `rmax` Number of times rad is extended beyond its original value. Used to define the outer edge of the observer field.

  `thinc` Azimuth increment for plane generation, in degrees

4 - Footprint: The observers are evenly distributed on a (ground) plane below the scattering surfaces. The acoustic field, as a function of time, is calculated for the same set of observers, for a specific period. The size/location of the footprint is controlled with the following parameters:

- `periodf`: Points per wavelength. Recommended value = 5 to 10.
- `ypmin,ypmax`: Minimum and maximum values of y, which define the width of the observer plane.
- `zpmin,zpmax`: Minimum and maximum values of z, which define the length of the observer plane.
- `tmin,tmax`: Bounds of time segment to be considered, seconds
- `nt`: Number of intervals within time segment.
- `psi`: Climb angle for scattering surfaces.
- `xplane`: Location of plane below scattering surfaces, meters.
- `isurf` 0 - Calculate footprint only
  1 - Calculate acoustic field on the scattering surfaces instead of a time-dependent footprint.
- `ibmot` 0 - Do not calculate body motion
  1 - Calculate body motion. In addition to the footprint, the time-dependent rectilinear motion of the scattering surfaces is generated. Used for visualization purposes.
- `iunit` Dimensional units of input (scattering) surfaces. See section 2.3.1.5.
- `icoord` 0 - Do not perform coordinate rotation/transformation on input surfaces. See section 2.3.1.5.
  1 - Perform coordinate rotation/transformation of input surfaces.

5 - User-supplied observer field: The observers are provided by the user.

6 - Acoustic data are calculated for all of the above observer distributions.

#### 2.3.2.9 Lines 28 and 29 - Body Motion Files

*Input_geometry*: File containing the geometric definition of the scattering surfaces. It is usually the same file as that specified in the geometry module (see section 2.3.1.2).

*Body_motion*: Output file containing time dependent locations of the scattering surfaces. For visualization purposes only, to be used in conjunction with *Footprint_observer*.

#### 2.3.2.10 Line 30 - User-Supplied Field

*User_field*: File containing (x, y, z) coordinates for an arbitrary collection of observers. File format is plot3d grid file (see section 2.3.1.2).

### 2.3.3 ESM Module Preprocessor

The preprocessor takes the user's parameter choices (specified in the *esm_input* file), determines which subroutines are needed, and then assembles, compiles, and creates an executable suited to those choices. Rules relating parameters and subroutine selection are provided in the *dependen-*

*cies* file. Baseline *dependencies* files for Unix and Linux systems are included in the FSC distribution file.

### 2.3.3.1 Dependencies File

```
$BEGIN_PARAMETERS
       ifield        0  1
       inflow        0  1
       incp          1 2 3 4 5 6 7 8 9 10 11
       isctp         1 2 3 4 5
       inoise        0 1 3
       iobs          1 2 3 4 5 6
       inac          0 1
       isurf         0 1
       ibmot         0 1
       iunit         0 1 2
       icoord        0 1
$END_PARAMETERS

$BEGIN_ROUTINES
     main
     acoustics
     assign_reference_values
     boundary_conditions
     compute_derivatives
     compute_exponential_term
     compute_loc_diffs
     compute_matrix_term
     cylinder
     determine_max_value
     dgdr
     dgdxci
     dipole_deriv
     dipole
     draw_radius
     field
     flowin
     footprint
     general
     geometry
     greens_function_spin
     incident_dpressure_calc
     incident_pressure_calc           incp
                                        1       p1inc1.f90
                                        2       p1inc2.f90
                                        3       p1inc3.f90
                                        4       p1inc4.f90
                                        5       p1inc5.f90
                                        6       p1inc6.f90
                                        7       p1inc7.f90
                                        8       p1inc8.f90
                                        9       p1inc9.f90
                                       10      p1inc10.f90
```

```
                                   11        p1inc11.f90
     incident_velocity_calc      incp
                                    1         v1inc1.f90
                                    2         v1inc2.f90
                                    3         v1inc3.f90
                                    4         v1inc4.f90
                                    5         v1inc5.f90
                                    6         v1inc6.f90
                                    7         v1inc7.f90
                                    8         v1inc8.f90
                                    9         v1inc9.f90
                                   10        v1inc10.f90
                                   11        v1inc11.f90
     inputs
     limit_range
     matrix
     matrix_product
     monopole_deriv
     monopole
     plane
     radius_calc
     read_input_deck
     read_restart
     readfil2
     rhs_incident_dpressure_calc
     rhs_incident_pressure_calc
     rhs_incident_velocity_calc
     r_theta_calc
     set_location
     set_vectors
     source_dpressure_calc
     source_pressure_calc       isctp
                                    1         p1src1.f90
                                    2         p1src2.f90
                                    3         p1src3.f90
                                    4         p1src4.f90
                                    5         p1src5.f90
     source_velocity_calc       isctp
                                    1         v1src1.f90
                                    2         v1src2.f90
                                    3         v1src3.f90
                                    4         v1src4.f90
                                    5         v1src5.f90
     sphere
     spinning_pole_parameters
     sum_of_squares
     timer
$END_ROUTINES

$BEGIN_LIBRARIES
/usr/lib/libscs.so
$END_LIBRARIES

$BEGIN_COMPILE_COMMAND
```

```
    /ump/geo/share/linux_local/intel/compiler70/ia32/bin/ifc -g
$END_COMPILE_COMMAND
```

Information between the tag line pair `$BEGIN_PARAMETERS` and `$END_PARAMETERS` constitutes a complete list of all user-specified parameters to be considered when determining the proper set of subroutines to use during construction of the ESM module executable file. Beside the parameter name (which must match its name in the *esm_input* file), all values the parameter may assume are also provided. Information between the tag line pair `$BEGIN_ROUTINES` and `$END_ROUTINES` contains a list of all routines that may be considered for inclusion in the ESM executable file, along with their parameter dependencies. Information between the tag lines `$BEGIN_LIBRARIES` and `$END_LIBRARIES` lists the location and names of all libraries that will be included in the ESM executable file. Information between the tag line pair `$BEGIN_COMPILE_COMMAND` and `$END_COMPILE_COMMAND` lists the location and name of the FORTRAN 90 compiler, along with any flags required by the code.

A successful compilation of a case-dependent executable file depends on 1) inclusion of all relevant dependencies, 2) proper order of the tag line pairs: the parameters section must precede the routines section, and 3) the object file for the main routine (`main`) must be the first entry in the routines section. The dependencies file is general in its structure, i.e., any information outside the tag line pairs is ignored. Thus, comments or other information may be freely included anywhere in the file, as long as they are not between tag line pairs. **Note that empty lines between tag line pairs are not permitted**. If there is no information relevant to a particular tag line pair, then the `$END` line follows immediately after the `$BEGIN` line.

### 2.3.4 Code Compilation and Execution

Only the executable files `geo.sgi` and `geo.linux` (for SGI and Linux operating systems, respectively) are provided for the geometry module. The geometry module is invoked as follows:

`geo` < *geo_input*

Where *geo_input* is the standard geometry module input file, described in section 2.3.1. Note that the executable file is usually invoked from the directory where *geo_input* resides. Thus, if the executable file is located in a different directory, its full path must be specified in the command line.

Only the executable files `esmpre.sgi` and `esmpre.linux` are provided for the ESM module preprocessor. The preprocessor may be invoked to build the ESM executable file as follows:

`esmpre` *esm_input dependencies esm*

Where *esm_input* is the standard ESM module input file (see section 2.3.2), *dependencies* is the dependencies file (see section 2.3.3.1), and *esm* is the name of the ESM module executable file. Note that `esmpre` must be invoked from the directory where the object files reside. If any of the other files in the command line does not include its full path, it is assumed that the file resides in the local directory (the directory where `esmpre` was issued from). Following creation of *esm*, the file `report.txt` is generated in the local directory. This file contains creation time and date, and lists of all included parameters, subroutines, and libraries. Finally, the ESM module may be invoked as follows:

*esm* < *esm_input*

Note that the executable file is usually called from the directory where *esm_input* resides. Thus, if the executable file is located in a different directory, its full path must be specified in the command line.

CHAPTER 3

# Test Cases

The capabilities and versatility of the FSC are illustrated with several numerical examples involving the generation and scattering of engine noise by model commercial transport and blended wing body airframes. All calculations were performed on an SGI Onyx workstation with R12000 (400MHz) processors and 8GB of RAM. Computational time varied from about 1 minute for the full scale commercial transport nacelle to 8.3 hours for the model commercial transport.

## 3.1 COMMERCIAL TRANSPORT NACELLE

A full scale representation of a commercial transport nacelle without core (diameter ~ 2.8 m), similar to that used with GE90 engines on Boeing 777 aircraft, was used in this visualization of sound propagation within ducts of arbitrary shape. The noise source is a disk of spinning monopoles (diameter ~ 2.41 m) placed in the approximate location of the fan rotor. The excitation frequency is 2.0 kHz (which exceeds 2 x BPF), without/with background flow. To simulate solid nacelle walls, an admittance A = (0.0 + 0.0i) was used everywhere. The input deck used to generate the system of collocation points/equivalent sources for the M = 0 case is as follows:

```
ESM source calculation for ge90 full scale nacelle
input geometry file
nac-ffoil_s0.p3d
nac-ffoil_s0-adm0.p3d
output geometry files
ge90-nac.out
ge90_axi_M0.0-c2k.vis
ge90_axi_M0.0-s2k.vis
ge90_axi_M0.0-cesm2k.fil
ge90_axi_M0.0-sesm2k.fil
grid parameters
      nsurf      iunit   srcalph        iaxi
          1          0      0.70           1
         Nw     srcpct      umin        umax       vmin        vmax
         10       0.60     0.000       1.000       0.02        0.98
spline fit parameters
      itype         ku        kv          lu         lv
          4          3         3          20         20
kinematic parameters
       freq      xmach        cc      factsz
      2000.        0.0      340.         1.0
```

Because no unique solution exists for determining the number and position of equivalent sources inside the scatterer, numerical experimentation is often necessary. The size of the source surface (`srcalph`) and the number of equivalent sources (`srcpct`, referenced to the number of collocation points) used in the present exercise work well for the given nacelle geometry. Note that because an axisymmetric nacelle is assumed (`iaxi` = 1), the resulting collocation points and equivalent sources will be generated for the first airfoil in the geometry definition only. This permits the simulation of acoustic behavior at any full scale frequency of interest. The input deck used to generate the acoustic field solution for M = 0.0 is as follows:

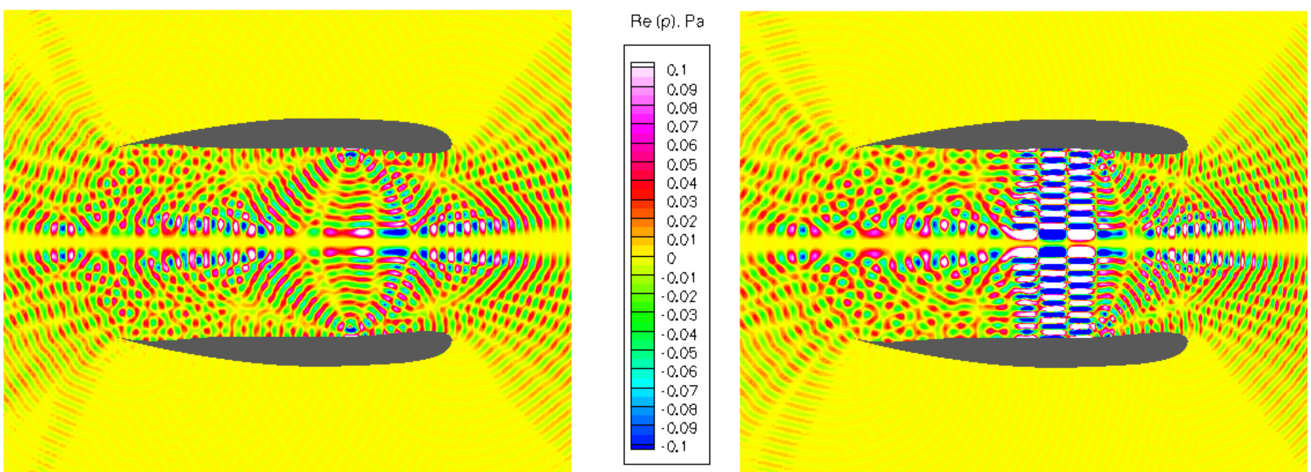
```
ESM calculation for ge90 full scale nacelle
input files
ge90_axi_M0.0-cesm2k.fil
ge90_axi_M0.0-sesm2k.fil
inflow_cyl.p3d
inflow_sphere.p3d
inflow_plane.p3d
inflow_foot.p3d
inflow_general.p3d
noisein.rst
colloc
field
output files
ge90-axi_2kM0.0-m4_cyl.dat
ge90-axi_2kM0.0-m4_sphere.dat
ge90-axi_2kM0.0-m4_plane.dat
ge90-axi_2kM0.0-m4_fprint.dat
ge90-axi_2kM0.0-m4_surf.dat
ge90-axi_2kM0.0-m4_general.dat
source.dat
restart file
ge90-axi_2kM0.0-m4.rst
kinematic parameters
   freq     mach      cc    rrho0
   2000.     0.0    340.     1.22
$BEGIN_PARAMETERS   -----   restart and inflow parameters
 ifield   inflow    incp    isctp  inoise
      0        0       6       5       0
source location coordinates
    X10      X20     X30    mpole    drad
  0.000    0.000    0.90        4   1.205
observer locations
   iobs
      3
periodc   offset   zminc    zmaxc  cylrad   shift
      7      0.0    -2.0      2.0     2.0     0.0
periods    x-off   y-off    z-off  sphrad
      7      0.0     0.0      0.0     2.0
periodp    xminp   xmaxp    yminp   ymaxp   zminp   zmaxp  inac    rad     rmax
thinc
     10     -3.3     3.3      0.0     0.0    -4.0     4.0     0  1.655      2.0
10.0
periodf    ypmin   ypmax    zpmin   zpmax    tmin    tmax    nt    PSI   xplane
isurf   ibmot  iunit   icoord
```

```
      7      0.0      2.4      5.5      9.5      0.0      0.2     40    0.38     -0.25
0           0       0         1
$END_PARAMETERS     -----   body motion files
2d_ell-nac2.p3d
geo-time.dat
user supplied observer field
usr_field.dat
```

Because the nacelle is axisymmetric, spinning monopoles have been selected for the incident field generators (`incp` = 6) and equivalent sources (`isctp` = 5); a circumferential mode of order 4 (m = 4) is used. The observer field is a plane in the x-z direction, bisecting the nacelle at y = 0.

### 3.1.1 Background Flow Effects

Results from the simulations for M = 0 and M = 0.2 (uniform) are presented in Figures 3.1a and 3.1b, respectively, for a nacelle with solid walls. It is clearly seen from figure 3.1a that 8 radial modes propagate in the axial direction. It is also obvious from these results that the strongest propagating mode is the first radial mode. Note from Figure 3.1b that the main effect of background flow is to reduce the wavelength of forward travelling waves, while increasing the wavelength of aft travelling waves.

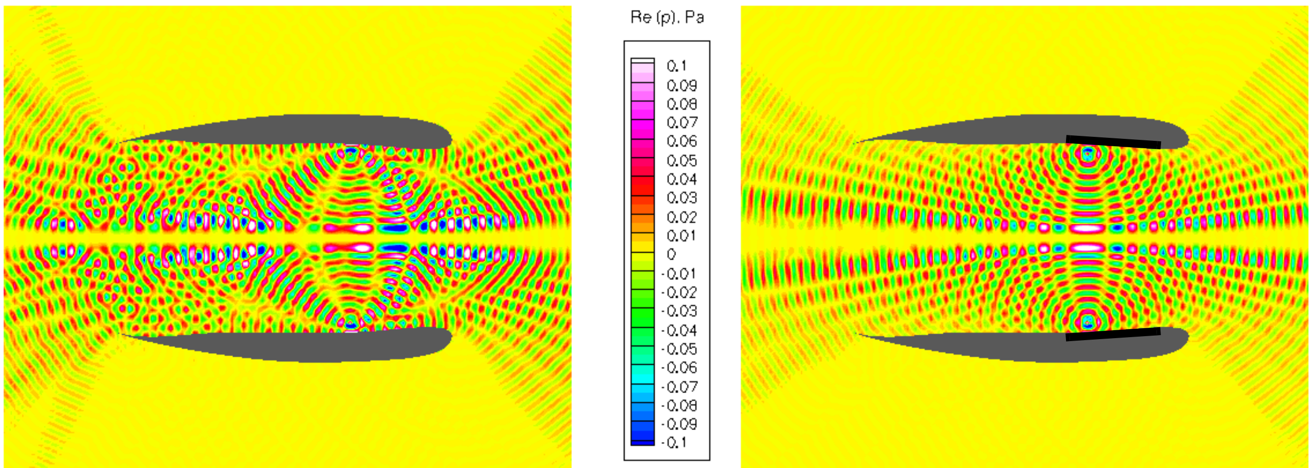



(a) M = 0.0 (b) M = 0.2 (uniform)

Figure 3.1 - Instantaneous acoustic pressure contours for full scale nacelle (hardwall), f = 2.0 kHz, m = 4.

### 3.1.2 Acoustic Treatment Effects

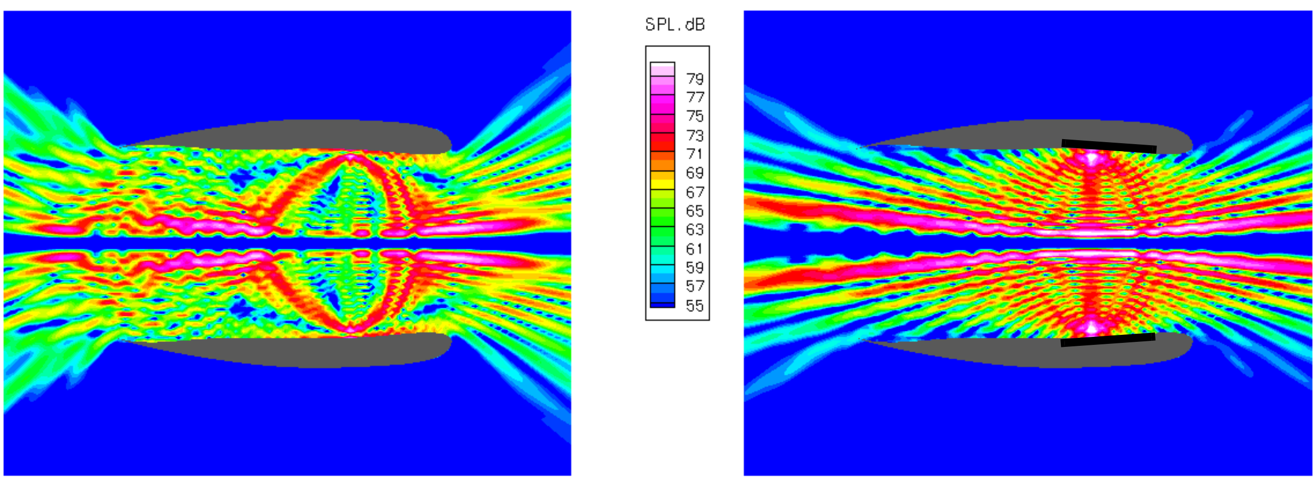
Acoustic treatment was also simulated on a circumferential band of the inner nacelle wall spanning from 10% of the nacelle length to 43% of the nacelle length, and shown as dark lines in Figure 3.2a. The admittance used in the treated region was A = (0.48 + 0.13i)($\rho_0 c_0$), which is within the range of applicability for single degree of freedom honeycomb liners. Acoustic pressure contours in the vicinity of the nacelle are given in Figures 3.2a and 3.2b for solid and treated interior walls, respectively. Note from the figures that the main effect of treatment is to modify the amplitude/interaction patterns of the acoustic waves within the nacelle, especially near the walls. These changes enhance propagation of lower order modes and decrease propagation of higher order modes, a behavior that is better seen in Figures 3.3a and 3.3b.




(a) Hardwall

(b) Lined, A = $(0.48+0.13i)/\rho_0 c_0$

Figure 3.2 - Instantaneous coustic pressure contours for full scale nacelle, M = 0.0, f = 2.0 kHz, m = 4.




(a) Hardwall

(b) Lined, A = $(0.48+0.13i)/\rho_0 c_0$

Figure 3.3 - Sound pressure level contours for full scale nacelle, M = 0.0, f = 2.0 kHz, m = 4.

## 3.2 COMMERCIAL TRANSPORT

The results presented here were obtained for a 2.68% scale model of a commercial transport, similar to the Boeing 777. The symmetric configuration consists of a fuselage, wings, and nacelles. The incident acoustic sources are disks of spinning monopoles of order 2 (m = 2) rotating in opposite directions, located at the nacelle centers. Excitation frequency is 7.0 kHz, with a quiescent background flow (M = 0.0). The option of using a pre-existing nacelle only solution as incident source field will be utilized in this exercise.

### 3.2.1 Nacelle-Only Simulations

Geometry Deck:

```
ESM noise calculation for 3% scale ge90 nacelle
input geometry file
nac00_port.p3d
nac00_port-adm0.p3d
output geometry files
nacp_geo.out
nacp_M0.0-c7k_s60.vis
nacp_M0.0-s7k_s60.vis
nacp_M0.0-cesm7k_s60.fil
nacp_M0.0-sesm7k_s60.fil
grid parameters
      nsurf      iunit   srcalph       iaxi
          1          1      0.60          0
         Nw     srcpct      umin       umax       vmin       vmax
         10       0.60     0.005      0.995       0.02       0.98
spline fit parameters
      itype         ku         kv         lu         lv
          4          3          3         30         50
kinematic parameters
 Hz xmach       cc      factsz
       7000.       0.0      340.        1.0
```

ESM Deck:

```
ESM calculation for 3% scale ge90 geometry
input files
nacp_M0.0-cesm7k_s60.fil
nacp_M0.0-sesm7k_s60.fil
inflow_cyl.p3d
inflow_sphere.p3d
inflow_plane.p3d
inflow_foot.p3d
inflow_general.p3d
noisein.rst
colloc
field
output files
cyl.dat
sphere.dat
nacp_M0.0_m2-7k61-s60_plane.dat
fprint.dat
surf.dat
general.dat
source.dat
restart file
```

```
nacp_M0.0_m2-7k61-s60.rst
kinematic parameters
     Hz    xmach      cc    rrho0
   7000.     0.0    340.     1.22
$BEGIN_PARAMETERS     -------     restart and inflow parameters
 ifield   inflow    incp    isctp  inoise
      0        0       6       1       0
source location coordinates
    X10      X20     X30    mpole    drad
  0.077   0.2581   -0.65        2   0.033
observer locations
   iobs
      3
periodc   offset   zminc    zmaxc  cylrad   shift
      7      0.0  -2.25     0.25     1.25     0.0
periods    x-off   y-off    z-off  sphrad
      8      0.0     0.0     -1.0    1.25
periodp    xminp   xmaxp    yminp   ymaxp   zminp   zmaxp  inac    rad     rmax
thinc
      8    -0.10    0.25   0.2581  0.2581   -0.85   -0.50     0   0.05      2.0
10.0
periodf    ypmin   ypmax    zpmin   zpmax    tmin    tmax    nt    PSI   xplane
isurf   ibmot  iunit   icoord
      8      0.0     2.4      5.5     9.5     0.0     0.2    40   0.38    -0.25
1          0      1        1
$END_PARAMETERS       -------     body motion files
nac00_port.p3d
geo-time.dat
user supplied observer field
usr_field.dat
```

Note from the geometry deck that the equivalent source surface size (`srcalph` = 0.60) is smaller than that used in the nacelle only exercise (see section 3.1.1). Although both cases used the same geometry, the scales and frequencies are different. Thus, numerical experimentation was necessary to achieve a suitable size for the equivalent source surface.

### 3.2.2 Fuselage/Wing/Nacelle Configuration

Geometry Deck:

```
ESM noise calculation for 3% scale 777 fuselage/wing/nacelle combination
input geometry files
777_geo+nac00.p3d
777_geo+nac00_adm0.p3d
output geometry files
777_geo.out
777wfn_M0.0-c7k.vis
777wfn_M0.0-s7k.vis
777wfn_M0.0-cesm7k.fil
777wfn_M0.0-sesm7k.fil
grid parameters
      nsurf      iunit   srcalph       iaxi
          4          1      0.85          0
```

```
         Nw      srcpct       umin        umax       vmin        vmax
         10        0.60       0.00        1.00       0.02        0.98
         10        0.60       0.00        1.00       0.01        0.99
         10        0.60       0.00        1.00       0.01        0.99
         10        0.60      0.005       0.995       0.02        0.98
spline fit parameters
      itype          ku         kv          lu          lv
          1           4          4          50          50
          2           4          4          50          20
          3           4          4          50          20
          4           3          3          30          50
kinematic parameters
        freq      xmach        cc      factsz
       7000.        0.0      340.         1.0
```

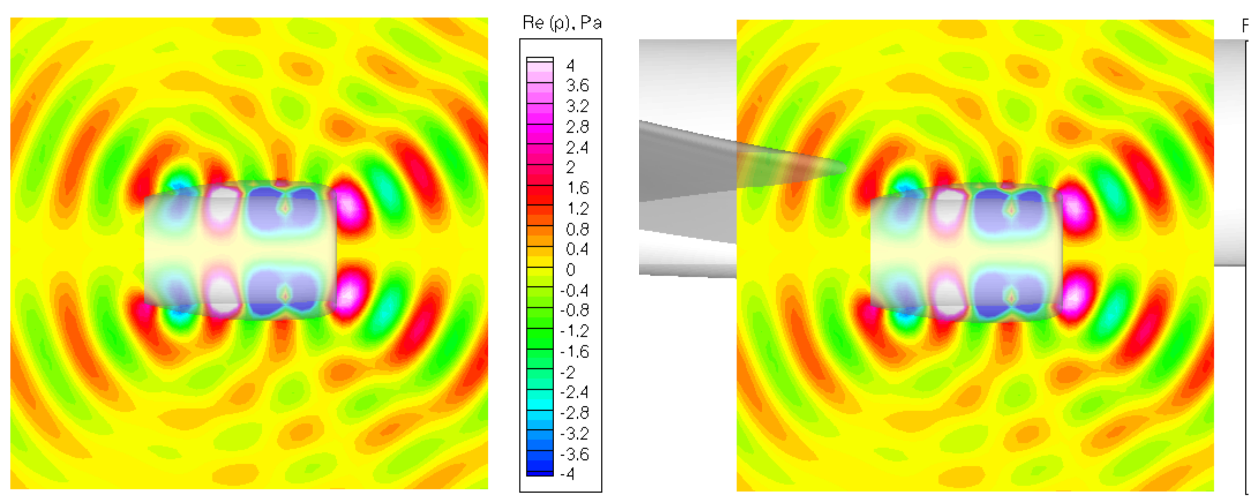
ESM Deck:

```
ESM calculation for 777 wing+fuselage 3% scale geometry
input files
777wfn_M0.0-cesm7k.fil
777wfn_M0.0-sesm7k.fil
nacp_M0.0_m2-7k61-s60.rst
inflow_cyl.p3d
inflow_sphere.p3d
inflow_plane.p3d
inflow_foot.p3d
inflow_general.p3d
colloc
field
output files
cyl.dat
sphere.dat
777wfn_M0.0_m2-7k_plane102-xy.dat
fprint.dat
777wfn_M0.0_m2-7k_surf102.dat
general.dat
source.dat
restart file
777wfn_M0.0_m2-7k102.rst
kinematic parameters
     Hz    xmach      cc    rrho0
   7000.     0.0    340.     1.22
$BEGIN_PARAMETERS     -------     restart and inflow parameters
 ifield   inflow    incp    isctp   inoise
      1        0      10        2        1
source location coordinates
    X10      X20     X30    mpole     drad
  0.077   0.2581   -0.65        2    0.033
observer locations
   iobs
      3
periodc   offset   zminc    zmaxc  cylrad   shift
      7      0.0  -2.25      0.25    1.25     0.0
periods    x-off   y-off    z-off  sphrad
```

```
       8       0.0      0.0      -1.0     1.25
periodp    xminp    xmaxp     yminp    ymaxp    zminp    zmaxp   inac     rad      rmax
thinc
       8    -0.10     0.30       0.0      0.9    -0.65    -0.65      0    0.05       2.0
10.0
periodf    ypmin    ypmax     zpmin    zpmax     tmin     tmax     nt     PSI    xplane
isurf    ibmot   iunit    icoord
       8      0.0      2.4       5.5      9.5      0.0      0.2     40    0.38     -0.25
1          0       1         1
body motion files
777_geo+nac00.p3d
geo-time.dat
user supplied observer field
usr_field.dat
```

Using a pre-existing nacelle-only solution (`inoise` = 1) as input incident noise for simulations involving multi-component configurations has several advantages. First, the incident field can be better defined. Note that the size of the equivalent source surfaces for the combination is 0.85, which is adequate for the combination but not for the nacelle (`srcalph` is a global variable). Although a new source surface will be created for the nacelle, it will not be used during the acoustic field calculations. Second, since the equivalent sources for the nacelle, $N_{s,nac}$, will not be used in the calculation, the size of the matrix to be solved is reduced from $N_c$ x $N_s$ to $N_c$ x $N_s$-$N_{s,nac}$.

The total acoustic (incident plus scattered) field for the nacelle-only simulation is presented in Figure 3.4a; the incident field for the fuselage/wing/nacelle combination is given in Figure 3.4b. Note that, as expected, the two are identical. Forward and aft propagation of noise is clearly seen in the figures. Also observe that, because the wave and nacelle lengths are comparable ($\lambda$ = 0.048 m, L = 0.13 m), sound emanating from the nacelle openings diffracts around the edges and surrounds the nacelle; thus, no clear shadow zones can be seen. Incident acoustic pressure contours on the surface of the fuselage/wing/nacelle combination, and on a plane coincident with the spinning monopole disks, are given in Figure 3.5. Two spinning modes are present in each nacelle.




(a) Total acoustic pressure field for nacelle-only case

(b) Incident acoustic pressure field for combination

Figure 3.4 - Instantaneous acoustic pressure contours in the vicinity of the nacelle.
M = 0.0, f = 7.0 kHz, m = 2.

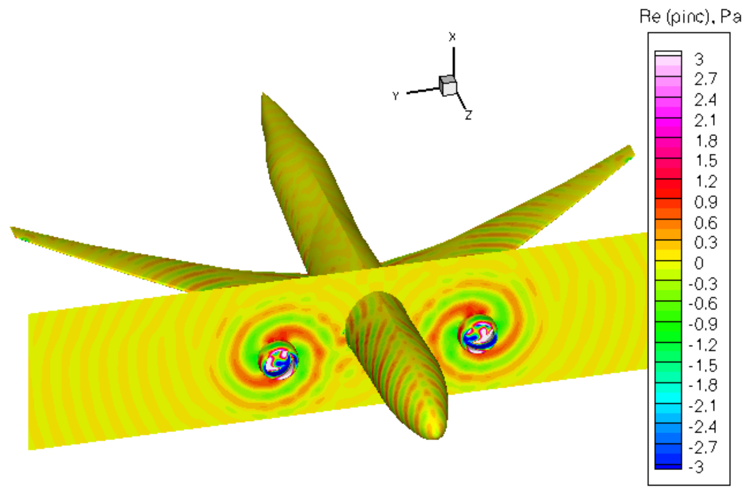



Figure 3.5 - Incident instantaneous acoustic pressure field for combination. M = 0.0, m = 2, f = 7.0 kHz.

Figure 3.6 depicts sound pressure levels on the surface of the 2.68% scale commercial transport that result from the scattering of engine noise. The nacelles are situated about one nacelle length forward of, and slightly below, the wings. Note from the figures that, as a result of wing shielding, the noise levels on the top surfaces are noticeably lower than those on the bottom surfaces.

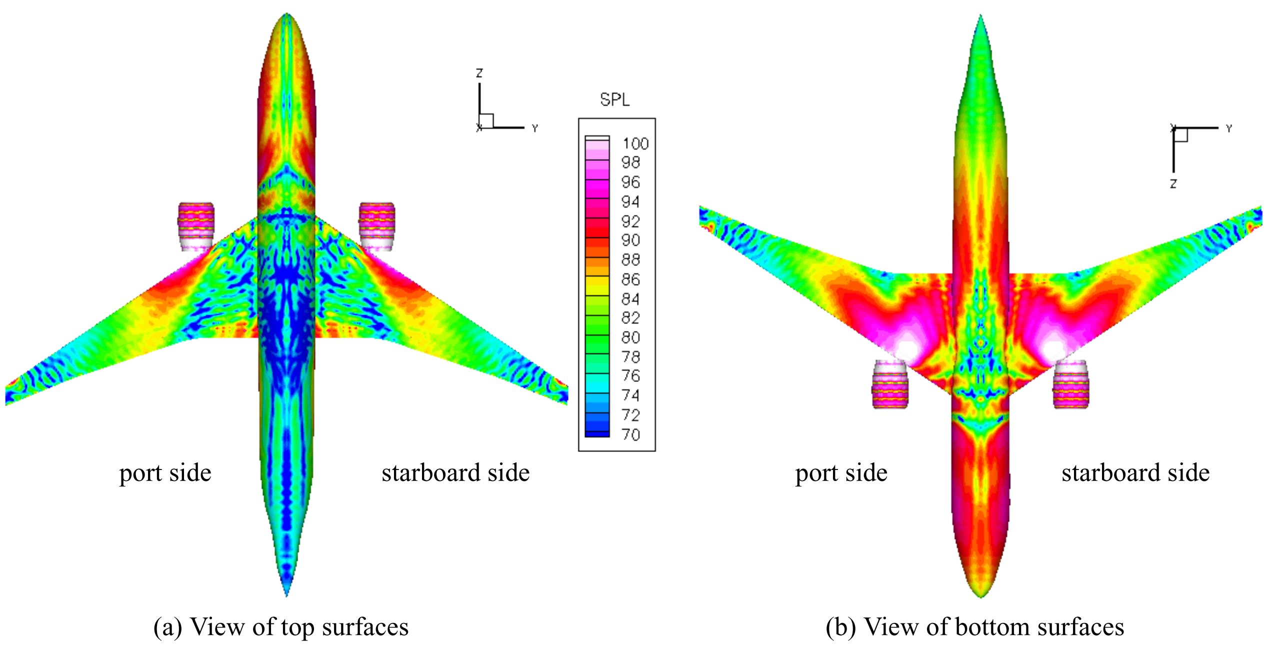



Figure 3.6 - Sound pressure level contours on the surface of a 2.68% scale model of a commercial transport. M = 0.0, f = 7.0 kHz, m = 2.

## 3.3 BLENDED WING BODY

As a last numerical example, the patterns of engine noise scattered by a full scale blended wing body (BWB) configuration with center nacelle only are considered. The acoustic source, a spinning monopole of order zero (m = 0), is placed at the center of the nacelle. Excitation frequency is 63.0 Hz, without/with background flow. The option of using a pre-existing nacelle only solution as incident sound field for the combination will be utilized in this exercise.

### 3.3.1 Nacelle-only Simulations

Geometry Deck:

```
ESM source calculation for full scale BWB center nacelle
input geometry files
ctr-nac_full-whole.p3d
ctr-nac_full-whole_adm0.p3d
output geometry files
cnac.out
cnac-c.063k-mod.vis
cnac-s.063k-mod.vis
cnac_whole-cesm.063k_s55.fil
cnac_whole-sesm.063k_s55.fil
grid parameters
      nsurf      iunit    srcalph       iaxi
          1          1       0.55          0
         Nw     srcpct       umin       umax      vmin       vmax
         10       0.60       0.01       0.99     0.025      0.975
spline fit parameters
      itype         ku         kv         lu         lv
          4          4          4         25         50
kinematic parameters
       freq      xmach          c     factsz
        63.        0.0       340.        1.0
```

ESM Deck:

```
ESM calculation for full scale BWB center nacelle
input files
cnac_whole-cesm.063k_s55.fil
cnac_whole-sesm.063k_s55.fil
inflow_cyl.p3d
inflow_sph.p3d
inflow_pla.p3d
inflow_foot.p3d
inflow_general.p3d
inc_noise_coeff.rst
colloc
field
output files
cnac_cyl.dat
cnac_sphere.dat
cnac_0.063k61-m0-M0.0_plane-s55.dat
```

```
cnac_fprint.dat
cnac_surf.dat
general.dat
source.dat
restart file
cnac_0.063k61-m0-M0.0-s55.rst
kinematic parameters
     Hz    xmach      cc     rrho0
     63.     0.0    340.      1.22
$BEGIN_PARAMETERS   ------   restart and inflow parameters
 ifield   inflow    incp   isctp   inoise
      0        0       6       1        0
source location coordinates
    X10      X20      X30   mpole     drad
    4.2     0.00   -46.65       0    0.833
observer locations
   iobs
      3
periodc   offset   zminc    zmaxc  cylrad   shift
      7      0.0    -2.5     0.75    2.25     0.0
periods    x-off   y-off    z-off  sphrad
      7      0.0     0.0     -1.0    2.25
periodp    xminp   xmaxp    yminp   ymaxp   zminp   zmaxp  inac    rad     rmax
thinc
      7     -0.5     9.0      0.0     0.0   -53.0   -40.0     0   1.66      3.0
10.0
periodf    ypmin   ypmax    zpmin   zpmax    tmin    tmax    nt    PSI   xplane
isurf   ibmot   iunit   icoord
      7      0.0     2.4     -2.0     9.5     0.0     0.2    40   0.38    -0.25
0          0       1        0
$END_PARAMETERS    ------    body motion files
bwb_sym-0.04s.p3d
bwb-time.dat
user supplied obsrver field
usr_field.dat
```

Note from the geometry deck that the equivalent source surface size is smaller (`srcalph` = 0.55) than those used in the previous exercises (see sections 3.1 and 3.2.1). Again, numerical experimentation was necessary to achieve a proper size since this nacelle has thin airfoils.

### 3.3.2 BWB/Nacelle configuration

Geometry Deck:

```
ESM source calculation for full scale BWB plus center nacelle.
input geometry file
fus-wing-cnac_nwlet_full.p3d
fus-wing-cnac_nwlet_full-adm0.p3d
output geometry files
fwnh-nwlt_0.063k_s85.out
fwnh-nwlt_c0.063k_s85.vis
fwnh-nwlt_s0.063k_s85.vis
fwnh-nwlt-cesm0.063k_s85.fil
```

```
fwnh-nwlt-sesm0.063k_s85.fil
grid parameters
      nsurf      iunit    srcalph       iaxi
          2          1       0.85          0
         Nw     srcpct       umin       umax      vmin        vmax
         10       0.60      0.000      1.000      0.01        0.99
         10       0.60      0.010      0.990     0.025       0.975
spline fit parameters
      itype         ku         kv         lu         lv
          1          4          4         50         50
          4          3          3         25         50
kinematic parameters
 Hz xmach       cc     factsz
         63.       0.0      340.        1.0
```

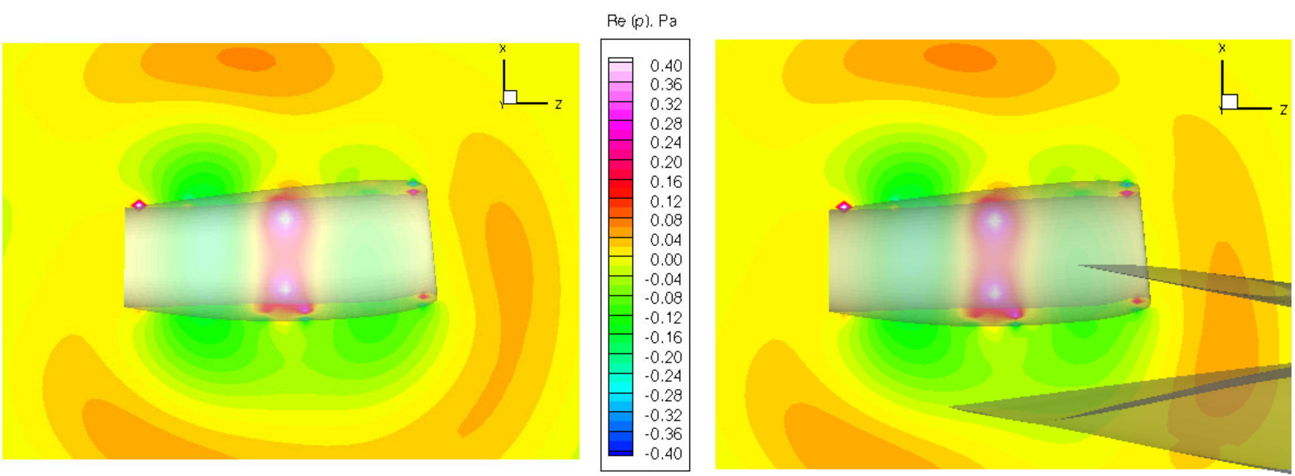
ESM Deck:

```
ESM calculation for full scale BWB and center nacelle
input files
fwnh-nwlt-cesm0.063k_s85.fil
fwnh-nwlt-sesm0.063k_s85.fil
inflow_cyl.p3d
inflow_sph.p3d
inflow_pla.p3d
inflow_foot.p3d
inflow_general.p3d
cnac_0.063k61-m0-M0.0-s55.rst
colloc
field
output files
cyl.dat
sphere.dat
fwnh-nwlt_plane_0.063k102-m0-M0.0_s85.dat
fprint.dat
surf.dat
general.dat
source_0.063k_s85.dat
restart file
fwh-nwlt_0.063k102-m0-M0.0_s85.rst
kinematic parameters
     Hz    xmach      cc     rrho0
     63.     0.0    340.      1.22
restart and inflow parameters
 ifield   inflow    incp    isctp   inoise
      0        0      10        2        1
source location coordinates
    X10      X20      X30    mpole    drad
    4.2     0.00  -46.65        0   0.833
observer locations
   iobs
      3
periodc   offset   zminc    zmaxc  cylrad   shift
      9      0.0   -62.7    11.2    39.05     0.0
periods    x-off   y-off    z-off  sphrad
```

```
       7       0.0      0.0      -1.0     2.25
periodp    xminp    xmaxp     yminp    ymaxp    zminp    zmaxp   inac     rad      rmax
thinc
       9    -20.0     20.0      0.0      0.0    -65.0     15.0      0    1.66      3.0
10.0
periodf    ypmin    ypmax     zpmin    zpmax     tmin     tmax     nt     PSI    xplane
isurf    ibmot    iunit    icoord
       8      0.0      2.4     -2.0      9.5      0.0      0.2     40    0.38    -0.25
1           0        1          1
body motion files
fus-wing_nwlet_full.p3d
bwb-time.dat
user supplied observer field
usr_field.dat
```

The scattered field for the nacelle-only simulation is presented in Figure 3.7a; the incident field for the BWB/nacelle combination is given in Figure 3.7b. Note that the two are very similar, the differences being caused by a slightly different set of collocation points[4]. For such a low excitation frequency, the wave and nacelle lengths are comparable ($\lambda$ = 5.4 m, L = 7 m). In this case, sound emanating from the nacelle openings diffracts around the edges and envelops the nacelle, precluding the formation of a shadow zone.

Sound pressure level contours for the BWB/nacelle combination, for M = 0.0 and M = 0.2, are presented in Figures 3.8a and 3.8b, respectively. Several observations can be made from these figures: 1) there is considerable shielding by the fuselage; 2) some of the noise is diffracted around the fuselage trailing edge; 3) the presence of background flow tends to reduce the length of forward travelling waves and increase the length of aft travelling waves (compare Figures 3.9a and 3.9b); and 4) the presence of background flow also enhances noise propagation.

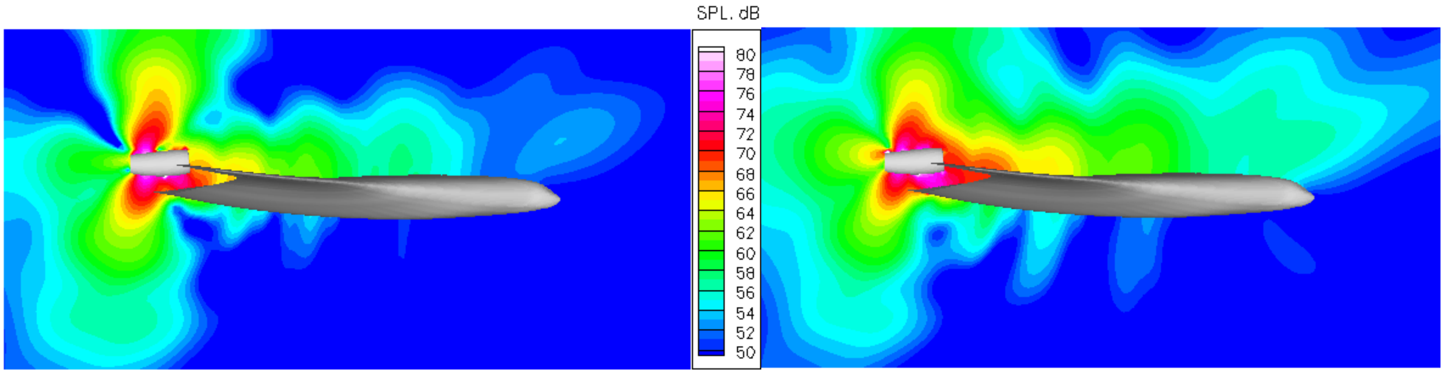



(a) Scattered field for nacelle-only simulation

(b) Incident field for BWB/nacelle

Figure 3.7 - Instantaneous acoustic pressure contours in the vicinity of the center nacelle, f = 63 Hz, M = 0.0, m = 0.

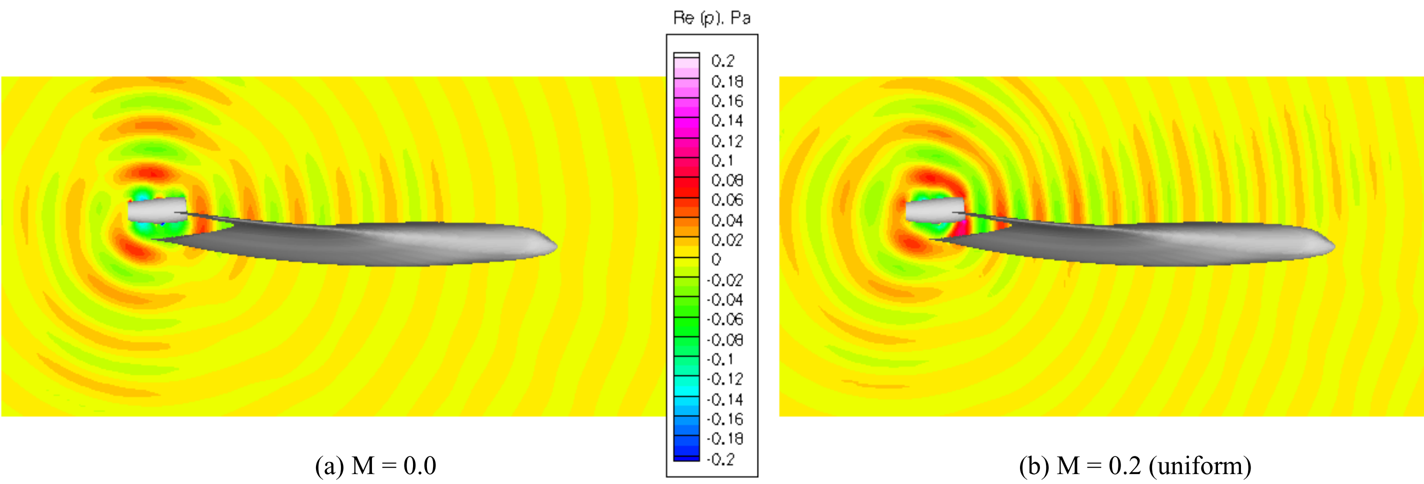
4 For the nacelle-only simulations, the entire nacelle geometry was used. For the BWB/nacelle simulations, only half the geometry was utilized, and symmetry was assumed by invoking `isctp` = 2.




(a) M = 0.0

(b) M = 0.2 (uniform)

Figure 3.8 - Sound pressure level contours for full scale BWB configuration,
f = 63 Hz, m = 0.




(a) M = 0.0

(b) M = 0.2 (uniform)

Figure 3.9 - Instantaneous acoustic pressure contours for full scale BWB configuration,
f = 63 Hz, m = 0.

# Acknowledgements

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# References

1. Dunn, M. H., and Tinetti, A. F., "Aeroacoustic Scattering Via the Equivalent Source Method," AIAA 2004-2937, May 2004.

2. Tinetti, A. F., and Dunn, M. H., "Aeroacoustic Noise Prediction Using the Fast Scattering Code," AIAA 2005-3061, May 2005.

3. Gerhold, C. H., Clark, L. R., Dunn, M. H., and Tweed, J., "Investigation of Acoustical Shielding by a Wedge-Shaped Airframe," AIAA 2004-2866.

4. Reimann, C. A., Tinetti, A. F., and Dunn, M. H., "Noise Prediction Studies for the Blended Wing Body Using the Fast Scattering Code," AIAA 2005-2980.

5. Myers, M. K., "On the Acoustic Boundary Condition in the Presence of Flow," *Journal of Sound and Vibration*, Vol. 71, pp. 429-434, 1980.

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The Fast Scattering Code (version 2.0) is a computer program for predicting the three-dimensional scattered acoustic field produced by the interaction of known, time-harmonic, incident sound with aerostructures in the presence of potential background flow. The FSC has been developed for use as an aeroacoustic analysis tool for assessing global effects on noise radiation and scattering caused by changes in configuration (geometry, component placement) and operating conditions (background flow, excitation frequency).

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