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USER'S MANUAL FOR THE LANGLEY BOUNDARY LAYER NOISE PROPAGATION PROGRAM (MRS-BLP)

Peter L. Spence

LOCKHEED ENGINEERING & SCIENCES COMPANY
Hampton, Virginia

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Langley Research Center
Hampton, Virginia 23665-5225

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Abstract

The computer program, McAninch-Rawls-Spence Boundary Layer Propagation (MRS-BLP) is described. This program models the refractive and scattering effects on acoustic pressure waves propagating through a boundary layer encompassing an aircraft's fuselage. The noise source is assumed known and generated by a propeller. The fuselage is represented by an infinitely long cylinder embedded in a longitudinal flow. By matching a numerical solution inside the boundary layer with an analytical solution outside the boundary layer, the program calculates the acoustic pressure at the surface of the cylinder given the incident field at the top of the boundary layer. The boundary layer flow velocity and sound speed profiles as well as the boundary layer thickness may be specified by the user. A detailed description of the input parameters and how to execute the program is given. Example executions of MRS-BLP showing results are also included.

Introduction

In many problems of helicopter rotor and propeller acoustics, the noise is measured under a boundary layer. It has been shown that the propagation effects through the boundary layer are significant and should be included in noise predictions. McAninch and Rawls[1] presented results for a flat plate model which showed a significant reduction of the freefield-plus-six-dB noise prediction forward of the plane of the propeller. In the realistic case of a curved fuselage, the study of wave propagation in the boundary layer becomes fairly complex, particularly when numerical calculations are involved. Hanson and Magliozzi[2] modeled an infinitely long cylinder with an isothermal, thin boundary layer and found the same shielding effects forward of the propeller. Further analysis by Lu[3] dropped the restrictions that the boundary layer had to be isothermal and thin with respect to the fuselage diameter. In all of this work (references 1, 2, and 3), however, a laminar boundary layer velocity profile was used. This paper describes the development of the computer program, McAninch-Rawls-Spence Boundary Layer Propagation (MRS-BLP) which is based on the analytic results of McAninch[1] for an infinitely long cylinder which includes a turbulent boundary layer velocity profile option.

In order to compute the propagation effects on the noise due to the velocity gradient in the boundary layer, the shear flow wave equation must be solved. This is a linear homogeneous ordinary differential equation with variable coefficients. Singularities can occur in the computational domain. Near the region of the singular points the computational domain is analytically continued into the complex plane[1]. The shear flow wave equation is solved by integrating from the fuselage surface, assuming unit pressure and zero admittance initially, to the top of the boundary layer using standard fourth order Runge-Kutta integration techniques. The resulting acoustic pressure and velocity are then used along with the freefield incident pressure to compute the actual surface acoustic pressure. This is accomplished by using a transfer function derived from Bessel's equation which governs the acoustic propagation outside the boundary layer.

A description of how to access and execute MRS-BLP is included. Results for varying boundary layer profiles and thicknesses are given.

Symbols

a_o	cylinder radius [m]
a_1	outgoing wave amplitude from propeller

c_o	freestream speed of sound [m/sec]
c	speed of sound, re c_o
c_c	speed of sound at cylinder's surface, re c_o
c_∞	freestream speed of sound, re c_o ($c_\infty = 1$)
$H_n^{(1)}$	Hankel function of the first kind
$H_n^{(2)}$	Hankel function of the second kind
i	$\sqrt{-1}$
J_n	Bessel function of the first kind
k_r	radial wave number
k_x	axial wave number
m	circumferential wave number
M_∞	freestream Mach number
N_b	number of propeller blades
N_x	number of axial grid points
N_θ	number of circumferential grid points
P	acoustic pressure, re $\rho_o c_o^2$
r	radial coordinate, re a_o
r_p	propeller centered radial coordinate, re a_o
R_c	cylinder radius, re a_o ($R_c = 1$)
R_s	distance from propeller axis to point of closest blade approach at the top of the boundary layer around cylinder, re a_o
R_δ	distance from center of cylinder to top of boundary layer, re a_o
$R_{\delta s}$	distance between propeller and cylinder centers ($R_\delta + R_s$)
t	time, re a_o/c_o
u_r	radial velocity, re c_o
U	axial velocity, re c_o
U_∞	freestream axial velocity, re c_o

x	axial coordinate, re a_o
α, α_T	transfer functions
β	cylinder surface admittance
δ	boundary layer thickness, re a_o
ζ	boundary layer coordinate, re δ
θ	angular coordinate, on cylinder
μ	radial velocity in Fourier transformed space
Π	acoustic pressure in Fourier transformed space
ρ_o	freestream density [kg/m^3]
ρ	density, re ρ_o
ψ	angular coordinate, on propeller
ω	blade passage frequency

Superscripts

$()'$	radial derivative

Theoretical Formulation

The problem to be solved is illustrated in figure 1. An aircraft fuselage is modeled by an infinitely long cylinder of radius a_o immersed in an axially directed uniform flow, U. A propeller whose axis of rotation is parallel to the center line of the cylinder acts as the axisymmetric exterior noise source. The coordinate system has its origin at the center of the cylinder in the plane containing the propeller. Around the cylinder is a boundary layer of thickness δ whose velocity gradient refracts the incident waves from the noise source. Due to the presence of this velocity gradient, from $U = 0$ at the cylinder's surface to the uniform freestream velocity (U_∞) at the boundary layer edge, some waves are refracted out of the boundary layer before reaching the surface of the

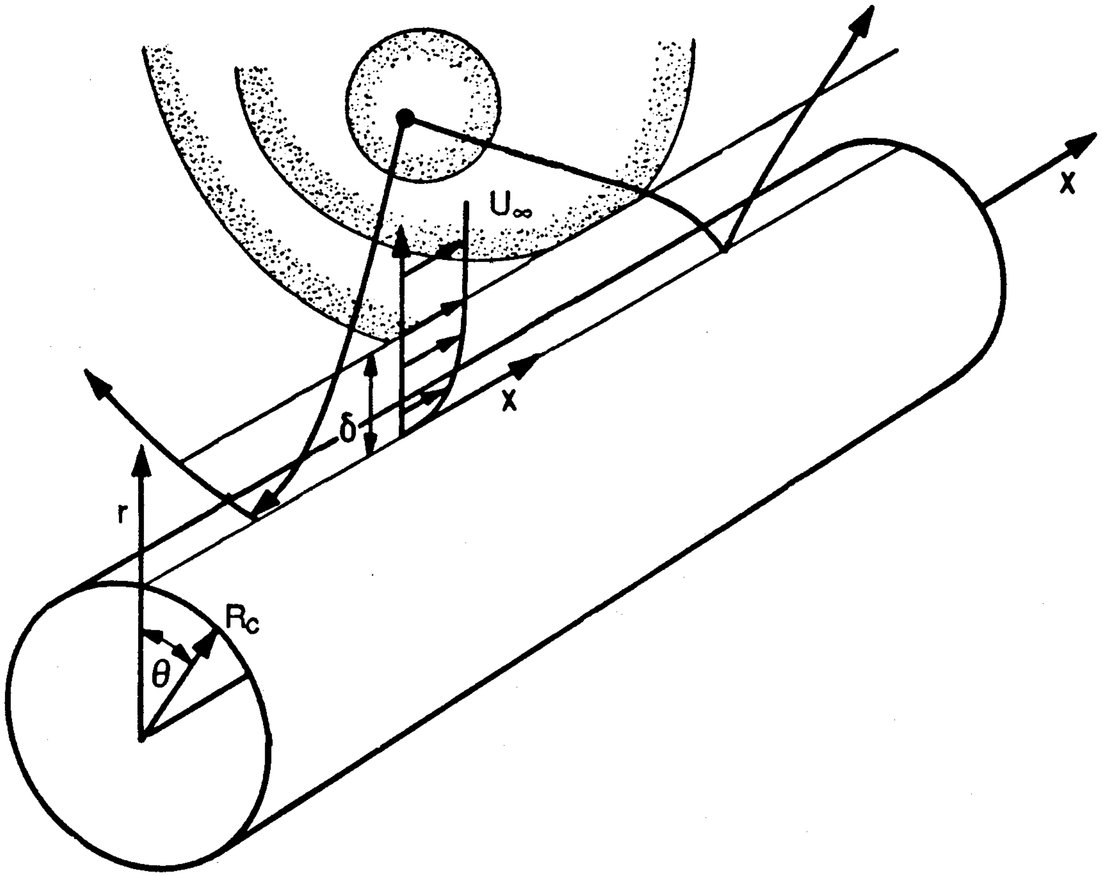

Figure 1. Circular cylinder model and coordinate system used in scattering and refraction problem.

cylinder. Acoustic waves striking the surface of the cylinder are scattered according to an admittance criteria which can be specified as a function of the propagating frequency of the incident noise source. Also, it is assumed that the sound speed and axial velocity profile are only dependent upon the radial coordinate r, thus, U = U(r) and c = c(r). The objective is to calculate the surface acoustic pressure on the cylinder given the incident acoustic pressure at the edge of the cylinder's boundary layer. In order to do so the equations governing the conservation of mass, entropy, and momentum within the boundary layer must be combined to form the shear flow wave equation.

The following derivation is for the first harmonic of the propagating frequency (blade passage frequency, ω). Higher harmonics are computed in the same manner by multiplying N_b by the harmonic number. This affects the order of two of the Hankel functions and ω.

Governing Equations

Following the analysis of McAninch and Rawls[1], the pressure inside the boundary layer can be expressed as,

$$\frac{D}{Dt}\left[\nabla^2 P + \frac{2c'}{c}\frac{\partial P}{\partial r} - \frac{1}{c^2}\frac{D^2 P}{Dt^2}\right] - 2U'\frac{\partial^2 P}{\partial r\,\partial x} = 0 \quad , \qquad (1)$$

where,

$$\nabla^2 \equiv \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial x^2} \quad ,$$

which is the Laplacian for cylindrical coordinates. Also, the velocity in the radial direction can be expressed as,

$$\frac{1}{c^2}\frac{Du_r}{Dt}+\frac{\partial P}{\partial r}=0 \tag{2}$$

Nondimensionalization is accomplished using the freestream sound speed, c_o, and density ρ_o. Revelant mass, length, and time scales used are $\rho_o a_o^3$, a_o, and a_o/c_o. Fourier transforming equations (1) and (2) results in the following,

$$(\omega - Uk_x)\,\Pi'' + \left[(\omega - Uk_x)\left(\frac{1}{r}+\frac{2c'}{c}\right) + 2U'k_x\right]\Pi' + (\omega - Uk_x)\left[\left(\frac{\omega - Uk_x}{c}\right)^2 - k_x^2 - \left(\frac{m}{r}\right)^2\right]\Pi = 0 \tag{3}$$

and,

$$\mu = \frac{-\,i\,c^2\,\Pi'}{\omega - Uk_x} \tag{4}$$

where the complex Fourier coefficient, F, of the function, f, is defined as,

$$F(r,k_x,m,\omega) = \frac{1}{8\pi^3}\int_{-\infty}^{\infty}\int_{0}^{2\pi}\int_{-\infty}^{\infty} f(r,x,\theta,t)\, e^{i\,(\omega t + k_x x - m\theta)}\, dx\, d\theta\, dt \quad . \tag{5}$$

Here, Π is the Fourier coefficient of P and μ is the Fourier coefficient of u_r. In addition, k_x is the axial wave number, ω is the angular frequency, and m is the circumferential wave number.

Governing Equations Outside the Boundary Layer

Outside the boundary layer around the cylinder, where the axial flow speed and speed of sound become constant, equation (3) reduces to

$$\Pi'' + \frac{1}{r}\,\Pi' + \left[\left(\frac{\omega}{c_\infty} - M_\infty k_x\right)^2 - k_x^2 - \left(\frac{m}{r}\right)^2\right]\Pi = 0 \quad . \tag{6}$$

With a simple change in variable, equation (6) can be written as a Bessel equation. Therefore, solutions to (6) can be expressed in the form of a Bessel function J_m, or as a combination of Hankel functions, $H_m^{(1)}$ and $H_m^{(2)}$. From the noise source in the propeller centered coordinate system, Π can be expressed as an outward propagating wave with the Hankel function $H^{(1)}_{N_b}$. Specifically,

$$\Pi(r_p,k_x,\omega) = a_1(k_x,\omega)\, H^{(1)}_{N_b}(k_r\, r_p) \quad . \tag{7}$$

The radial variable r is subscripted with a p to emphasize that its origin is with respect to the propeller centered coordinate system and,

$$k_r = \sqrt{\left(\frac{\omega}{c_\infty} - M_\infty k_x\right)^2 - k_x^2} \tag{8}$$

is the radial wave number. The Hankel function of the first kind, $H^{(1)}_{N_b}$ represents the waves generated by a propeller with N_b blades and satisfies the boundary condition that all waves are propagating outward from the source.

The propeller centered coordinate system must be transformed to the cylinder centered coordinate system in order to solve for the pressure on the surface of the cylinder. Referring to figure 2, the transformation is accomplished by using the Hankel function identity (Graf's Theorem)[4]

$$H^{(1)}_{N_b}(k_r\, r_p)\, e^{i N_b \psi} = \sum_{m=-\infty}^{\infty} H^{(1)}_{N_b+m}(k_r\, R_{\delta s})\, J_m(k_r\, R_\delta)\, e^{i m \theta} \quad . \tag{9}$$

In the cylinder centered coordinate system, the transformed freefield acoustic pressure at the top of the boundary layer is given by

$$\Pi(R_\delta,k_x,m,\omega) = \left[\frac{\Pi_s}{H^{(1)}_{N_b}(k_r\, R_s)} H^{(1)}_{N_b+m}(k_r\, R_{\delta s})\right] J_m(k_r\, R_\delta) \quad , \tag{10}$$

where,

$$\Pi_s \equiv \Pi(R_s,k_x,\omega) \quad .$$

Π_s is calculated using the Advanced Subsonic and Supersonic Propeller Induced Noise (ASSPIN)[8] computer program developed at NASA Langley. The program uses Farassat's time domain formulation of the Ffowcs Williams - Hawkings equation[6].

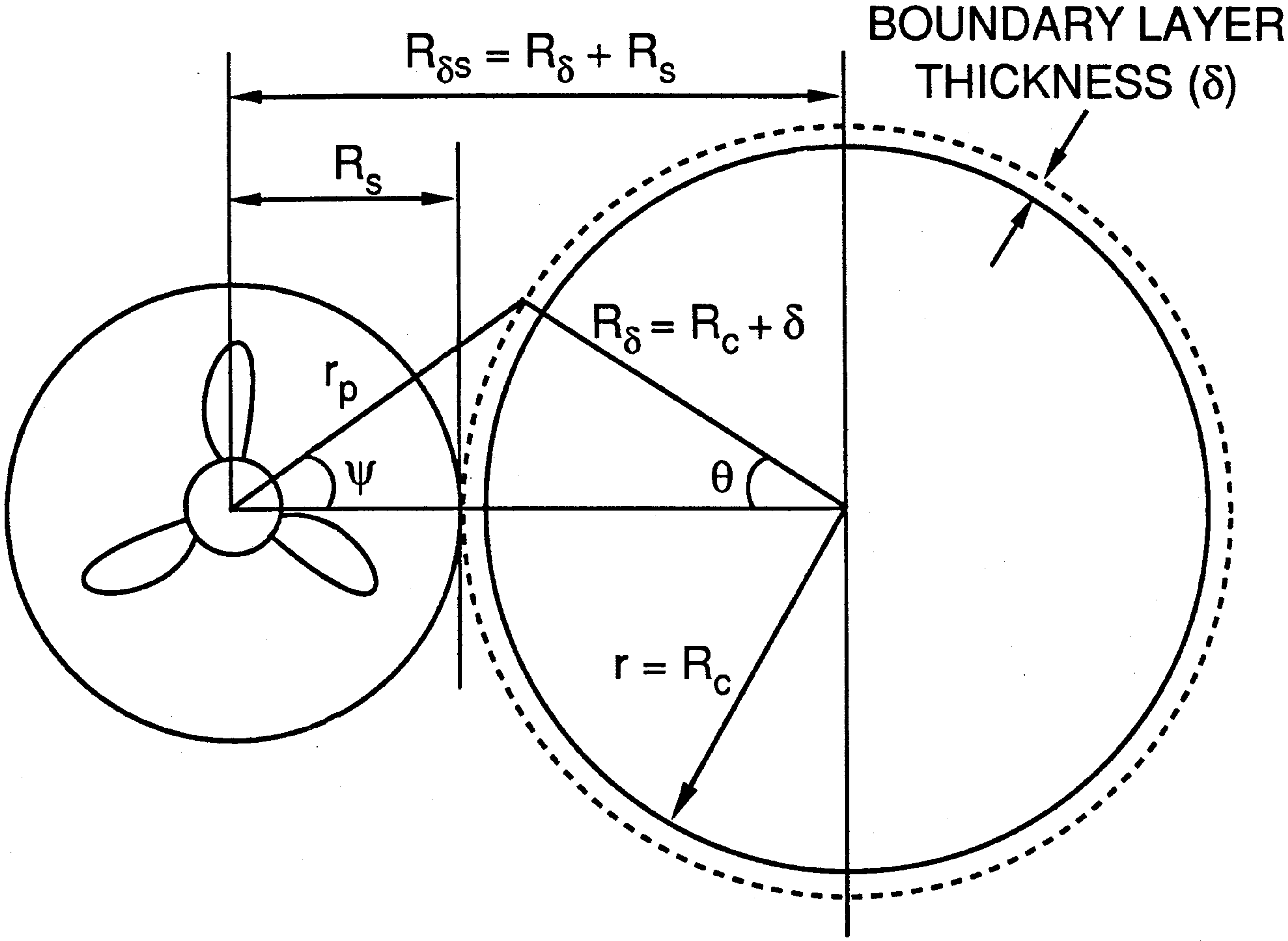

Figure 2. Relationship between propeller and fuselage centered coordinate systems.

Using the acoustic pressure specified along the line of closest blade approach parallel to the propeller's rotational axis at the top of the boundary layer surrounding the cylinder, Π_s, the acoustic pressure can be calculated everywhere on the top of the boundary layer using equation (10). However, what is of interest is the acoustic pressure at the surface of the cylinder under the boundary layer. In order to obtain this, equation (3) must be solved numerically with some initial conditions at the cylinder's surface and the results matched with the freefield prediction calculated using equation (10).

Boundary Layer Analysis

Mathematical singular points occur when solving equation (3) when the condition

$$\omega - Uk_x = 0 \tag{11}$$

is satisfied. Physically this represents the critical point at which the acoustic wave propagation speed equals the flow speed. Mathematically, the coefficient of the highest order derivative is lost changing the nature of the governing equation. Obviously this is dependent on the boundary layer flow velocity profile.

There are several methods available to either analytically or numerically cope with these singularities. The method which is used here and derived by McAninch[1] uses analytic continuation across the entire domain to be integrated whenever a singular point exists in the boundary layer on the real axis. The use of this method allows the velocity profile and sound speed profile within the boundary layer to be changed without redefining the series expansion (and hence rewriting computer code). Details of this derivation can be found in reference 1.

In order to perform the integration U and c must be defined inside the boundary layer. Usually c is assumed constant. For convenience, the boundary layer coordinate ζ is used to specify U and c.

$$\zeta \equiv \frac{(r - R_c)}{\delta} \quad . \tag{12}$$

The change in variable is accounted for when computing U′ and c′ during integration of (3) by making use of the chain rule,

$$\frac{\partial}{\partial r} = \frac{1}{\delta} \frac{\partial}{\partial \zeta} \quad . \tag{13}$$

Two boundary layer profiles are used in the current study. One representing a laminar boundary layer and one representing a turbulent boundary layer. The default laminar case makes use the Pohlhausen profile[7],

$$U = U_\infty \left[\zeta^4 - 2\,\zeta^3 + 2\,\zeta \right] \quad , \tag{14}$$

and the one-over-n power law is used for the turbulent boundary layer, where n is specified at input.

$$U = U_\infty\, \zeta^{1/n} \quad . \tag{15}$$

Boundary Conditions

The boundary conditions used to start the numerical integration are,

$$\Pi(R_c) = 1$$
$$\Pi'(R_c) = \frac{-i\,\omega\,\beta}{c_c^2} \tag{16}$$

where β is the surface admittance of the cylinder which can be specified as a complex function of ω. The radial derivative of Π at the surface is related to the radial velocity at the surface through the momentum equation (4). Thus, setting $\Pi'(r)$ to zero means zero admittance ($\beta = 0$). This is the condition representing a perfectly reflecting hard wall.

Matching Solutions at the Top of the Boundary Layer

McAninch[1] showed that the acoustic pressure at the surface of the cylinder is linearly related to the incident acoustic pressure at the top of the boundary layer. This multiplicative constant is determined by matching the resulting pressure and radial velocity computed from the boundary layer analysis to the freefield acoustic pressure and velocity at the top of the boundary layer.

$$\Pi(R_\delta,k_x,m,\omega) = \alpha\, \Pi_{BL}(R_\delta,k_x,m,\omega) \tag{17}$$

$$\mu(R_\delta,k_x,m,\omega) = \alpha\, \mu_{BL}(R_\delta,k_x,m,\omega) \tag{18}$$

Here the subscript BL denotes results via the boundary layer analysis (integrating (3)). Outside of the boundary layer the flow is uniform and homogeneous. In this region, both the pressure and radial velocity can be unambiguously split into their incident and scattered components denoted by the subscripts i and sc.

$$\Pi = \Pi_i + \Pi_{sc} \tag{19}$$

$$\mu = \mu_i + \mu_{sc} \tag{20}$$

Writing the incident and scattered waves in their analytical form denoted be Hankel and Bessel functions and solving for α, yields the analogous transfer function (α_T) for a cylinder as that for a flat plate derived by McAninch[1].

$$\alpha_T \equiv \frac{\alpha}{\Pi_{in}} = \frac{-2}{\left(\frac{\pi R_\delta}{2}\right) H_m^{(2)}(k_r R_\delta)\left[i\, k_r\, \Pi_{BL}\, H_m^{(1)\prime}(k_r R_\delta) + (\omega - U_\infty k_x)\, \mu_{BL}\, H_m^{(1)}(k_r R_\delta)\right]} \tag{21}$$

Thus the surface pressure on the cylinder is given by

$$\Pi(R_c,k_x,m,\omega) = \alpha\, \Pi_{BL}(R_c,k_x,m,\omega) \tag{22}$$

Here $\Pi_{BL}(R_c,k_x,m,\omega)$ can be any value to start the numerical integration of equation (3). For simplicity $\Pi_{BL}(R_c,k_x,m,\omega)$ is set to 1 as stated in the previous section. Because of this, it can be seen that α_T is the ratio of the magnitude of the incoming pressure at the top of the boundary layer to the same at the cylinder's surface. Hence, α_T is referred to as a transfer function.

Once $\Pi(R_c,k_x,m,\omega)$ is obtained, the acoustic pressure at the cylinder's surface is expressed in physical space and the frequency domain as,

$$P(R_c,x,\theta,\omega) = \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \Pi(R_c,k_x,m,\omega)\, e^{i(k_x x + m\theta)}\, dk_x \quad . \tag{23}$$

Solution Procedure

A general flow chart of the solution procedure is shown in figure 3. All Fourier transforms and inverse transforms are done making use of Fast Fourier Transform (FFT) techniques. As mentioned previously, the computer program ASSPIN is used to compute the incident pressure on the cylinder. This incident pressure is specified along a line of equally spaced grid points parallel to the propeller hub axis at the point of closest blade approach along the cylinder on top of the boundary layer. Due to the use of the FFT, the number of grid points must be the result of 2^y, where y is a positive integer. Further, once discretization occurs for programing on a computer, the number and range of the grid points must adequately resolve the phase variation along this axial grid, Spence[8].

Program Description

The layout of the file structure is illustrated in figure 4. MRS-BLP is a Fortran V program which, in order to run, requires one input file for execution. A standard

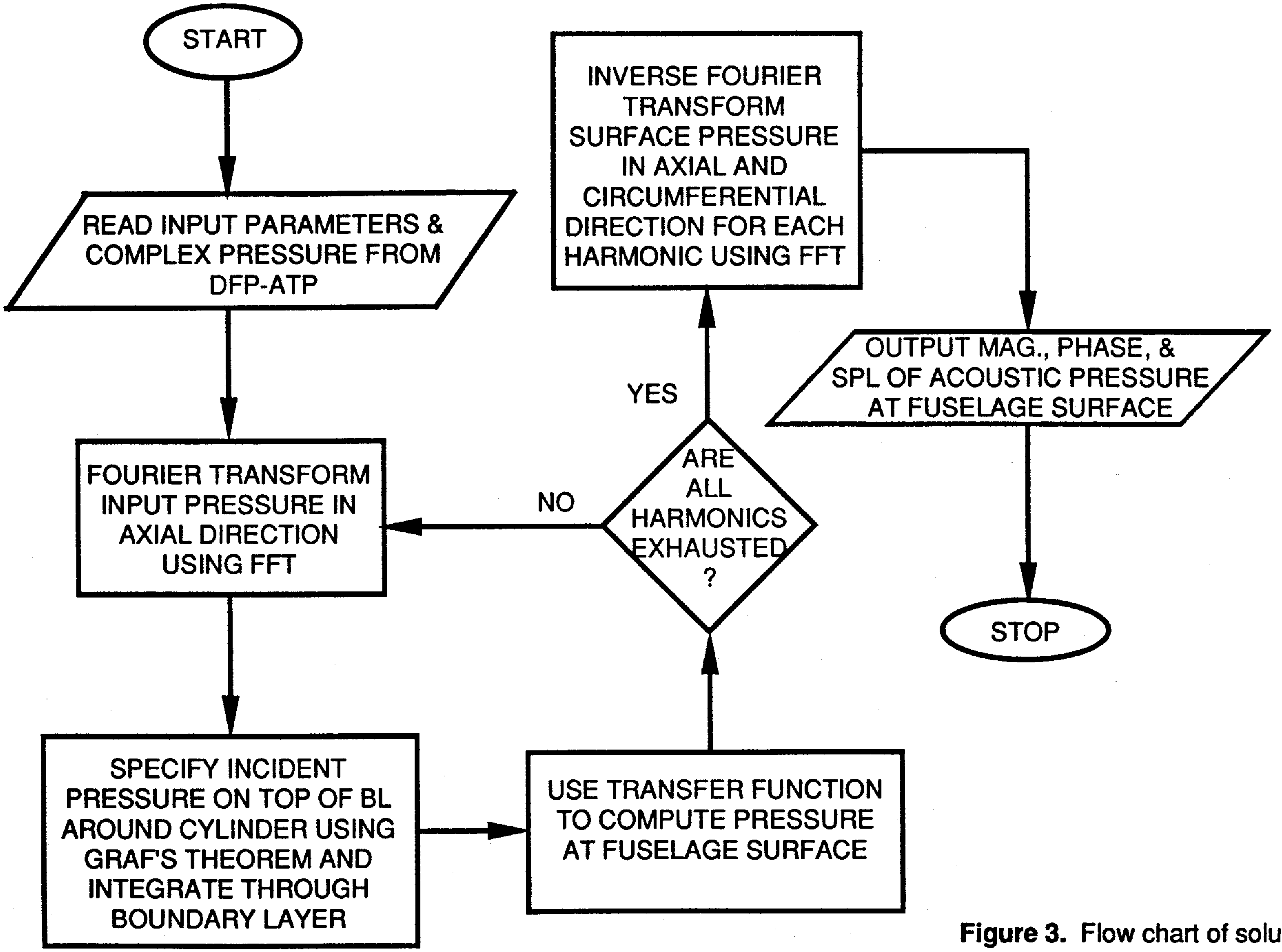

Figure 3. Flow chart of solution procedure.

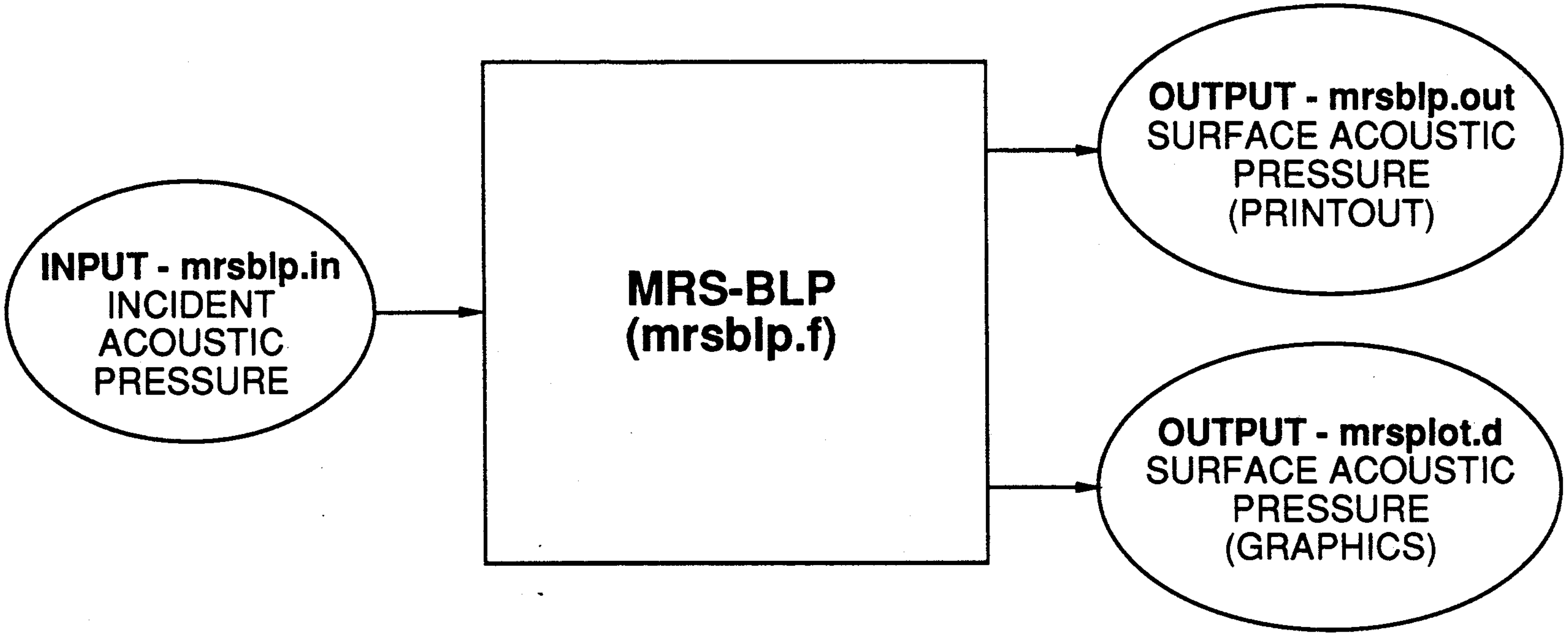

Figure 4. Layout of the file structure comprising a MRS-BLP execution.

(printed) output file as well as an output file for graphical purposes are created upon execution of MRS-BLP. The input file name is mrsblp.in, the output file name is mrsblp.out and output file containing plotting information is named mrsplot.d. These names are compatible with the UNIX operating system and are defined in OPEN statements in the main program. Following is provided a more detailed description of the files involved with a MRS-BLP execution.

Input File (mrsblp.in)

The first line of mrsblp.in is a character variable, 80 characters in length. This may be used to write a comment label on the resulting output file. Apart from this first line, mrsblp.in is comprised of two types of input. First, parameters defining the operating conditions and physical dimensions are given in the namelist SCATTER. Second, the axial locations and values of the complex acoustic pressure incident on the top of the boundary layer surrounding the cylinder are defined. Parameters making up namelist SCATTER are defined in Table 1. The example runs in the next section discuss setting these parameters.

Table 1. Namelist SCATTER parameters. Note: dimensional variables must be given in SI units.

Parameter Name	Description
AD	fuselage radius, [m]
CAD	free-stream sound speed, [m/sec]
DELTAD	boundary layer thickness, [m]
MINF	free-stream Mach number
NBLADE	number of propeller blades
NTHETA	number of evenly spaced circumferential grid points (NTHETA=2^y; y is a positive integer)
NX	number of evenly spaced axial grid points (NX=2^y; y is a positive integer)
NOMEGA	number of harmonics to be computed
NPWR	inverse power for the turbulent boundary layer velocity profile
RHOAD	free-stream density, [kg/m^3]
RXD	source radius from hub to fuselage surface at the point of closest blade approach, [m]
TURBLP	turbulent boundary layer profile flag .TRUE. - use turbulent boundary layer profile .FALSE. - use boundary layer profile defined in MRS-BLP
X1D	initial axial grid point (upstream), [m]
XFD	final axial grid point (downstream), [m]

Following namelist SCATTER is a list of the complex acoustic pressure incident on the top of the boundary layer. One line separates SCATTER from the list of incident pressure. Two values are placed here in free format. The value of the fundamental blade passage frequency (BPF) and the integer number of harmonics included in the incident pressure list. The order of the input list is important. The first line must contain the complex surface admittance corresponding to the frequency being input. The values of the incident pressure must be given from the forward-most position (upstream) to the aft-most position (downstream) of the propeller. Each line is comprised of the dimensional axial (x) distance form the propeller plane followed by the corresponding real and imaginary parts of the free-field complex acoustic pressure. Both the admittance and the incident pressure are read in free format.

The number of lines which comprise this section of the input file for each harmonic must be the same as the NX parameter in the namelist SCATTER. This is the number of equally spaced axial grid points specified at the top of the boundary layer. Because use is made of the Fast Fourier Transform (FFT) within MRS-BLP, NX must be a value equal to 2^y where y is a positve integer. This is also true of the variable NTHETA in SCATTER which is the number of circumferential grid points used. Figure 5 illustrates the format of how to supply this incident pressure.

Because the input must go from the forward-most position to the aft-most position, the x_1 value in figure 5 is the largest negative value increasing down the file to x_{N_x} which is the largest positive value. The higher harmonics follow sequentially with nothing separating the division between harmonics.

MRS-BLP (mrsblp.f)

MRS-BLP is stored in file mrsblp.f. This file must be edited to properly set PARAMETER statements at the top of the file. Also, if the user wishes to specify their

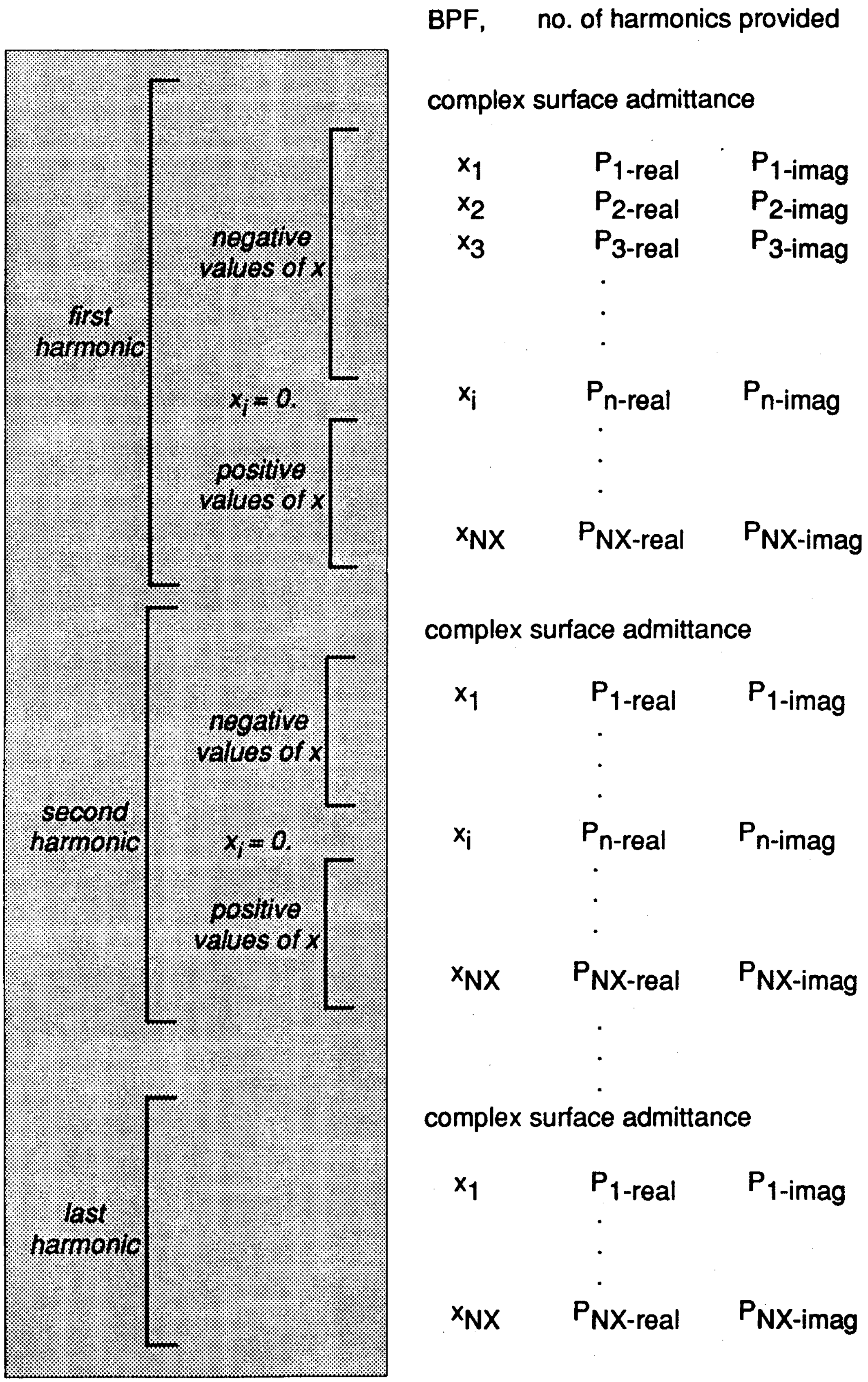

Figure 5. Input structure of the incident pressure.
(Shaded area provides comments)

own boundary layer velocity or sound speed profile, additional editing, although minimal, must be done.

The PARAMETER statement on the second line of the program contains four symbolic constants, NXDIM, NTHDIM, NVCOEF, and NSCOEF. NXDIM and NTHDIM are the axial and circumferential grid number respectively. These constants are used for dimensioning arrays and must be the same as the SCATTER variables NX and NTHETA (see Table 1). The second two symbolic constants, NVCOEF and NSCOEF define the number of coefficients used to define the boundary layer velocity and sound speed profiles respectively. The default velocity profile is the laminar velocity profile specified by Pohlhausen (equation 14) and the sound speed profile may be taken as constant. These are the profiles coded into MRS-BLP. The user may change these coefficients by editing subroutine MRSVSC within MRS-BLP. Note that the profiles must be defined in the form of a polynomial in decreasing powers of ζ. Comment cards provide an example. However, it must be emphasized that turbulent velocity profiles can be run by merely changing the variables TURBLP and NPWR in SCATTER. Setting TURBLP to .TRUE. overrides the velocity profile defined within MRS-BLP. Also, by setting TURBLP false and setting NVCOEF and NSCOEF equal to 1, a scattering-only calculation can be made. For these reasons, unless a very special case of velocity profile is desired, it is not recommended to change the velocity coefficients within the program.

Output Files (mrsblp.out, mrsplot.d)

Upon completion of a MRS-BLP execution two files are created, mrsblp.out and mrsplot.d. Normally, mrsblp.out is routed to a printer for a standard printed output.

Two displays are printed. The first lists the magnitude and phase for each grid point while the second gives the sound pressure levels (SPL) in dB.

A running average filter is applied to the SPL output to smooth oscillations in the axial direction near the end points of the axial domain. These oscillations are due the discontinuity in the incident noise at the forward-most and aft-most locations of the axial grid. This discontinuity results in oscillations upon taking the axial FFT (Gibbs phenomenon). As a general rule, the axial grid should extend beyond the forward and aft points of interest to insure that any oscillations occur outside the range of interest.

The second file, mrsplot.d, may be used for graphical purposes. Figure 6 shows the format by which mrsplot.d is read. This illustration assumes Fortran UNIT 1 has been assigned to mrsplot.d. The array SPLIP contains the incident SPL in dB and X is the axial position in meters. Two output arrays are written to mrsplot.d. The first is the magnitude and phase of the complex acoustic pressure at the cylinder's surface. The magnitude is in Pascals and the phase is in radians. The array P is defined as complex in the MRS-BLP code, however, P is overwritten so as to contain the magnitude in the real part of P and the phase is stored in the imaginary part of P. The second array contains the SPL of the surface acoustic pressure. Again the format used to write this is shown below. As can be seen in figure 6, BETA, SPLIP, P, and SPL are redefined for each harmonic computed.

Example Executions of MRS-BLP

The operating conditions corresponding to the Propfan Test Assessment (PTA)[9,10] design conditions are used to demonstrate the use of the developed code. The PTA program involved a 2.74 m propfan consisting of 8 blades. These conditions are listed

```
READ ( 1, 10 ) LABEL
10      FORMAT ( 1X, A80 )
READ ( 1, SCATTER )
READ ( 1, * ) BPF

DO 80 K = 1, NOMEGA

READ ( 1, * ) BETA
DO 20 I = 1, NX
READ ( 1, 30 ) X, SPLIP ( I )
20      CONTINUE
30      FORMAT ( 1X, F8.2, 5X, F8.2 )

J2 = 0
DO 40 J = 1, NTHETA, 5
J1 = J
J2 = J2 + 5
IF ( J2 .GT. NTHETA) J2 = NTHETA
DO 40 I = 1, NX
READ ( 1, 50 )  ( P ( I, JJ ), JJ = J1, J2 )
40      CONTINUE
50      FORMAT ( 10X, 10E12.5 )

J2 = 0
DO 60 J = 1, NTHETA, 10
J1 = J
J2 = J2 + 10
IF ( J2 .GT. NTHETA) J2 = NTHETA
DO 60 I = 1, NX
WRITE ( 1, 70 )  ( SPL ( I, JJ ), JJ = J1, J2 )
60      CONTINUE
70      FORMAT ( 10X, 10F12.3 )

80      CONTINUE
```

Figure 6. Illustration of format for reading mrsplot.d

in Table 2. The aerodynamic blade loading for input to ASSPIN was computed by Dunn and Farassat[11].

Table 2. Flight conditions used in example executions of MRS-BLP. Taken from PTA flight conditions (references 9, 10). SR-7 propeller, 8 bladed, 2.74 m diameter.

	DESIGN CONDITION
Flight Mach Number, M_∞	0.813
Rotational Tip Mach Number	0.814
Helical Tip Mach Number	1.150
BPF [Hz]	226.13
Altitude [km (ft)]	10.7 (35000)
Speed of Sound, c_o [m/sec (ft/sec)]	299.3 (982.0)
Density, ρ_o [kg/m^3 (slug/ft^3)]	0.372 (7.22E-4)

Following are three examples of executing MRS-BLP. These examples are given to illustrate how to define the boundary layer profiles as well as how to execute the code in general. Three boundary layer profiles are demonstrated, a laminar, a turbulent, and a constant free-stream velocity profile, i e, no boundary layer. Because the third profile has no velocity gradient at the cylinder's surface, no refraction of the incident acoustic waves take place and hence this is considered a scattering-only calculation. A sample input file is provided for each example as well as graphical output of the acoustic pressure at the cylinder's surface. In all three examples an axial grid of 128 points by 32 circumferential points are used. And as stated previously the incident pressure was calculated using ASSPIN. Also the boundary layer thickness in all examples is 10 cm and the sound speed within the boundary layer is assumed constant. Lastly, the complex admittance is set to zero in all cases. This is the condition for a perfectly reflecting hard surface.

<u>Example 1</u> - Laminar Boundary Layer Profile

The input file to MRS-BLP is as follows.

```
EXAMPLE 1 - LAMINAR BOUNDARY LAYER PROFILE
$SCATTER
        AD          = 1.1938,
        CAD         = 299.25,
        DELTAD      = .1,
        MINF        = 0.813,
        NBLADE      = 8,
        NTHETA      = 32,
        NX          = 128,
        NOMEGA      = 1,
        NPWR        = 7,
        RHOAD       = 0.372,
        RXD         = 3.0632,
        TURBLP      = .FALSE.,
        X1D         = -5.400675,
        XFD         =  5.4864$
226.133             5
( 0., 0. )
-5.400675           P1 - real        P1 - imag
      .                  .                .
      .                  .                .
      .                  .                .
 5.4864             PNX - real       PNX - imag
```

Likewise, the PARAMETER statement at the top of MRS-BLP should read.

```
PARAMETER ( NXDIM = 128, NTHDIM = 32, NVCOEF = 5, NSCOEF = 1)
```

The fuselage radius, AD and the source radius, RXD were obtained from references 9 and 10. X1D and XFD are defined so as to include two propeller diameters (propeller diameter = 2.74 m) forward and aft of the plane of the propeller.

Because TURBLP is set to .FALSE. the boundary layer profile will be defined by MRS-BLP. By setting NVCOEF = 5 (default) and NSCOEF = 1 (default) the profile will be Pohlhausen's laminar profile for the flow velocity with a constant sound speed within the boundary layer. Also, in the PARAMETER statement, NXDIM must be set to 128 (the value of NX in SCATTER) and NTHDIM must be set to 32 (the value of NTHETA in SCATTER).

Results of this run are illustrated in figure 7. Figure 7a shows the axial variation of both the incident and surface pressure in sound pressure levels (SPL) along the line parallel to the propeller axis on the cylinder. The circumferential surface acoustic pressure in the plane of the propeller around the cylinder is shown in figure 7b.

Example 2 - Turbulent Boundary Layer Profile

The input file to MRS-BLP is as follows.

```
EXAMPLE 2 - TURBULENT BOUNDARY LAYER PROFILE
$SCATTER
        AD       = 1.1938,
        CAD      = 299.25,
        DELTAD   = .1,
        MINF     = 0.813,
        NBLADE   = 8,
        NTHETA   = 32,
        NX       = 128,
        NOMEGA   = 1,
        NPWR     = 7,
        RHOAD    = 0.372,
        RXD      = 3.0632,
        TURBLP   = .TRUE.,
        X1D      = -5.400675,
        XFD      =  5.4864$
```

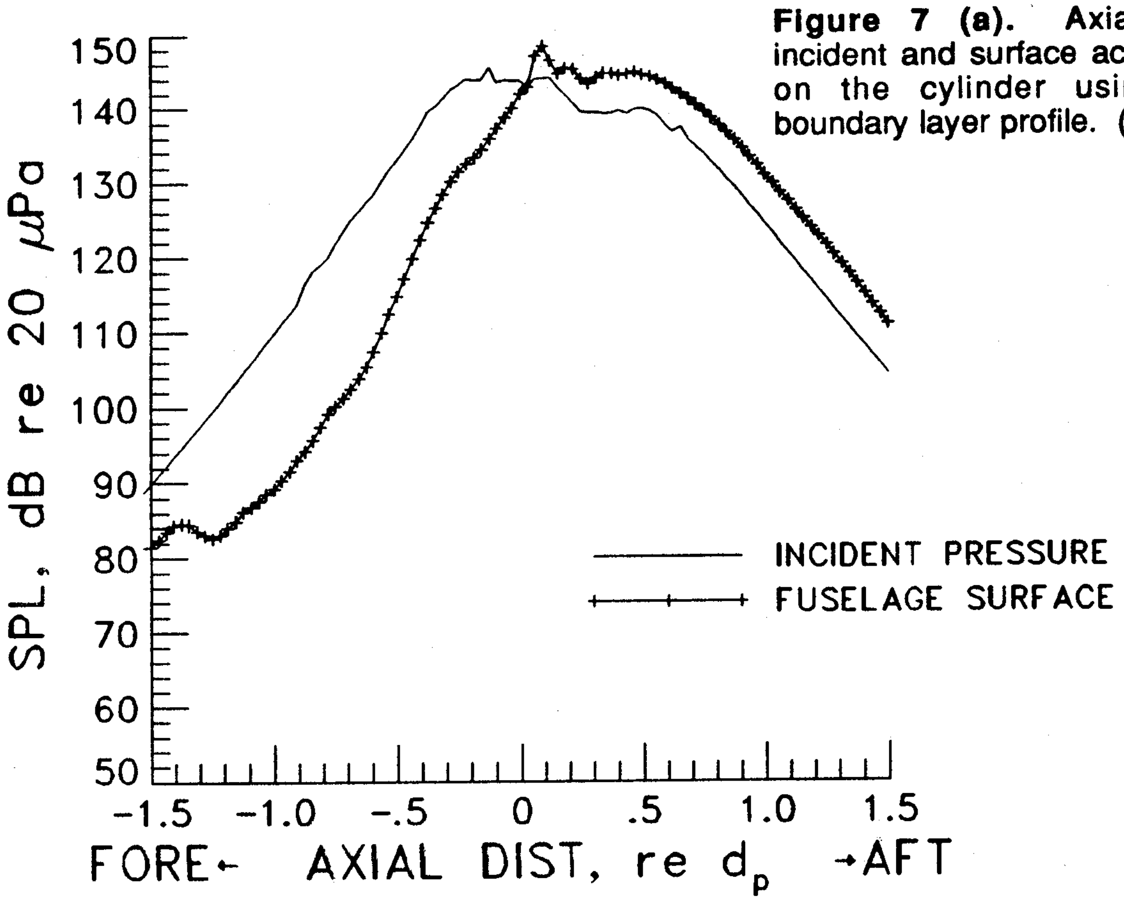

Figure 7 (a). Axial variation of incident and surface acoustic pressure on the cylinder using a laminar boundary layer profile. (d_p = 2.74m)

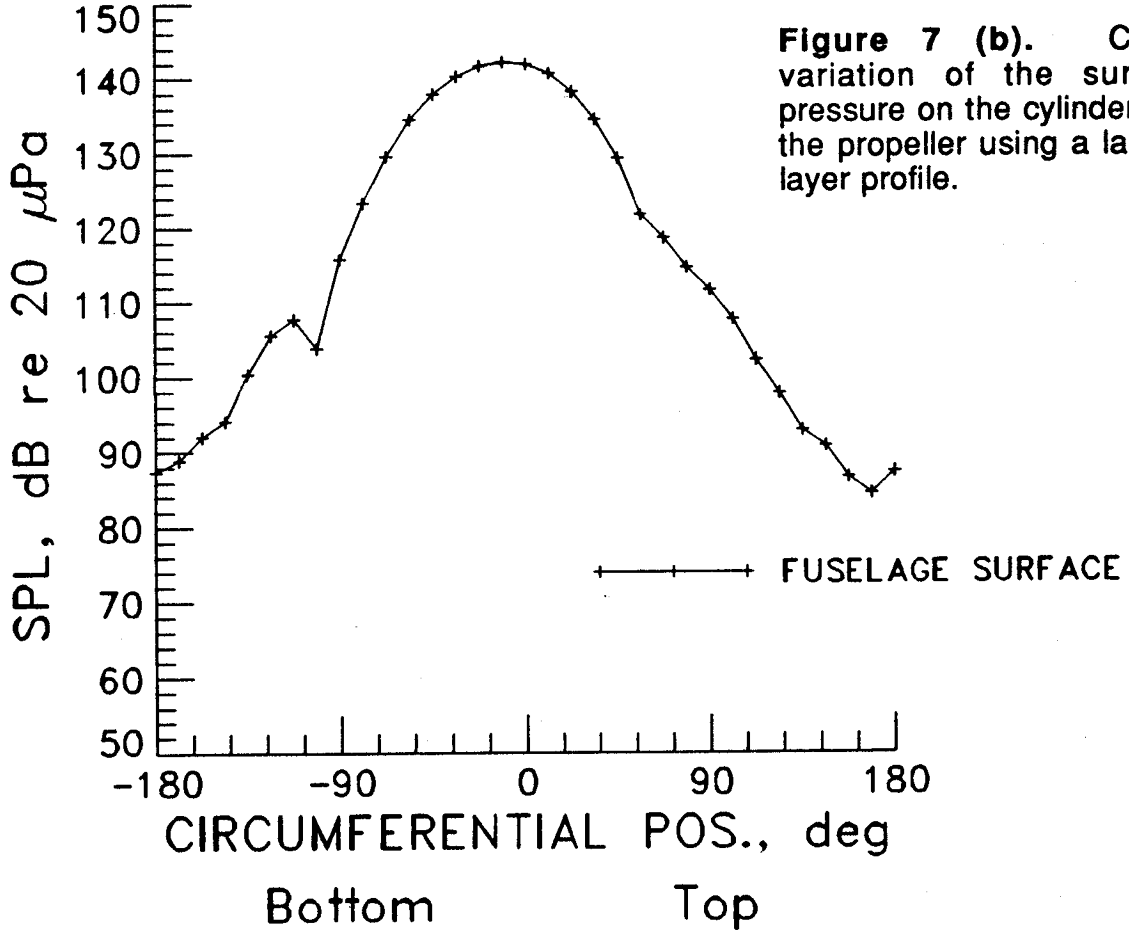

Figure 7 (b). Circumferential variation of the surface acoustic pressure on the cylinder in the plane of the propeller using a laminar boundary layer profile.

```
226.133          5
( 0., 0. )
-5.400675        P1 - real        P1 - imag
    .               .                .
    .               .                .
    .               .                .
 5.4864          PNX - real       PNX - imag
```

The PARAMETER statement should read as it did in Example 1. Actually NVCOEF will be ignored except for allocating storage. Setting TURBLP to .TRUE. in SCATTER overrides the polynomial boundary layer profile defined in subroutine MRSVSC within MRS-BLP. Here the boundary layer profile will be the 1/7 power law since NPWR is set to 7.

As in Example 1, the axial and circumferential acoustic pressure varialtion on the cylinder is shown in figure 8.

Example 3 - Scattering-Only Calculation

The input file to MRS-BLP is as follows.

```
EXAMPLE 3 - SCATTERING-ONLY CALCULATION
$SCATTER
        AD          = 1.1938,
        CAD         = 299.25,
        DELTAD      = .1,
        MINF        =0.813,
        NBLADE      = 8,
        NTHETA      = 32,
        NX          = 128,
        NOMEGA      = 1,
        NPWR        = 7,
        RHOAD       = 0.372,
        RXD         = 3.0632,
        TURBLP      = .FALSE.,
        X1D         = -5.400675,
        XFD         =  5.4864$
```

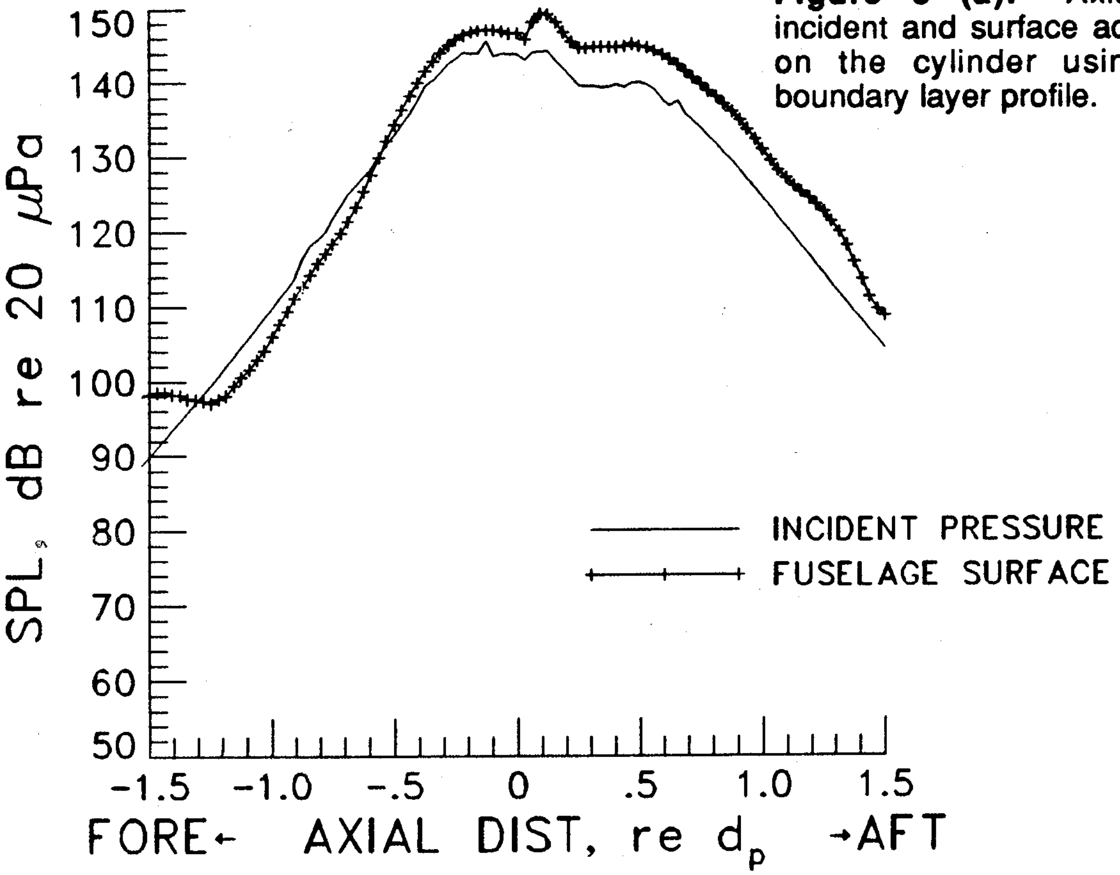

Figure 8 (a). Axial variation of incident and surface acoustic pressure on the cylinder using a turbulent boundary layer profile. (d_p = 2.74m)

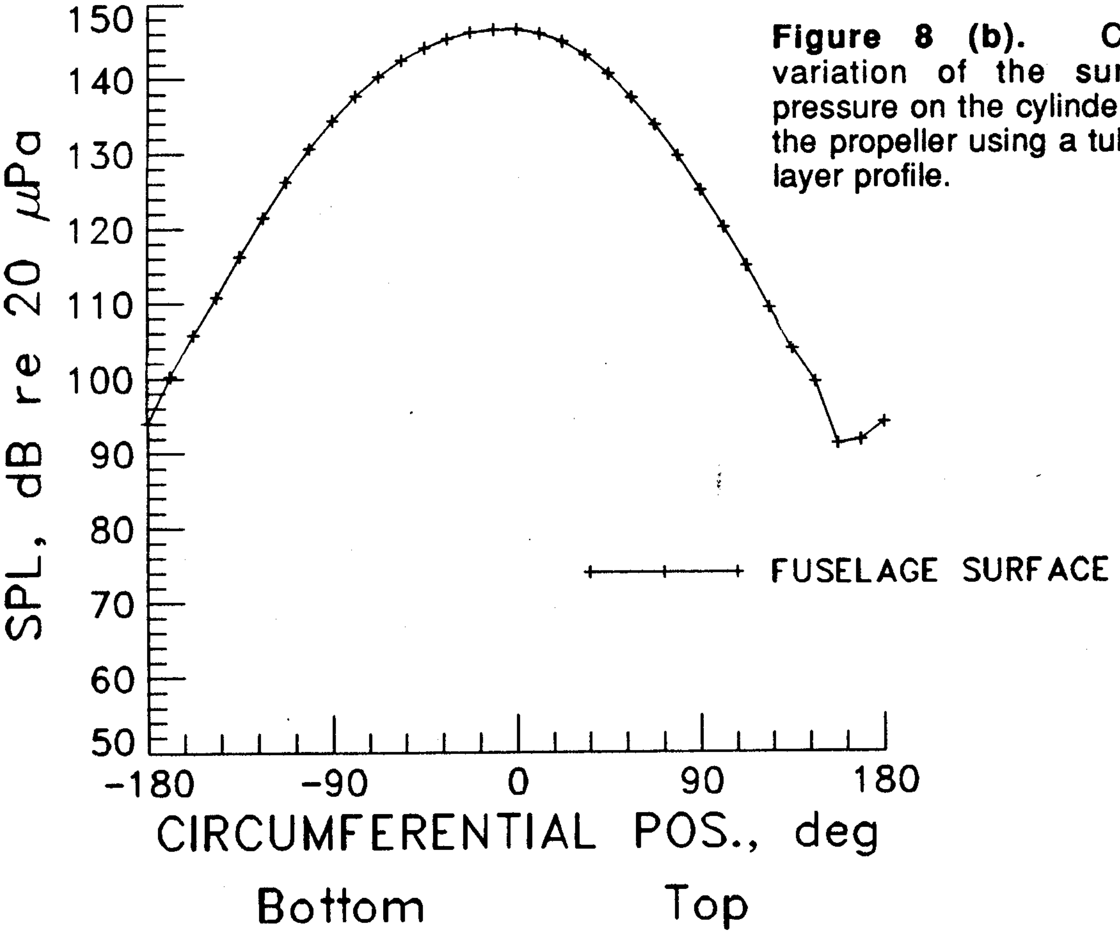

Figure 8 (b). Circumferential variation of the surface acoustic pressure on the cylinder in the plane of the propeller using a tubulent boundary layer profile.

```
226.133       5
( 0., 0. )
-5.400675     P1 - real     P1 - imag
    .             .             .
    .             .             .
    .             .             .
 5.4864       PNX - real    PNX - imag
```

And the PARAMETER statement at the beginning of MRS-BLP should read.

```
PARAMETER ( NXDIM = 128, NTHDIM = 32, NVCOEF = 1, NSCOEF = 1)
```

In this example, the input file would be identical to that of example 1 (except for the first line which is used for comments only). The key is setting TURBLP to .FALSE. in SCATTER and NVCOEF to 1 in the PARAMETER statement. MRS-BLP will set the velocity profile in the boundary layer to the constant free-stream velocity when NVCOEF is 1.

Again, as with the two previous examples, axial and circumferential variation of the acoustic pressure on the cylinder are plotted in figure 9.

Computational Time

The examples were executed on the CRAY computers at NASA Langley Research Center which have a UNIX operating system. It was determined that using either a Pohlhausen or turbulent boundary layer velocity profile required approximately 0.016 CPU sec / grid point / harmonic to execute the code on the CRAY Y-MP and approximately 0.023 CPU sec / grid point / harmonic on the CRAY-2S. When turning off the velocity gradient within the boundary layer and doing a scattering-only calculation the time required was approximately 0.0058 CPU sec / grid point /

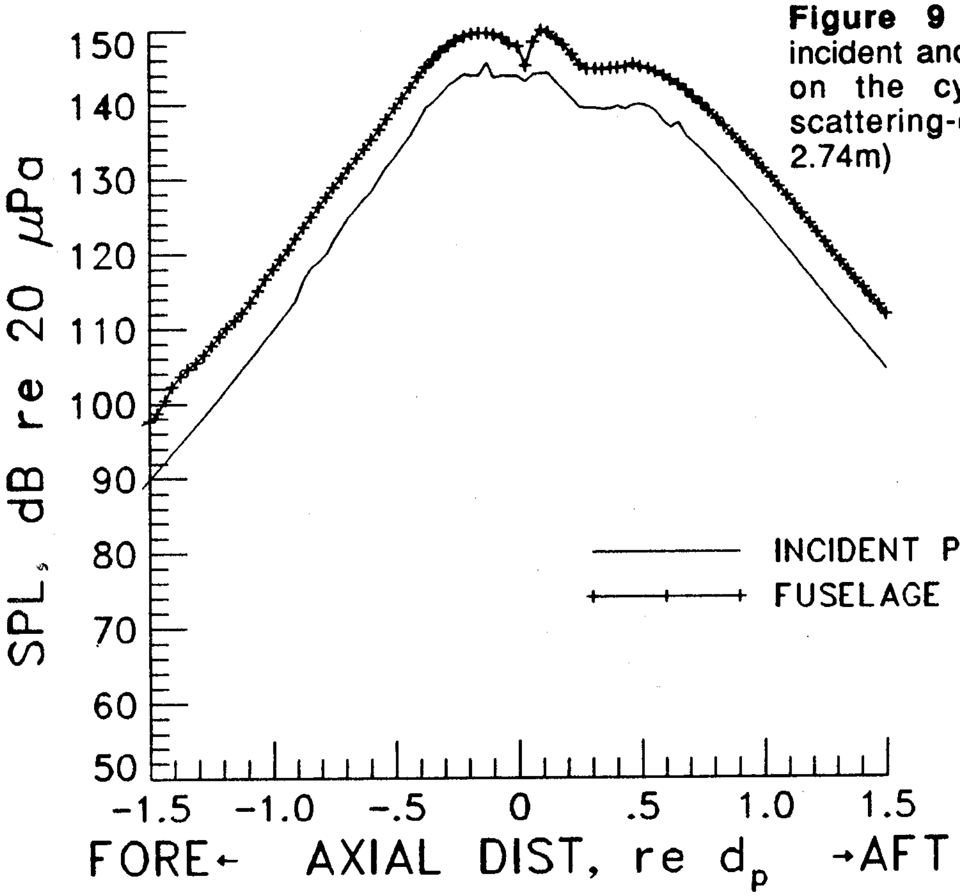

Figure 9 (a). Axial variation of incident and surface acoustic pressure on the cylinder resulting from a scattering-only calculation. (d_p = 2.74m)

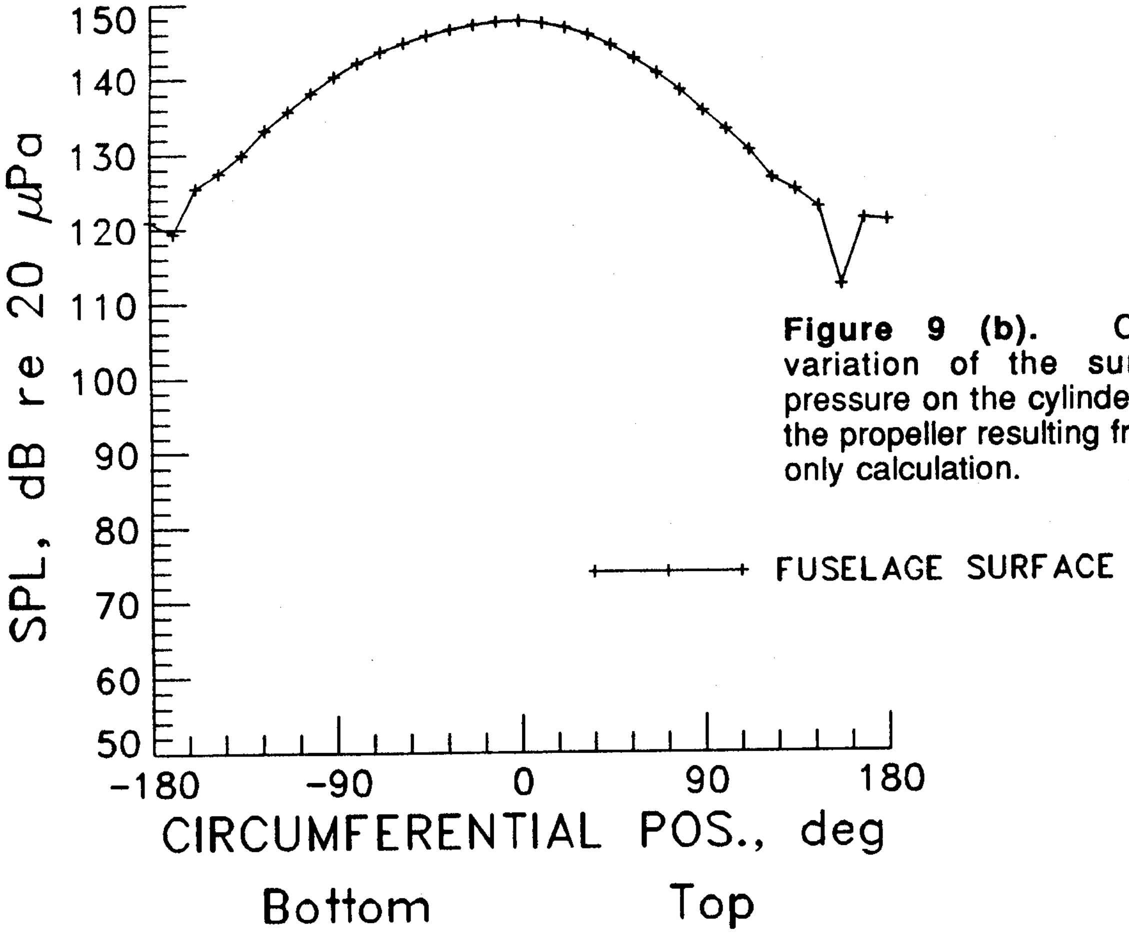

Figure 9 (b). Circumferential variation of the surface acoustic pressure on the cylinder in the plane of the propeller resulting from a scattering-only calculation.

harmonic on the CRAY Y-MP and 0.0086 CPU sec / grid point / harmonic on the CRAY-2S.

Summary

The computer program, MRS-BLP, which can compute the effects on noise propagating through a boundary layer has been documented. Scattering of the incident acoustic pressure waves off cylindrical bodies is included in the code. The inclusion of boundary layer refraction and scattering from a cylindrical surface has been shown to have a dramatic effect on the noise levels predicted under a boundary layer. Examples of how to execute the program using three different boundary layer profiles are included.

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16. Abstract

The computer program, McAninch-Rawls-Spence Boundary Layer Propagation (MRS-BLP), is described. This program models the refractive and scattering effects on acoustic pressure waves propagating through a boundary layer encompassing an aircraft's fuselage. The noise source is assumed known and generated by a propeller. The fuselage is represented by an infinitely long cylinder embedded in a longitudinal flow. By matching a numerical solution inside the boundary layer with an analytical solution outside the boundary layer, the program calculates the acoustic pressure at the surface of the cylinder given the incident field at the top of the boundary layer. The boundary layer flow velocity and sound speed profiles, as well as the boundary layer thickness may be specified by the user. A detailed description of the input parameters and how to execute the program is given. Example executions of MRS-BLP showing results are also included.

17. Key Words (Suggested by Author(s))

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