Coupled 2-Dimensional Cascade Theory for Noise and Unsteady Aerodynamics of Blade Row Interaction in Turbofans

Volume 2—Documentation for Computer Code CUP2D

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Summary

A 2D linear aeroacoustic theory for rotor/stator interaction with unsteady coupling was derived and explored in Volume 1 of this report. Computer program CUP2D has been written in FORTRAN embodying the theoretical equations. This volume (Volume 2) describes the structure of the code, installation and running, preparation of the input file, and interpretation of the output. A sample case is provided with printouts of the input and output. The source code is included with comments linking it closely to the theoretical equations in Volume 1.
Section 1
Introduction

This volume provides documentation and user information for the coupled 2D linearized cascade code CUP2D. Theory for the code is derived and explored in Volume 1 of this report. Material herein discusses how to install and run the code, explains the input file and the printed output, outlines the code structure, and provides a listing of the source code.

CUP2D is written as strictly as possible in FORTRAN 77 and is self-contained so that no system subroutines are needed. One exception is that the DOUBLE COMPLEX variable type is used; this should be accepted by any modern compiler. The only other exception is that the subroutine TIMDAT calls a system-dependent time and date function. This has been found to work on Sun™ and Iris™ systems but can be deleted or modified by the user, if necessary. Figure 1 shows the hierarchy of subroutines with a brief description of the subroutine functions. More description can be found in the subroutine comments. To interpret the figure 1, note that each routine calls only those routines indented underneath. Thus, for example, READIN calls only ALFBET, RTCOEF, GTWAKE, and PRNTIN. Each routine is called only once with the exception of GETVS and DSWK, as shown in figure 1.

The entire code is supplied on disk in a single module (or file) called cup2d.f and can be compiled on a UNIX™ system by entering f77 -o cup2d cup2d.f. This generates an executable file which can be run by typing cup2d. The code then looks for the input file cupin.dat, which must be in the same directory as cup2d. Normally, the output is written to the screen only. However, if the user wishes the output written to a file, cupout.dat for example, the command cup2d > cupout.dat would be used.

Sections 2 and 3 give detailed descriptions of the input and output. The source listing in Section 4 is heavily commented with descriptions of subroutine function at the top and throughout each routine. Also, to help in linking the code to the theory, variable names were chosen to be as close to the names used in the theory derivation as possible. Finally, wherever appropriate in the code, equation numbers from Volume 1 are given next to the corresponding FORTRAN statements.
HIERARCHY OF SUBROUTINES

PROGRAM CUP2D .......... main program
READIN ............. read input file (UNIT 8) and compute some constants
ALFBET ........... compute arrays of alphas and betas
RTCOEF .......... compute arrays of reflection and transmission coefficients
GTWAKE .......... compute upwash vectors
PRNTIN .......... print input
TIMDAT ............ print time and date of execution

INFNS ................ compute elements of KMATRX
RCOEFS ........... rotor on stator effect
GETVS ........ compute Smith’s $v_1, v_2, v_3$
SCOEFS ........... stator on rotor effect
GETVS ........ compute Smith’s $v_1, v_2, v_3$
GENKRR ............ rotor on rotor effect
DSWK & WAVE . Smith’s routines for matrix elements
GENKSS ............ stator on stator effect
DSWK & WAVE . Smith’s routines for matrix elements

SOLVE ............ solve coupled system for loading on both blade rows
MATINV ............ invert the matrix KMATRX

LINPAC Routines
LOADS ............. compute loads from $[\text{KMATRX}]^{-1} \ast \text{WASH} = \text{LOAD}$

OUTPUT ............. print out sound pressure and sound power by mode
GETPWL ........... compute modal sound power

Figure 1. This figure indicates all subroutine calls. Except where shown, each routine is called only once.
Section 2
Explanation of Input File

The sample case input for code CUP2D is supplied on the same disk with the source listing in the file called `cupin.dat`, which is shown in figure 2. To facilitate verification of input, all of the input numbers are printed with the normal output. Brief definitions of the input are included at the bottom of the file. Some further explanations are provided below.

**Line 1** - The comment is provided for user convenience and is printed on the 4th line of output.

**Line 2** - In the theory, a 2D cascade is considered to be wrapped into a narrow annulus to simulate a fan and to permit a mixture of fan nomenclature and cascade nomenclature. In particular, this permits numbers of blades to appear directly. The radius to the annulus provides a common dimension for the 2 blade rows which is considered to be the effective radius of the fan. It is used for non-dimensionalization in the axial spacing of the blade rows. In simulating a fan, the effective radius could be taken as 85 percent of the tip radius, in which case the rotor rotational Mach numbers at that radius would be input below in line 6.

**Line 3** - The number of panels $N_p$ is fixed to be the same for both blade rows. The number of harmonics $N_h$ is the number used for the coupling equations and in the printout of sound pressure and sound power. The code is delivered with dimensioning for a max $N_h=5$ and a max $N_p=51$. Section 5 gives array dimension information if this needs to be changed.

**Line 4** - See figure 2 of this volume.

**Line 5** - Speed of sound is in feet per second. Density is in pounds mass per cubic foot.

**Line 6** - The code can treat counter-rotation configurations. In this case, input a positive rotational Mach number for the front rotor and a negative number for the rear. If either row is a stator, set its rotational Mach number to zero.

**Line 7** - Here the user specifies the axial locations where he wants the modal sound pressure to be evaluated for the final table in the printout. Distances are measured downstream from the front row leading edge and are normalized by rotor effective radius.

**Line 8 and 9** - For line 8, input the value of INTYPE to be used by the subroutine GTWAKE in evaluating the upwash at the two blade rows for excitation of the system.

- **INTYPE = 1** is used to apply the Silverstein wake formulas derived in appendix E of Volume 1 of this report. Here, the user only specifies the drag coefficient on line 9 and the code computes upwash at $N_p$ control points along the chord for each of $N_h$ harmonics. This option was used for figure 15 of Volume 1.

- **INTYPE = 2** is the same as 1 except that the harmonics above BPF are set to zero. This is useful for evaluation of the frequency scattering effect and was used for most of the figures in Volume 1.
**INTYPE = 3** also applies the formulas from appendix E of Volume 1 for computing upwash along the stator chord. However, in Equations E-12 and E-14, the absolute values of the wake harmonics \( F_n \) in those equations are input directly by the user in line 9. Since the wake amplitudes do not decay using this input, this is equivalent to specifying excitation by a vorticity wave. **INTYPE 3** was used to check the Kousen/Verdon results in Section 4 of Volume 1.

**INTYPE = 4** is provided so that the user can excite the rotor and stator with an upwash distribution of his own choosing. Thus, the upwash vectors WREXT(\( n,i \)) and WSEXT(\( n,i \)) that would computed from wake formulas using **INTYPE 1** are input directly for harmonic order \( n \) and control point \( i \). These are entered as real numbers in tabular form starting on line 9 as shown below for a two harmonic case.

<table>
<thead>
<tr>
<th>Real[WREXT(1,1)]</th>
<th>Imag[WREXT(1,1)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real[WREXT(1,N_p)]</td>
<td>Imag[WREXT(1,N_p)]</td>
</tr>
<tr>
<td>Real[WREXT(2,1)]</td>
<td>Imag[WREXT(2,1)]</td>
</tr>
<tr>
<td>Real[WREXT(2,N_p)]</td>
<td>Imag[WREXT(2,N_p)]</td>
</tr>
<tr>
<td>Real[WSEXT(1,1)]</td>
<td>Imag[WSEXT(1,1)]</td>
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<tr>
<td>Real[WSEXT(1,N_p)]</td>
<td>Imag[WSEXT(1,N_p)]</td>
</tr>
<tr>
<td>Real[WSEXT(2,1)]</td>
<td>Imag[WSEXT(2,1)]</td>
</tr>
<tr>
<td>Real[WSEXT(2,N_p)]</td>
<td>Imag[WSEXT(2,N_p)]</td>
</tr>
</tbody>
</table>

This mode of input could be used to simulate excitation of one blade row by the potential field of the other or could be used to simulate blade vibration effects.
File cupin.dat

' Sample case for Code CUP2D, B=38, V=72'
38 72  .7628  .9567  .556
30  3
  .318  .360  .427  0.231
1037.7 1070.0 1070.3  0.0293  0.0328  0.0326
  .75  0.0
  -0.217  0.86
2
  .02

The above is input for a sample case for code CUP2D

Line 1  Comment - up to 70 characters - in single quotes
Line 2  # Blades-upstream row, # Blades-downstream row,
gap/chord-1, gap/chord-2,
axial dist LE1 to LE2 normalized by fan effective radius
Line 3  Number of panels each row, Number of harmonics
Line 4  Axial Mach number - upstream, inter-row, downstream
       Tangential Mach number - inter-row
Line 5  Speed of sound upstream, inter-row, downstream
       Density upstream, inter-row, downstream
Line 6  Rotational Mach number-front blade row (0 for IGV)
       Rotational Mach number- rear blade row (0 for EGV, negative # for
       rotor)
Line 7  Axial locations for acoustic pressure printout normalized by fan
effective radius, measured positive downstream from front blade leading
edge.
Line 8  1 or 2 for input based on drag coefficient.  2 sets the wake harmonics
       above BPF to zero.  See code documentation for other options.
Line 9  Drag coefficient

Figure 2.  Input data set for sample case.
Section 3
Explanation of Code Output

Output for the sample case is shown in figure 3. Most of the input is printed on the first page. Subscripts 1 and 2 refer to the upstream and downstream blade rows respectively. Also, subscripts a, b, and c refer to the regions upstream of the upstream row, between rows, and downstream of the downstream row.

For the axial spacing of the blade rows, the user inputs the distance from between leading edges of the rows in fan effective radii. The code then computes and prints the axial distance from the upstream trailing edge to the downstream leading edge normalized by the upstream chord. Input values printed in the output include:

- $M_{xa}$, $M_{xb}$, and $M_{xc}$ - axial Mach numbers
- $M_s$ - swirl Mach number (in Region b)
- $M_{yl}$, $M_{y2}$ - blade row rotational Mach numbers
- $\rho_a$, $\rho_b$, and $\rho_c$ - densities
- $a$, $b$, and $c$ - speeds of sound

Relative Mach numbers of the two blade rows $M_{rel1}$ and $M_{rel2}$ are computed from the velocity triangles in figure 5 of Volume 1. Smith's reduced frequencies are based on full chord.

Flow angles $\Theta_1$ and $\Theta_2$ and Swirl Angle are computed from the input Mach numbers. Note that $\Theta_1$ is normally negative per figure 5 of Volume 1.

The long table entitled "EXTERNAL VELOCITY IMPOSED ON CASCADE" gives the upwash values used as external excitation of the system. These are listed by harmonic order $N$ and control point along the chord, counted by $I$. The control points are at Smith's unevenly spaced locations given by $z_i = 0.5^*[(1 - \cos(\pi(2I-1))/(2N))]/$. Values in the table become the vectors $W_{REXT}$ and $W_{SEXT}$ used in the call to the SOLVE routine.

After the listing of the upwash vectors, the printout in figure 3 shows the items "Entering RCOEFS", and so forth to show the user how near execution is to completion. The "condition number" indicates whether the KMATRIX is close to being singular.

"VALUES OF LIFT COEFFICIENTS" are the $\Delta C_p$ values computed in the LOADS routine integrated over the chords of each blade row.

In the final table showing modal sound pressures and sound powers, the $FREQ$ column gives the value of $\Omega_{nk} = nB_1M_{y1} - kB_2M_{y2}$ and the mode column gives $nB_1 - kB_2$, which is defined so that positive values correspond to co-rotating modes. (Co-rotation implies a mode rotating in the direction of positive rotation of the blade rows and in the direction of positive swirl.) The cutoff ratios on the right are printed to help with diagnosis. For example, with the first harmonic ($N=1$) the $K=1$ mode can be seen to be cut on between the rotor and stator (region b) and cut off in the upstream and downstream regions. (Cutoff ratios larger than 9.99 are printed as 9.99.) This is the "trapped mode" discussed at length in Volume 1. It produces pressure but no power in regions a and b. Note that the downstream powers for $n = 2$ and 3 (namely 56.1 dB and 62.6 dB) can be found in the top part of figure 14 in Volume 1 for the rotor rotational Mach number = 0.75.
Code CUP2D for coupled cascade aeroacoustics - Version 1.1
Developed for NASA-Lewis by Pratt & Whitney under Contract NAS3-25952 - Task 10
Theory documented in NASA CR-4506, Volume I.

COMMENT: Sample case for Code CUP2D, B=38, V=72
Time of execution: Mon Mar  1 12:56:37 1993

Bi= 38  B2= 72
Gap/Chord(1) = 0.763, Gap/Chord(2) = 0.957
(Rotor LE to Stator LE)/(Local Radius of Rotor)= 0.556 (input)
Axial Spacing Between Blade Rows/Rotor Chord 1.9951  (computed)
Drag Coefficient = 0.020

Number of panels=30, Number of harmonics= 3

\[
\begin{align*}
Mxa &\quad Mxb &\quad Mxc &\quad Ms &\quad My1 &\quad My2 &\quad Mrel1 &\quad Mrel2 \\
0.318 &\quad 0.360 &\quad 0.427 &\quad 0.231 &\quad 0.750 &\quad 0.000 &\quad 0.632 &\quad 0.428
\end{align*}
\]

RHOa  RHOb  RHOc  Aa  Ab  Ac
0.02930  0.03280  0.03260  1037.7  1070.0  1070.3

Remainder of printout is computed from input above
Smiths reduced freqs @ BPF front row, rear row = 18.532 6.078
Thetal, Theta2 (in degrees) = -55.253 32.687
Swirl Angle (in degrees) = 32.69
Ambient Pressure/Sea Level STD (upstream, downstream) = 0.331 0.391

**EXTERNAL VELOCITY IMPOSED ON CASCADE**

\[
\begin{align*}
N &\quad I &\quad WREXT(\text{real, imag}) &\quad WSEXT(\text{real, imag}) \\
1 &\quad 1 &\quad 0.0000 0.0000 &\quad 0.0186 0.0261 \\
1 &\quad 2 &\quad 0.0000 0.0000 &\quad 0.0194 0.0254 \\
1 &\quad 3 &\quad 0.0000 0.0000 &\quad 0.0210 0.0241 \\
1 &\quad 4 &\quad 0.0000 0.0000 &\quad 0.0232 0.0218 \\
1 &\quad 5 &\quad 0.0000 0.0000 &\quad 0.0257 0.0186 \\
1 &\quad 6 &\quad 0.0000 0.0000 &\quad 0.0282 0.0142 \\
1 &\quad 7 &\quad 0.0000 0.0000 &\quad 0.0302 0.0087 \\
1 &\quad 8 &\quad 0.0000 0.0000 &\quad 0.0312 0.0021 \\
1 &\quad 9 &\quad 0.0000 0.0000 &\quad 0.0306 -0.0053 \\
1 &\quad 10 &\quad 0.0000 0.0000 &\quad 0.0280 -0.0128 \\
1 &\quad 11 &\quad 0.0000 0.0000 &\quad 0.0233 0.0068 \\
1 &\quad 12 &\quad 0.0000 0.0000 &\quad 0.0166 -0.0254 \\
1 &\quad 13 &\quad 0.0000 0.0000 &\quad 0.0082 0.0289 \\
1 &\quad 14 &\quad 0.0000 0.0000 &\quad -0.0011 -0.0298 \\
1 &\quad 15 &\quad 0.0000 0.0000 &\quad -0.0102 -0.0277 \\
1 &\quad 16 &\quad 0.0000 0.0000 &\quad -0.0192 -0.0229 \\
1 &\quad 17 &\quad 0.0000 0.0000 &\quad -0.0242 -0.0160 \\
1 &\quad 18 &\quad 0.0000 0.0000 &\quad -0.0277 -0.0078 \\
1 &\quad 19 &\quad 0.0000 0.0000 &\quad -0.0285 0.0009 \\
1 &\quad 20 &\quad 0.0000 0.0000 &\quad -0.0269 0.0089 \\
1 &\quad 21 &\quad 0.0000 0.0000 &\quad -0.0233 0.0158 \\
1 &\quad 22 &\quad 0.0000 0.0000 &\quad -0.0184 0.0210 \\
1 &\quad 23 &\quad 0.0000 0.0000 &\quad -0.0128 0.0246 \\
1 &\quad 24 &\quad 0.0000 0.0000 &\quad -0.0073 0.0266 \\
1 &\quad 25 &\quad 0.0000 0.0000 &\quad -0.0022 0.0273 \\
1 &\quad 26 &\quad 0.0000 0.0000 &\quad -0.0021 0.0272 \\
1 &\quad 27 &\quad 0.0000 0.0000 &\quad -0.0056 0.0266 \\
1 &\quad 28 &\quad 0.0000 0.0000 &\quad -0.0082 0.0259 \\
1 &\quad 29 &\quad 0.0000 0.0000 &\quad -0.0098 0.0253 \\
1 &\quad 30 &\quad 0.0000 0.0000 &\quad -0.0107 0.0249
\end{align*}
\]

**Figure 3 (beginning).** Output for sample case.
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Figure 3 (continued). Output for sample case.
Entering RCOEFS
Entering SCOEFS
Entering GENKRR
Entering GENKSS
Entering MATINV

Condition number of KMATRIX = 4.3478710669121D-05

*** VALUES OF LIFT COEFFICIENTS ***

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<th>CLSTATOR(N) imag</th>
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Axial locations for sound pressure output in radii from rotor leading edge
For PRESup,XA = -.217, For PRESdn, Xc = 0.860

Decibel Levels for Pressure Waves and Power Levels
<table>
<thead>
<tr>
<th>N</th>
<th>K</th>
<th>FREQ</th>
<th>nB1-kB2</th>
<th>PRESup</th>
<th>PRESdn</th>
<th>PWLup</th>
<th>PWLdn</th>
<th>A</th>
<th>B</th>
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--------------- Total power for N= 1

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--------------- Total power for N= 2

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<th>PWLup</th>
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--------------- Total power for N= 3

Figure 3. (concluded) Output for sample case.
Section 4
Source Code Listing

The remainder of this volume gives the listing of the routines shown in figure 1. The routines can be categorized as follows. The first group comprises new code as described in Volume 1. Then there are two routines taken verbatim from the Smith code: DSWK and WAVE. Finally, there is a series of routines for inverting the (double precision, real) matrix of influence coefficients. These were taken from LINPAC (see LINPAC User’s Guide, SIAM, Philadelphia, 1979) and are not shown here since they are in the public domain and are commonly available. Of course, they are included on the disk with the rest of the source code. The routine MATINV is included, since this was written for the present purposes to call the LINPAC routines.
PROGRAM CUP2D

Calculates the unsteady loading and associated acoustic and vorticity waves on 2 mutually interacting blade rows in a 2 dimensional, linear, subsonic analysis. Blade rows can be rotor/egv, igv/rotor, or rotor/rotor, depending on input values of rotor rotational Mach numbers, MY1 and MY2.

Simultaneous solution for flow tangency for 2 blade rows, NH harmonics, and NP panels via inversion of the matrix coupling equation KMATRX*LOAD=WASH. A disturbance upwash distribution at either, or both, blade rows is generated either from direct user input or from Silverstein's wake formulas. The code then finds the unsteady loading (LOAD) that produces an upwash (WASH) that just cancels the disturbance wash. These loads are used to find the acoustic waves and the sound power. Blade row self-effect is computed via subroutines from Smith Code. Effect of each row on the other is computed via an extension of Smith's theory by D.B. Hanson. Reflections at inlet and exit interfaces are treated with reflection and transmission coefficients derived from continuity of mass & momentum based on an actuator disk model.

Overall theory documented in NASA CR-4506, Volume I. Comments in this listing refer to equation numbers in the same Contractor Report. Coding by Hanson.

This routine is the main program.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

DOUBLE PRECISION MXA,MXB,MXC,MY1,MY2,MS;LAM1,LAM2,
> KMATRX(1020,1020)
> DOUBLE COMPLEX WREXT(5,51), WSEXT(5,51), LR(5,51), LS(5,51),
> ALF(9,-5:5,-5:5),
> KRUP(5,-5:5,51),KRUPN(5,-5:5,51), KSDN(5,-5:5,51),
> R12(-5:5,-5:5), R21(-5:5,-5:5),R31(-5:5,-5:5),
> T14(-5:5,-5:5), T28(-5:5,-5:5),T38(-5:5,-5:5)
INTEGER BI, B2, BETA(-5:5,-5:5)

WRITE(*,*) ' ' WRITE(*,*) 'Cod_ CUP2D for coupled cascade aeroacoustics - Version 1.0
Developed for NASA-Lewis by Pratt & Whitney under Cont
act NAS3-25952 - Task 10'
WRITE(*,*) 'Theory documented in NASA CR-4506, Volume I'

Read input, generate wavenumbers and reflection coefficients, establish external disturbance vectors from wake formulas or direct input, and print input geometry and flow conditions.

GENERATE matrices of influence functions:

Solve coupled system of equations for loading by matrix inversion.

Compute output waves and print their sound pressure and sound power.

END

Figure 4. Source code for CUP2D.
SUBROUTINE READIN(NH,NP,BI,B2,C1,C2,SCI,SC2,CT1,CT2,ST1,ST2,
> XS,XA,XC,MXA,MXB,MCX,MS,MY1,MY2,LAM1,LAM2,ALF,BETA,
> R12,R21,R13,R31,T14,T28,T38,AA,AB,AC,WREXT,WSEXT,POPSA,POPS)

C. Reads input from data set on disk (UNIT 8); generates constants for the
C. Smith common block; and calls routines for alpha and beta wavenumbers,
C. reflection and transmission coefficients, and external input velocity
C. vectors.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXA,MXB,MCX,MS,MY1,MY2,LAM1,LAM2
INTEGER BI, B2, BETA(-5:5,-5:5)
DOUBLE COMPLEX WREXT(5,51),WSEXT(5,51),ALF(9,-5:5,-5:5),
> RI2(-5:5,-5:5),R21(-5:5,-5:5),R13(-5:5,-5:5),R31(-5:5,-5:5),
> T14(-5:5,-5:5),T28(-5:5,-5:5),T38(-5:5,-5:5)
CHARACTER*70 COMMENT

C. Read and compute data for common block
OPEN(UNIT=8,FILE='cupin.dat')

C. Read comment
READ(8,*) COMMENT

C. Read geometry from disk file and compute normalized chords
READ(8,*) BI, B2, SCI, SC2, XS
C1 = 6.2831853D0/(BI*SCI) ! Chord/radius, front row
C2 = 6.2831853D0/{B2*SC2} ! Chord/radius, back row

C. Read number of panels and number of harmonics
READ(8,*) NP, NH

C. Read operating conditions from disk file. 1 & 2 refer to upstream and
C. downstream blade rows. A, B, & C refer to regions upstream of blade row 1,
C. between blade rows, and downstream of blade row 2. POPSA & POPSC = ambient
C. pressure in upstream and downstream regions divided by sea level standard
C. pressure.
READ(8,*) MXA, MXB, MCX, MS
READ(8,*) AA, AB, AC, RHOA, RHOB, RHOC
READ(8,*) MY1, MY2

C. Read x locations for pressure output. (x over radius from front row LE.)
READ(8,**) XA, XC
! Make XA < 0 and XB > 0.

C. Compute remaining items for passage to other routines
ST1 = (-MY1+MS) / SQRT(MXB**2 + (-MY1+MS)**2) ! Sine(theta1)
ST2 = (-MY2+MS) / SQRT(MXB**2 + (-MY2+MS)**2) ! Sine(theta2)
CT1 = SQRT(ID0 - ST1**2) ! Cosine(theta1)
CT2 = SQRT(ID0 - ST2**2) ! Cosine(theta2)

LAM1 = B2*(MY1-MY2)/(MCX/CT1) ! Reduced freq, front row
LAM2 = B1*(MY1-MY2)/(MCX/CT2) ! Reduced freq, back row

C. Compute axial wavenumbers (alpha's) and tangential wavenumbers (beta's)
CALL ALFBET(BI,B2,NH,MXA,MXB,MCX,MS,MY1,MY2,
> AA,AB,AC,ALF,BETA)

C. Get reflection and transmission coefficients
CALL RTCOEF(NH,BI,B2,ALF,BETA,AA,AB,AC,RH0A,RH0B,RH0C,
> MXA,MXB,MCX,MS,MY1,MY2, R12,R21,R13,R31, T14,T28,T38)

C. Read wake input data and compute upwash vectors. Leave unit 8 open to
C. read from GTWAKE.
CALL GTWAKE(NH,NP,C1,C2,SCI,CT1,CT2,ST1,ST2,XS,INTYPE,CD,
> WREXT,WSEXT)
CLOSE(8)

Figure 4. (continued) Source code for CUP2D.
c. Compute $P_{ambient}/P_{standard}$ to be used in OUTPUT for SPL's
   $P_{OPSA} = \frac{\rho_a A_A^2}{(1.4 \times 32.2 \times 2116)}$
   $P_{OPSC} = \frac{\rho_c A_C^2}{(1.4 \times 32.2 \times 2116)}$

c. Print input data
   CALL PRNTIN(NH,NP,B1,B2,C1,C2,SC1,SC2,CT1,CT2,ST1,ST2,XS,
   > AA,AB,AC,RHOA,RHOB,RHOC,MXA,MXR,MXC,MS,MY1,MY2,
   > LAM1,LAM2,COMMENT,INTYPE,CD,WREXT,WSEXT,POPSA,POPSA)

RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE ALFRET(B1,B2,NH,MXA,MXB,MXC,MS,MY1,MY2,
   AA,AB,AC,ALF,BETA)
   c.. Computes alpha and beta wavenumbers from formulas derived in appendix B.
   c.. The alphas are Smith's normalized by source radius R rather than by chord.
   c.. Prints message if a resonance condition occurs for any combination of n & k.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXA,MXB, MXC, MS,MYI,MY2
INTEGER BI,B2,BETA(-5:5,-5:5)
DOUBLE COMPLEX ALF(9,-5:5,-5:5)

DENOMA = 1.000D0 - MXA**2
DENOMB = 1.000D0 - MXB**2
DENOMC = 1.000D0 - MXC**2
DO 100 N = -NH, NH
DO 100 K = -NH, NH
IF (ABS(N)+ABS(K) .EQ. 0) GOTO 100
BETA(N,K) = - (N*B1 K*B2)
OMEGA = N*B1*MYI - K*B2*MY
EA = DENOMA*BETA(N,K)**2 - (OMEGA*AB/AA)**2
EB = DENOMB*BETA(N,K)**2 - (OMEGA + BETA(N,K)*MS)**2
EC = DENOMC*BETA(N,K)**2 - (OMEGA*AB/AC)**2
FA = MXA*OMEGA*AB/AA
FB = MXB*(OMEGA ÷ BETA(N,K)*MS)
FC = MXC*OMEGA*AB/AC

c.. Check for resonance in upstream region, swirl region, and downstream region

c.. E=0 for resonance, E < 0 for propagation, E > 0 for decay. Then compute

c.. alphas for pressure waves. Use Eqs. B-8,9,10 in Region B and variations

c.. for Regions A and C.

c.. Do Region A first (upstream of swirl region).
IF (EA .EQ. 0.0) THEN
  WRITE(*,1) N,K
1 FORMAT(iX,'Resonance in Region A for N=',I3,' K=',I3)
  STOP 'Execution terminated due to resonance'
ELSE IF (EA .LT. 0.0) THEN
  ALF(4,N,K) = (FA + SIGN(SQRT(-EA), FA))/DENOMA
  ALF(5,N,K) = (FA - SIGN(SQRT(-EA), FA))/DENOMA
ELSE
  ALF(4,N,K) = CMPLX(FA, -SQRT(EA))/DENOMA
  ALF(5,N,K) = CMPLX(FA, +SQRT(EA))/DENOMA
ENDIF

c.. Do Region B next (swirl region).
IF (EB .EQ. 0.0) THEN
  WRITE(*,2) N,K
2 FORMAT(iX,'Resonance in Region B for N=',I3,' K=',I3)
  STOP 'Execution terminated due to resonance'
ELSE IF (EB .LT. 0.0) THEN
  ALF(1,N,K) = (FB + SIGN(SQRT(-EB), FB))/DENOMB
  ALF(2,N,K) = (FB - SIGN(SQRT(-EB), FB))/DENOMB
ELSE
  ALF(1,N,K) = CMPLX(FB, -SQRT(EB))/DENOMB
  ALF(2,N,K) = CMPLX(FB, +SQRT(EB))/DENOMB
ENDIF

c.. Finally, do Region C (downstream of swirl region)
IF (EC .EQ. 0.0) THEN
  WRITE(*,3) N,K
3 FORMAT(iX,'Resonance in Region C for N=',I3,' K=',I3)
  STOP 'Execution terminated due to resonance'
ELSE IF (EC .LT. 0.0) THEN
  ALF(7,N,K) = (FC + SIGN(SQRT(-EC), FC))/DENOMC
ENDIF

Figure 4. (continued) Source code for CUP2D.
ALF(8, N, K) = (FC - SIGN(SQRT(-EC), FC))/DENOMC
ELSE
   ALF(7, N, K) = CMPLX(FC, -SQRT(EC))/DENOMC
   ALF(8, N, K) = CMPLX(FC, +SQRT(EC))/DENOMC
ENDIF

c.. Wavenumbers for vorticity waves in Region B from eq. B-11 and variations
   c.. for Regions A and C.
   ALF(3, N, K) = -(OMEGA + MS*RETA(N, K))/MXB
   ALF(6, N, K) = - OMEGA /MXA
   ALF(9, N, K) = - OMEGA /MXC

100 CONTINUE

RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE RTCOEF(NH, B1, B2, ALF, BETA, AA, AB, AC, RHOA, RHOB, RHOC,  
> MXA, MXB, MXC, MS, MY1, MY2, R12, R21, R13, R31, T14, T28, T38)

This subroutine computes reflection and transmission coefficients for the  
c. inlet and exit for the transverse velocity component. Coefficients derived  
c. in NASA CR-4506, Volume I, appendix D.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXA, MXB, MXC, MS, MY1, MY2
INTEGER BI, B2, BET, BETA(-5:5,-5:5)
DOUBLE COMPLEX CI, C2, C3, C4, CS, C9, FI, F2, F3, F4, FS, F9,  
> GI, G2, G3, G4, G8, G9, E0, E1, E2, E3, E4, E5, E6, E7, E8, E9, E10,  
> E11, E12, E13, E14, E15, E16, E17, E18, E19, E20, E21
DOUBLE COMPLEX ALF(9,-5:5,-5:5),  
> R12(-5:5,-5:5), R21(-5:5,-5:5), R13(-5:5,-5:5), R31(-5:5,-5:5),  
> T14(-5:5,-5:5), T28(-5:5,-5:5), T38(-5:5,-5:5)

C.. Compute rho*c0 for 3 regions
ROCA = RHOA*AA
ROCB = RHOB*AB
ROCC = RHOC*AC

C.. Compute reflection and transmission coefficients
DO 10 N = -NH, NH
  DO 10 K = -NH, NH
    IF ((ABS(N)+ABS(K)) .EQ. 0) GO TO 10
    BET = BETA(N, K)
    OMEGA = N*BI*MY1 - K*B2*MY2

C.. Coefficients from continuity equations
C1 = ROCB*((1D0-MXB**2)*ALF(1,N,K) - MXB*(OMEGA+MS*BET))
C2 = ROCB*((1D0-MXB**2)*ALF(2,N,K) - MXB*(OMEGA+MS*BET))
C3 = ROCA*((1D0-MXA**2)*OMEGA - (ID0-MXA**2)*MXA*ALF(4,N,K)*AA/AB)
C4 = ROCC*((1D0-MXC**2)*ALF(8,N,K) - MXC*OMEGA*AB/AC)
C9 = ROCC*(-BET)

C.. Coefficients from axial momentum equations
FI=ROCB* ( (ID0+MXB**2) * (OMEGA+MS* BET) - (ID0-MXB**2) *MXB*ALF(I,N,K) )
F2=ROCB* ( (ID0+MXB**2) * (OMEGA+MS* BET) - (ID0-MXB**2) *MXB*ALF(2,N,K) )
F3=ROCB* (2D0*MXB*BET)
F4=ROCA* (MXA*BET*AA/AB)
G2= ROCC* (MXB*ALF(9,N,K)*AC/AB)
G9= ROCC* (MXC*ALF(9,N,K)*AC/AB)

C.. Coefficients from transverse momentum equations
G1=ROCB* (MXA*ALF(9,N,K)*M*Bet)
G2= ROCC* (MXB*ALF(9,N,K)*M*Bet)
G3= ROCC* (MXC*ALF(9,N,K)*M*Bet)
G8= ROCC* (MXC*ALF(9,N,K)*M*Bet)
G9= ROCC* (MXC*ALF(9,N,K)*M*Bet)

Figure 4. (continued) Source code for CUP2D.
E11 = C9*F1 - C1*F9
E12 = C1*G8 - C8*G1
E13 = C9*G1 - C1*G9
E14 = C8*F2 - C2*F8
E15 = C8*F9 - C9*F8
E16 = C8*G2 - C2*G8
E17 = C8*G9 - C9*G8
E18 = C8*F3 - C3*F8
E19 = C8*G3 - C3*G8
E20 = C1*F3 - C3*F1
E21 = C1*G3 - C3*G1

C.. Reflection coefficients
R12(N,K) = (E2*E3-E0*E5) / (E1*E5-E2*E4)
R13(N,K) = (E1*E3-E0*E4) / (E1*E5-E2*E4)
R21(N,K) = (E15*E16-E14*E17) / (E12*E15-E10*E17)
R31(N,K) = (E15*E19-E17*E18) / (E12*E15-E10*E17)

C.. Transmission coefficients
T14(N,K) = (E7*E8-E6*E9) / (E4*E9-E1*E7)
T28(N,K) = (E6*E11-E8*E13) / (E10*E13-E11*E12)
T38(N,K) = (E11*E21-E13*E20) / (E11*E12-E10*E13)

10 CONTINUE
RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE GTWAKE(NH,NP,CI,C2,SC1,CT1,CT2,ST1,ST2,XS,
> INTYPE, CD, WREXT, WSEXT)
c.. This routine reads data from the input file and generates the upwash vectors
c.. WREXT and WSEXT, representing external excitation of the system. The
f.. disturbance can be described via various optional methods specified by the
.. input value of INTYPE as follows.
c.. INTYPE = 1 is used to represent viscous wakes via the Silverstein formulas.
c.. The wake is specified by the drag coefficient CD, i.e. by only one number.
c.. The upwash vectors are then computed from the formulas in appendix E.
c.. INTYPE = 2 is the same as INTYPE 1 except that the wake harmonics above BPF
.. are set to zero.
c.. INTYPE = 3 is the same as INTYPE 1 except that the velocity defect harmonics
.. are input rather than being computed from the wake formulas.
c.. For INTYPE = 4 the real and imaginary parts of WREXT and WSEXT are simply
.. read from the file. Here the upwash vectors are completely specified by the
.. user for all harmonics: N = 1...NH and all control points I = 1...NP.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION FW(5)
DOUBLE COMPLEX EXPON, WREXT(5,51), WSEXT(5,51), AI
PI   = 3.14159265D0
AI   = (0.0D0,1.0D0)

c.. Read INTYPE to identify type of input disturbance
READ(8,*), INTYPE
IF (INTYPE .EQ. 1) THEN

c.. For INTYPE=1, read drag coefficient and use Silverstein formulas as given
.. in appendix E.
READ(8,*), CD
DO 34 N = 1, NH
   DO 34 I = 1, NP
      Z2I = 0.50D0*(1D0-COS(Pİ*(Z2I/(CI/C2)*CT2)))/CT1
      ZI  = (XS/CI + Z2I/(CI/C2)*CT2)/CT1
      WCOWI = 1.21D0*SQRT(CD)/{Z1 - 0.70D0}
      YOCI = 0.68D0*SQRT(CD*{Z1 - 0.85D0})
      Q = 1.77245D0*SCI/YOCI*CTI
      FN = 3.54491D0/Q*WCOWI*EXP(-(PI*N/Q)**2)
      EXPON = EXP(AI*2.0D0*PI*N*({CT2*CTI-ST2}*{C1/C2}-SC1*Z2I + (XS/CI)/SCI*STI/CTI))
      WSEXT(N,I) = CT2/CTI* (ST2*CTI-CT2*STI)*FN*EXPON
      WREXT(N,I) = (0D0, 0D0)
34 CONTINUE

ELSE IF (INTYPE .EQ. 2) THEN

c.. For INTYPE=2, read drag coefficient and use Silverstein formulas as given
.. in appendix E. BUT, for harmonic order > BPF, set upwash to zero.
READ(8,*), CD
DO 24 N = 1, NH
   DO 24 I = 1, NP
      Z2I = 0.50D0*(1D0-COS(Pİ*(Z2I/(CI/C2)*CT2)))/CT1
      ZI  = (XS/CI + Z2I/(CI/C2)*CT2)/CT1
      WCOWI = 1.21D0*SQRT(CD)/{Z1 - 0.70D0}
      YOCI = 0.68D0*SQRT(CD*{Z1 - 0.85D0})
      Q = 1.77245D0*SCI/YOCI*CTI
      FN = 3.54491D0/Q*WCOWI*EXP(-(PI*N/Q)**2)
      EXPON = EXP(AI*2.0D0*PI*N*({CT2*CTI-ST2}*{C1/C2}-SC1*Z2I + (XS/CI)/SCI*STI/CTI))
      WSEXT(N,I) = CT2/CTI* (ST2*CTI-CT2*STI)*FN*EXPON
      IF (N .GT. I) WSEXT(N,I) = (0D0, 0D0)
      WREXT(N,I) = (0D0, 0D0)
24 CONTINUE

Figure 4. (continued) Source code for CUP2D.
c.. For INTYPE=3, read harmonics of an upwash that convects with the mean flow. c.. This is just like INTYPE 1 above except that FN(N) is read from input here c.. and is independent of x. By contrast, for INTYPE = 1 above, FN is computed c.. from the Silverstein formulas as a function of chordwise position on the c.. downstream blade row. To interpret these formulas, see appendix E.

ELSE IF (INTYPE .EQ. 3) THEN
READ(8,*) (FW(N),N=1,NH)
DO 14 N = 1, NH
DO 14 I = 1, NP
  Z2I = 0.5D0*(1D0 - COS(PI*(2.0D0*I-1D0)/(2.0D0*NP)))
  EXPON = EXP(AI*2D0*F(I)*N*(
    (CT2*STI/CTI-ST2)*(C2/CI)/SCI*Z2I + (XS/CI)/SCI*STI/CTI))
  WSEXT(N,I) = CT2/CTI*(ST2*CTI-CT2*STI)*FW(N)*EXPON
  WREXT(N,I) = (0D0, 0D0)
14 CONTINUE

C.. For INTYPE=4, read real and imaginary parts of vectors of external velocity c.. disturbance as direct input. Rotor input first, then stator.

ELSE IF (INTYPE .EQ. 4) THEN
DO 10 N=1,NH
DO 10 I=1,NP
  READ(8,*) WREXTR, WREXTI
  WREXT(N,I) = CMPLX(WREXTR, WREXTI)
10 CONTINUE
DO 12 N=1,NH
DO 12 I=1,NP
  READ(8,*) WSEXTR, WSEXTI
  WSEXT(N,I) = CMPLX(WSEXTR, WSEXTI)
12 CONTINUE

ELSE
  STOP 'Input type (INTYPE) for WSEXT AND WREXT not defined'
ENDIF
RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE PRNTINH,NP,B1,B2,C1,C2,SC1,SC2,CT1,CT2,ST1,ST2,XS,
     > AA,AB,AC,RHOA,RHOB,RHOC,MXA,MXB,MXC,MS,MY1,MY2,
     > LAM1,LAM2,COMMENT, INTYPE,CD,WREXT, WSEXT, POPSA, POPSC

.. This routine prints the input data (some of it manipulated) to the screen.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXA,MXB,MXC,MS,MY1,MY2,LAM1,LAM2
INTEGER B1,B2
DOUBLE COMPLEX WREXT(5,51), WSEXT(5,51)
CHARACTER* 70 COMMENT

.. Print input data and computed quantities
WRITE(*,*), ' ' 
WRITE(*,*), 'COMMENT: ',COMMENT 
CALL TIMDAT 
WRITE(*,*), '
WRITE(*,11) B1, B2 
11 FORMAT(I6, 'BI=' ,I3, ' B2=',I3) 
WRITE(*,13) C1, C2 
13 FORMAT(I6, 'Gap/Chord(l) = ',F6.3, ' Gap/Chord(2) = ',F6.3) 
WRITE(*,31) XS 
31 FORMAT(I6, 'Axial Spacing Between Blade Rows/Rotor Chord',F7.4, ' (computed)') 
IF (INTYPE .LT. 3) WRITE(*,1) CD 
1 FORMAT(I6, 'Drag Coefficient = ',F5.3) 
WRITE(*,15) NP, NH 
15 FORMAT(I6, 'Number of x:panels=',I2, ', Number of harmonics=',I2) 
WRITE(*,17) Mxa Mxb Mxc Ms My1 My2 Mrel1 Mrel2 
17 FORMAT(I6, 'Mxa Mxb Mxc Ms My1 My2 Mrel1 Mrel2') 
WRITE(*,19) RHOA, RHOB, RHOC, AA, AB, AC 
19 FORMAT(I6, 'RHOA, RHOB, RHOC, AA, AB, AC') 
WRITE(*,21) LAMI*C1, LAM2*C2 
21 FORMAT(I6, 'Smiths reduced freqs @ BPF front row, rear row = ',2F8.3) 
WRITE(*,23) 57.29578*ASIN(STI), 57.29578*ASIN(ST2) 
23 FORMAT(I6, 'Theta1, Theta2 (in degrees) = ', 2F8.3) 
WRITE(*,25) 57.29578*ATAN (MS/MXB) 
25 FORMAT(I6, 'Swirl Angle (in degrees) = ', F7.2) 
WRITE(*,16) POPSA, POPSC 
16 FORMAT(I6, 'Ambient Pressure/Sea Level STD (upstream, downstream) = ' 
     > ,2F7.3) 
WRITE(*,27) 
WRITE(*,29) 
WRITE(*,31) 
WRITE(*,33) 
33 FORMAT(2I6, 'WREXT(real, imag) WSEXT(real, imag)') 
DO 20 N=1,NH 
DO 22 I=1,NP 
WRITE(*,33) N,I,WREXT(N,I),WSEXT(N,I) 
20 CONTINUE 
WRITE(*,*), 'EXTERNAL VELOCITY IMPOSED ON CASCADE' 
WRITE(*,*), 'N I WREXT(real, imag) WSEXT(real, imag)'
DO 20 N=1,NH 
DO 22 I=1,NP 
WRITE(*,33) N,I,WREXT(N,I),WSEXT(N,I) 
22 CONTINUE 
WRITE(*,*), ' ' 
RETURN 
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE TIME_DAT ! This routine is specific to the Sun Workstations
CHARACTER*24 FDATE ! Modify this routine for other computers
WRITE(*,*) 'Time of execution: ',FDATE()
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE INFFNS(NH,NP,B1,B2,SCI,SC2,CT1,CT2,ST1,ST2,XS,
> MXB,LAM1,LAM2,ALF,BETA,R12,R21,R13,R31,T14,T28,T38,
> KMATRX,KRUP,KRDN,KSUP,KSDN )
c.. Calls routines to compute elements of KMATRX, the matrix of influence
functions. KMATRX is then returned to the main program. Algebra is
c.. based on NASA CR-4506, Volume I, Section 3.3.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXB, LAMI, LAM2, KMATRX(1020,1020)
INTEGER BI, B2, BETA(-5:5,-5:5)
DOUBLE COMPLEX ALF(9,-5:5,-5:5),
> R12(-5:5,-5:5), R21(-5:5,-5:5), R13(-5:5,-5:5), R31(-5:5,-5:5),
> T14(-5:5,-5:5), T28(-5:5,-5:5), T38(-5:5,-5:5),
> KRUP(5,-5:5,51),KRDN(5,-5:5,51),KSUP(5,-5:5,51),KSDN(5,-5:5,51)

C.. 6.28318530D0/(BI*SCI)
C2 : 6.28318530D0/(B2*SC2)

C.. Zero the Kmatrix before starting to compute the elements
DO 10 MU = 1, 4*NP*NH
DO 10 NU = 1, 4*NP*NH
KMATRX(MU,NU) = 0.0D0
10 CONTINUE

C.. Effect of rotor loading on stator
CALL RCOEFS(NH,NP,C1,C2,SCI,CT1,CT2,ST1,ST2,XS,
> MXB,LAM1,ALF,BETA,R12,R21,R13,R31,T14,T28,T38,KMATRX,KRUP,KRDN)

C.. Effect of stator loading on rotor
CALL SCOEFs(NH,NP,C1,C2,SCI,CT1,CT2,ST1,ST2,XS,
> MXB,LAM2,ALF,BETA,R12,R21,R13,R31,T14,T28,T38,KMATRX,KSUP,KSDN)

C.. Effect of rotor loading on rotor
CALL GENKRR(NH,NP,C1,C2,SCI,SC2,CT1,ST1,MXB,LAM1,KMATRX )

C.. Effect or stator loading on stator
CALL GENKSS(NH,NP,C1,C2,SCI,SC2,CT2,ST2,MXB,LAM2,KMATRX )

RETURN
END

C
C

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE RCOEFS(NH,NP,C1,C2,SCI,CT1,CT2,ST1,ST2,XS,
> MXB,LAMI,ALF,BETA,R12,R21,R13,R31,T14,T28,T38,KMATRX,KRUP,KRDN)

Generates elements of the matrix of influence coefficients KMATRX that give the upwash caused by rotor loading at control points on the stator and rotor. These are computed from KRS(N,K,I,J), effect of rotor on stator, and KRR'(N,I,J)I, effect of stator on stator. The prime on KRR indicates that only the part of KRR associated with waves reflected from the actuator disk is computed here. The remainder is computed in GENKRR using original routines from the Smith code. N counts the rotor loading harmonics, I the control points, and J the load elements. K counts the cascade wave index in the rotor frame which becomes the time harmonic index in the stator frame.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXB,MR1,MR2,LAMI,KMATRX(1020,1020)
INTEGER BET,BETA(-5:5,-5:5)
DOUBLE COMPLEX AI,ALFI,ALF2,ALF3,EXPE21,EXPE31,EXPE1,
> EII,EZI,E3I,KRI,KR2,KR3,V1,V2,VH1,VR1,VR2,VR3,KR8,KRR,
> ALF(9,-5:5,-5:5), KRUP(5,-5:5,-5:5), KRDN(5,5:5,51),
> R12(-5:5,-5:5), R21(-5:5,-5:5), R13(-5:5,-5:5), R31(-5:5,-5:5),
> T14(-5:5,-5:5), T28(-5:5,-5:5), T38(-5:5,-5:5)
AI = (0.0D0, 1.0D0)
PI = 3.14159265D0
WRITE(*,*), 'Entering RCOEFS'
M1 = MXB/CT1  ! Relative Mach #, row 1
M2 = MXB/CT2  ! Relative Mach #, row 2
CON = M1/SCI  ! A constant
XE = XS + C2*CT2  ! Axial coordinate of stator exit
NPNH2 = N*NH*2
DO 10 N = 1, NH
DO 10 K = -NH, NH
BET = BETA(K,N)
ALFI = ALF(I,K,N)
ALF2 = ALF(2,K,N)
ALF3 = ALF(3,K,N)
! Relative Mach #, row 1
! Relative Mach #, row 2
! A constant
! Axial coordinate of stator exit
EXPE21 = EXP(AI*(ALF2-ALFI)*XE)
EXPE31 = EXP(AI*(ALF3-ALFI)*XE)
EXPE1 = EXP(-AI*ALFI*XE)

CALL GETVS(BET,N*LAMI,MXB,STI,CTI,VI,V2,V3)
DO 10 J = 1, NP  ! Loop on load elements
Z03 = 0.50D0*(100 - COS(PI*(J-1D0)/NP))  ! Chordwise locations for loads
KRI = CON*V1*EXP(-AI*(ALF1*CT1+BET*ST1)*C1*Z03)  ! eq. 43
KR2 = CON*V2*EXP(-AI*(ALF2*CT1+BET*ST1)*C1*Z03)  ! eq. 43
KR3 = CON*V3*EXP(-AI*(ALF3*CT1+BET*ST1)*C1*Z03)  ! eq. 43

CALL GETVS(BET,N*LAMI,MXB,STI,CT1,V1,V2,V3)
DO 10 J = 1, NP  ! Loop on load elements
Z03 = 0.50D0*(100 - COS(PI*(J-1D0)/NP))  ! Chordwise locations for loads
KRI = CON*V1*EXP(-AI*(ALF1*CT1+BET*ST1)*C1*Z03)  ! eq. 43
KR2 = CON*V2*EXP(-AI*(ALF2*CT1+BET*ST1)*C1*Z03)  ! eq. 43
KR3 = CON*V3*EXP(-AI*(ALF3*CT1+BET*ST1)*C1*Z03)  ! eq. 43

VR1 = (KRI*R12(K,N)+KR2)*R21(K,N)*EXP(AI*ALF2*XE)
VR2 = (KR1+VR1*EXPE1)*R12(K,N)
VR3 = (KR1+VR1*EXPE1)*R13(K,N)

VR1 = (KRI*VR1*EXPE1)*R12(K,N)
VR2 = (KR1+VR1*EXPE1)*R12(K,N)
VR3 = (KR1+VR1*EXPE1)*R13(K,N)

KRUP(N,K,J) = (KRI + VR1*EXPE1) * T14(K,N)  ! eq. 85
KRDN(N,K,J) = (KR2+VR2)*T28(K,N)*EXP(AI*ALF2*XE)  ! eq. 97
>

Figure 4. (continued) Source code for CUP2D.
c.. Loop on stator control points
DO 10 I = 1, NP
ZI = 0.5D0*(1D0-COS(PI*(2D0*I - 1D0)/(2D0*NP)))
E1I = (ALF1*CT2+BET*ST2)*C2*ZI
E2I = (ALF2*CT2+BET*ST2)*C2*ZI
E3I = (ALF3*CT2+BET*ST2)*C2*ZI

c.. Effect of rotor on stator, eq. 51
IF (K .NE. 0) THEN
KRS = I/MR2 *
> ( (BET*CT2-ALFI*ST2) * VR1 * EXP(AI*(ALFI*(XS-XE)+EII))
> + (BET*CT2-ALFI*ST2) * (KR2+VR2) * EXP(AI*(ALF2* XS +E2I))
> + (ALF3*CT2+BET*ST2) * (KR3+VR3) * EXP(AI*(ALF3* XS +E3I))
> )
ENDIF

C.. Place elements in KMATRIX, forming real elements, from complex KRS, eq. 69
KMATRIX((2*N-2)*NP+I-json, (2*N-2)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-2)*NP+J) + REAL(KRS)
KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) - IMAG(KRS)
KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) + ISIGN(1,K) * IMAG(KRS)
KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) + ISIGN(1,K) * REAL(KRS)

ENDIF

C.. Compute the portion of the KRR coefs caused by the reflected waves, eq. 46.
KRR = I/MR1 *
> ( (BET*CT1-ALFI*ST1) * VR1 * EXP(AI*(ALFI*CT1+BET*ST1)*C1*ZI)*EXP1
> + (BET*CT1-ALFI*ST1) * VR2 * EXP(AI*(ALF2*CT1+BET*ST1)*C1*ZI)
> + (ALF3*CT1+BET*ST1) * VR3 * EXP(AI*(ALF3*CT1+BET*ST1)*C1*ZI) )

C.. Form real elements, do sum over K, and place in KMATRIX.
KMATRIX((2*N-2)*NP+I, (2*N-2)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-2)*NP+J) + REAL(KRR) ! eq. 62
KMATRIX((2*N-1)*NP+I, (2*N-2)*NP+J) =
> KMATRIX((2*N-1)*NP+I, (2*N-2)*NP+J) + IMAG(KRR) ! eq. 63

10 CONTINUE

C.. Fill in the remaining sections of the rotor-on-rotor quarter of the matrix
C.. from the second parts of Eqs. 62 and 63.
DO 20 N = 1, NH
DO 20 J = 1, NP
DO 20 I = 1, NP
KMATRIX((2*N-1)*NP+I, (2*N-2)*NP+J) =
> KMATRIX((2*N-2)*NP+I, (2*N-2)*NP+J)
> KMATRIX((2*N-2)*NP+I, (2*N-1)*NP+J) =
> -KMATRIX((2*N-1)*NP+I, (2*N-2)*NP+J)
20 CONTINUE

RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE GETVS(BETA, NLAM, MX, ST, CT, V1, V2, V3)
c.. Generates V1 and V2 (Smith's v1'/beta and v2'/beta) and V3 (Smith's v3'/
c.. alpha3) for either rotor waves or stator waves.
c.. For stator waves, call with BETA(N,K), NLAM=N*LAM2=N*B1*(MY1-MY2)/MR2, MXB,
c.. ST=SIN(THETA2), CT=COS(THETA2).
c.. For rotor waves, call with BETA(K,N), NLAM=N*LAM1=N*B2*(MY1-MY2)/MR1, MXB,
c.. ST=SIN(THETA1), CT=COS(THETA1). Derivation given in appendix C.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION NLAM, MX
DOUBLE COMPLEX ROOT, G, VI, V2
INTEGER BETA

ABAR = NLAM**2 + BETA**2 + 2.0D0*NLAM*BETA*ST  ! eq. C-18
E   = BETA**2 - ABAR*(MX/CT)**2                ! eq. C-19

c.. E < 0 for propagation, E > 0 for decay. Any E = 0 (resonance) cases
    c.. will be caught by the prior call to subroutine ALFBET.

IF (E .LT. 0.0D0) THEN
   ROOT = CMPLX(SQRT(-E), 0.0D0)
ELSE
   ROOT = CMPLX(0.0D0, -SQRT(E))
ENDIF

F = BETA + NLAM*ST
G = NLAM*BETA*CT/ROOT

V1 = (-F + G)/(2.0D0*ABAR) ! eq. C-15
V2 = ( F + G)/(2.0D0*ABAR) ! eq. C-16
V3 = - NLAM*CT/ABAR        ! eq. C-17

RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE SCOEPS(NH,NP,C1,C2,T1,T2,ST1,ST2,XS,
> MXB,LAM2,ALF,BETA,R12,R21,R13,R31,T14,T28,T38,KMATRX,KSUP,KSDN)
c.. Generates elements of the matrix of influence coefficients KMATRX that give
c.. the upwash caused by stator loading at control points on the rotor and
c.. stator. The rows of the matrix are computed from KSR(N,K,1,3), effect of stator on rotor,
c.. and KSS' (N,I,J1 effect of stator on stator. The prime on KSS' indicates
that only the part of KSS associated with waves reflected from the actuator
c.. disk is computed here. The remainder is computed in GENKSS using original
c.. routines from the Smith code. N counts the stator loading harmonics, I the
c.. control points, and J the load elements. K counts the cascade wave index in
c.. the stator frame which becomes the time harmonic index in the rotor frame.
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MXB,MR1,MR2,LAM2,KMATRX(1020,1020)
INTEGER BETA,-5:5,-5:5
DOUBLE COMPLEX AI,ALFI,ALF2,ALF3,EXPEI,EII,E3I,
> KS1,KS2,KS3,V1,V2,VS1,VS2,VS3,KSR,KSS,
> ALF(9,-5:5,-5:5),
> KSUP(5,-5:5,51),KSDN(5,-5:5,51),
> R12(-5:5,-5:5),R21(-5:5,-5:5),R31(-5:5,-5:5),R41(-5:5,-5:5),
> T14(-5:5,-5:5),T28(-5:5,-5:5),T38(-5:5,-5:5)
AI = (0.0D0, 1.0D0)
PI = 3.14159265D0
WRITE(*,*) 'Entering SCOEPS'

DO 10 N = 1, NH

KSI : CON*VI *EXP ( -AI* (ALFI *CTZ,BET*ST2 ) *C2*Z0J ) !
    CON*V2*EXP(-AI*(ALF2*CT2+BET*ST2)*C2*Z0J) ! eq. 22
    CON*V3* EXP ( -AI * (ALF3 *CT2 +BET*ST2 ) _C2* Z0J ) !
c.. Compute VI, V2, V3 from eq. 26
    Hold out EXPEI=exp(-AI*ALFI*XE) from VI here to avoid overflow later in KSR
    EXP1 = EXP(-AI*ALFI*XE)
    VS1 = ( ( R12(N,K)*R21(N,K)*EXP(AI*ALF2*XE)
    + R13(N,K)*R31(N,K)*EXP(AI*ALF3*XE)))*KS1*EXP(-AI*ALFI*XS)
    + R21(N,K)*KS2*EXP(AI*ALF2*XE-XS))
    / (1.0D0 - R12(N,K)*R21(N,K)*EXP(AI*ALF2*XE)) )
    VS2 = (KS1*EXP(-AI*ALFI*XS)+VS1*EXP1)*R12(N,K)
    VS3 = (KS1*EXP(-AI*ALFI*XS)+VS1*EXP1)*R13(N,K)

c.. KSUP and KSDN are passed out of the subroutine for later use in computing
c.. pressure in the nozzle-swirl region, upstream and downstream.
    KSUP(N,K,J) = (KS1*EXP(-AI*ALFI*XS1+VS1*EXP1) * T14(N,K) ! eq. 77
    KSDN(N,K,J) = (KS2*EXP(-AI*ALF2*XS2)+VS2)*EXP(AI*ALF2*XE) * T28(N,K) ! eq. 88
    + (KS3*EXP(-AI*ALF3*XS31+VS31)*EXP(AI*ALF3*XE) * T38(N,K)

Figure 4. (continued) Source code for CUP2D.
c.. Loop on rotor control points

DO 10 I = 1, NP
   ZI = 0.5D0*(1D0-COS(PI*(2*I-1D0)/(2*NP)))
   E11 = (ALF1*CT1+BET*ST1)*C1*ZI
   E21 = (ALF2*CT1+BET*ST1)*C1*ZI
   E31 = (ALF3*CT1+BET*ST1)*C1*ZI

10 CONTINUE

c.. Effect of stator on rotor, eq. 37

IF (K .NE. 0) THEN
   KSR = 1/MR1*
      > (BET*CT1 - ALFI*ST1)*KS1*EXP(A1*E11)*EXP(-AI*ALFI*X1)
      > + (BET*CT1 - ALFI*ST1)*VS1*EXP(A1*E11)*EXP1
      > + (BET*CT1 - ALFI*ST1)*VS3*EXP(A1*E11)

   Place elements in KMATRIX, forming real elements, from complex KSR, eq. 70
   KMATRIX((2*ABS(K)-2)*NP+I,NPNH2+(2*N-2)*NP+J) =
      > KMATRIX((2*ABS(K)-2)*NP+I,NPNH2+(2*N-2)*NP+J)+REAL(KSR)
   KMATRIX((2*ABS(K)-2)*NP+I,NPNH2+(2*N-1)*NP+J) =
      > KMATRIX((2*ABS(K)-2)*NP+I,NPNH2+(2*N-1)*NP+J)-IMAG(KSR)
   KMATRIX((2*ABS(K)-1)*NP+I,NPNH2+(2*N-2)*NP+J) =
      > KMATRIX((2*ABS(K)-1)*NP+I,NPNH2+(2*N-2)*NP+J)+ISIGN(1,K)*IMAG(KSR)
   KMATRIX((2*ABS(K)-1)*NP+I,NPNH2+(2*N-1)*NP+J) =
      > KMATRIX((2*ABS(K)-1)*NP+I,NPNH2+(2*N-1)*NP+J)-ISIGN(1,K)*REAL(KSR)
ENDIF

c.. Compute the portion of the KSS coeffs caused by the reflected waves, eq. 31.

   KSS = 1/MR2*
      > (BET*CT2 - ALFI*ST2)*VS1*
      > EXP(A1*(ALFI*(XS-XE)+(ALFI*CT2+BET*ST2)*C2*ZI))
      > + (BET*CT2 - ALFI*ST2)*VS2*
      > EXP(A1*(ALFI*ST2+BET*ST2)*C2*ZI))
      > + (ALFI*CT2 + BET*ST2)*VS3*
      > EXP(A1*(ALFI*CT2+BET*ST2)*C2*ZI))

   Form real elements, do sum over K, and place in KMATRIX
   KMATRIX(NPNH2+(2*N-2)*NP+I,NPNH2+(2*N-2)*NP+J) =
      > KMATRIX(NPNH2+(2*N-2)*NP+I,NPNH2+(2*N-2)*NP+J)+REAL(KSS) ! eq. 64
   KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J) =
      > KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J)+IMAG(KSS) ! eq. 65

10 CONTINUE

c.. Fill in the remaining sections of the stator on stator quarter of the matrix

c.. from the second parts of Eqs. 64 and 65.

DO 20 N = 1, NH
   DO 20 J = 1, NP
      DO 20 I = 1, NP
         KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J) =
            > KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J)
            + KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J)
            - KMATRIX(NPNH2+(2*N-1)*NP+I,NPNH2+(2*N-2)*NP+J)

20 CONTINUE

RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE GENKRR(NH,NP,CI,C2,SCI,SC2,CTI,STI,MXB,LAMI,KMATRX)

This generates the input needed to call Smith's matrix generation routines for the effect of the rotor on itself via the direct waves. It fills the WHEAD common block and calls Smith's routine DSWK. This returns the real and imaginary parts of the matrix. These are placed in the appropriate locations in KMATRX, adding to the elements already computed by RCOEFS that account for the effect of the rotor on itself via the reflected waves.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

COMMON /WHEAD/ SC,STAG,MACH,LAM,PHASE,DEG,PI,COST,SINST,
> MACH2,B,BETA2,BC,BC2

DOUBLE PRECISION MXB,LAMI,KR(51,51),KI(51,51),KMATRX(1020,1020)

WRITE(*,*) 'Entering GENKRR'

SC = SC
STAG = ASIN(STI)
MACH = MXB/CTI
MACH2 = MACH**2
BETA2 = ID0 MACH2
B = SQRT(BETA2)
DEG = 57.2957_D0
PI = 3.14159265D0
COST = CTI
SINST = ST1
BC2 = ID0 MXB**2
BC = SQRT(BC2)

Loop on rotor loading harmonic
DO 300 N=I, NH
LAM = N*LAMI*CI
PHASE = 2.0D0*PI*N*CI/C2*SCI/SC2

Call Smith's original matrix generation routine
CALL DSWK(KR,KI,NP, IW)
IF (IW .EQ. /) THEN
WRITE(*,1) N
1 FORMAT(I6, 'DSWK RETURNED IW:I TO GENKRR FOR N:',I2)
STOP
ELSE
ENDIF

Add Smith's real and imaginary matrix elements into KMATRX, see Eqs. 62 & 63
DO 100 I = 1, NP
DO 100 J = 1, NP

100 CONTINUE
300 CONTINUE
RETURN
END

Figure 4. (continued) Source code for CUP2D.

-29-
SUBROUTINE GENKSS(NH, NP, C1, C2, SCI, SC2, CT2, ST2, MXB, LAM2, KMATRIX)

C.. This generates the input needed to call Smith's matrix generation routines
C.. for the effect of the stator on itself via the direct waves. It fills the
C.. WHEAD common block and calls Smith's routine DSWK. This returns the real
C.. and imaginary parts of the matrix. These are placed in the appropriate
C.. locations in KMATRIX, adding to the elements already computed by SCOEFFS that
C.. account for the effect of the stator on itself via the reflected waves.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
COMMON /WHEAD/ SC, STAG, MACH, LAM, PHASE, DEG, PI, COSST, SINST,
>: MACH2, B, BET2, BC, BC2
DOUBLE PRECISION MXB, LAM2, KR(51,51), KI(51,51), KMATRIX(1020,1020)
DOUBLE PRECISION MACH, LAM, MACH2
WRITE(*,*) 'Entering GENKSS'

C... Fill /WHEAD/ common block (except for LAM and PHASE)
SC = SC2
STAG = ASIN(ST2)
MACH = MXB/CT2
MACH2 = MACH**2
BETA2 = 1.000 - MACH2
B = SQRT(BETA2)
DEG = 57.2957790
PI = 3.14159265D0
COSST = CT2
SINST = ST2
BC2 = 1.000 - MXB**2
BC = SQRT(BC2)

C... Loop on stator loading harmonic
NPNH2 = NP*NH*2
DO 300 N=I, NH
LAM = N*LAM2*C2
PHASE = -2.0D0*PI*N*C2/CI*SC2/SCI

C... Call Smith's original matrix generation routine
CALL DSWK(KR, KI, NP, IW)
IF (IW .EQ. 1) THEN ! Smith's resonance check
WRITE(*,1) N
1 FORMAT(IX, 'DSWK RETURNED IW=I TO GENKSS. FOR N=',I2)
STOP 'EXECUTION TERMINATED DUE TO RESONANCE'
ENDIF

C. Add Smith's real and imaginary matrix elements into KMATRIX, see Eqs. 64 & 65
DO 100 I = I, NP
DO 100 J = 1, NP
KMATRIX(NPNH2+(2*N-2)*NP+I, NPNH2+(2*N-2)*NP+J) =
> KMATRIX(NPNH2+(2*N-1)*NP+I, NPNH2+(2*N-2)*NP+J) + KR(I,J)
KMATRIX(NPNH2+(2*N-1)*NP+I, NPNH2+(2*N-2)*NP+J) =
> KMATRIX(NPNH2+(2*N-2)*NP+I, NPNH2+(2*N-1)*NP+J) + KR(I,J)
KMATRIX(NPNH2+(2*N-1)*NP+I, NPNH2+(2*N-2)*NP+J) =
> KMATRIX(NPNH2+(2*N-2)*NP+I, NPNH2+(2*N-1)*NP+J) + KI(I,J)
KMATRIX(NPNH2+(2*N-2)*NP+I, NPNH2+(2*N-1)*NP+J) =
> KMATRIX(NPNH2+(2*N-1)*NP+I, NPNH2+(2*N-2)*NP+J) - KI(I,J)
100 CONTINUE
300 CONTINUE
RETURN
END

Figure 4. (continued) Source code for CUP2D.

-30-
SUBROUTINE SOLVE(NH, NP, KMATRX, WR, WS, LR, LS)

This routine finds the loading on both the rotor and the stator simultaneously by matrix inversion. Externally imposed upwash velocities enter the routine in complex form (WR, WS) and are used to form a one dimensional real vector WASH. KMATRX is inverted using the LINPACK routines and multiplied by WASH. The result is the one dimensional load vector LOAD. This is decomposed into the complex load vectors LR and LS and these are sent to the LOADS routine for output.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION KMATRX(1020,1020), LOAD(1020), WASH(1020)
DOUBLE COMPLEX WR(5,51), WS(5,51), LR(5,51), LS(5,51)

! constant needed for element shifting
! size of one side of real matrix

CALL MATINV(KMATRX, NPNH4)

c.. Form real upwash vector from complex upwash vectors for rotor and stator.
c.. Minus signs because objective is to find the loading that produces upwash
to cancel wake upwash. Note, rotor upwash is zero for the usual rotor/stator
interaction problem, but the code could deal with rotor vibration or
stator potential field excitation also.
DO 10 K = 1, NH
DO 10 I = 1, NP
WASH( (2*K-2)*NP+I) = REAL (WR(K,I) ! eq. 71
WASH( (2*K-1)*NP+I) = IMAG (WR(K,I) !
WASH( NPNH2 + (2*K-2)*NP+I) = REAL (WS(K,I) !
WASH( NPNH2 + (2*K-1)*NP+I) = IMAG (WS(K,I) !
10 CONTINUE

DO 20 NU = 1, NPNH4
LOAD(NU) = ZERO
20 CONTINUE

DO 30 NU = 1, NPNH4
DO 30 MU = 1, NPNH4
LOAD(NU) = LOAD(NU) + KMATRX(NU,MU) * WASH(MU)
30 CONTINUE

DO 40 N = 1, NH
DO 40 J = 1, NP
LR(N,J) = CMPLX(LOAD( (2*N-2)*NP+J), LOAD( (2*N-1)*NP+J)) ! eq. 72
LS(N,J) = CMPLX(LOAD(NPNH2+(2*N-2)*NP+J), LOAD(NPNH2+(2*N-1)*NP+J)) ! 72
40 CONTINUE

CALL LOADS(NH, NP, LR, LS)
RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE LOADS(NH,NP,LR,LS)
c.. Computes and prints integrated loading on both blade rows for multiple

c.. harmonics. Formulas equivalent to Smith's eq. 56. Values are lift per

c.. unit span divided by chord*rho*relv**2. Treatment of first and last terms

c.. handled automatically by inversion process.

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE COMPLEX LR(5,51), LS(5,51), CLR, CLS

WRITE('** VALUES OF LIFT COEFFICIENTS **',*)
WRITE(' N ROTOR(N) STATOR(N)' real imag real imag

DO 20 N:I NH
    CLR = (0D0, 0D0)
    CLS = (0D0, 0D0)
    DO 10 J=1, N
        CLR = CLR - LR(N,J)
        CLS = CLS - LS(N,J)

WRITE(*,10) N, CLR, CLS
10 FORMAT(1X,2F10.5, 2F10.5)

CONTINUE

WRITE(*,20) N, CLR, CLS
20 FORMAT(1X,2F10.5, 2F10.5)

RETURN

END

C

C

Figure 4. (continued) Source code for CUP2D.

-32-
SUBROUTINE OUTPUT(NH, NP, B1, B2, MXA, MXB, MXC, MS, MY1, MY2, ALF, ABA, ABC,
>     XA, XC, POFSA, POFSB, KRUP, KRDN, KSUP, KSDN, LR, LS )
c.. Calculates sound pressure at axial locations XA and XB and sound power
c.. (average per unit area) upstream and downstream based on loading from
C.. SOLVE and influence functions from INFFNS.
IMPLICIT DOUBLE PRECISION (A-H, O-Z)
DOUBLE PRECISION Mxa, Mxb, Mxc, MS, MY1, MY2, PWLAT(5), PWLCT(5)
INTEGER BI, B2, ORDER
DOUBLE COMPLEX A4, A8, G4, GH, PUP, PDN, ALF(9,-5:5,-5:5), AI,
>     LR (5,51), LS (5,51), LUP (5,-5:5), LDN (5,-5:5),
>     LRUP(5,-5:5), LRDN(5,-5:5), LSUP(5,-5:5), LSDN(5,-5:5),
>     KRUP(5,-5:5,51), KRDN(5,-5:5,51), KSUP(5,-5:5,51), KSDN(5,-5:5,51)
AI = (0.0D0, 1.0D0)
WRITE(*,*) ' Axial locations for sound pressure output in radii from
> rotor leading edge '
WRITE(*,5) XA, XC
5 FORMAT(1X, ' For PRESup, Xa = ',F5.3,'. For PRESdn, Xc = ',F5.3)
WRITE(*,*) ' Decibel Levels for Pressure Waves and Power Levels
> Cutoff Ratio '
WRITE(*,*)' N  K  FREQ nBi-kB2 PRESup PRESdn PWLup PWL
A B C'
c.. Zero the wave accumulators
DO 10 N = I, NH
  DO 10 K = -NH, NH
    LRUP(N, K) = (0.0D0, 0.0D0)
    LRDN(N, K) = (0.0D0, 0.0D0)
    LSUP(N, K) = (0.0D0, 0.0D0)
    LSDN(N, K) = (0.0D0, 0.0D0)
10 CONTINUE
c.. Sum contributions to waves over load elements
DO 20 N = I, NH
  DO 20 K = -NH, NH
    DO 20 J = I, NJ
      LRUP(N, K) = LRUP(N, K) + KRUP(N, K, J) * LR(N, J) ! eq. 84
      LRDN(N, K) = LRDN(N, K) + KRDN(N, K, J) * LR(N, J) ! eq. 96
      LSUP(N, K) = LSUP(N, K) + KSUP(N, K, J) * LS(N, J) ! eq. 77
      LSDN(N, K) = LSDN(N, K) + KSDN(N, K, J) * LS(N, J) ! eq. 89
20 CONTINUE
c.. Add rotor waves to stator waves upstream and downstream
DO 30 N = I, NH
  DO 30 K = I, NH
    LUP(N, K) = LRUP(K, N) + LSUP(N, K) ! eq. 106
    LUP(N, K) = -CONJG(LRUP(K, -N)) + LSUP(N, -K)
    LDN(N, K) = LRDN(K, N) + LSDN(N, K) ! eq. 116
    LDN(N, K) = -CONJG(LRDN(K, -N)) + LSDN(N, -K)
30 CONTINUE
c.. Following terms computed without steady loading effect from rotor
LUP(N, 0) = LSUP(N, 0)
LDN(N, 0) = LSDN(N, 0)
30 CONTINUE
c.. Compute modal and total powers upstream and downstream
DO 50 N = I, NH
  PWLAT = 0.0D0 ! Total power accumulator, upstream
  PWLCT = 0.0D0 ! Total power accumulator, downstream
50 CONTINUE

Figure 4. (continued) Source code for CUP2D.
DO 52 K = -NH, NH
    FREQ = N*BI*MYI - K*B2*MY2
    ORDER = N*BI - K*B2  ! Negative of beta(n,k)
    CTRATA = 9.99D0
    CTRATB = 9.99D0
    CTRATC = 9.99D0
ELSE
    CTRATA = SQRT((ABA*FREQ)**2/((ID0-MXA**2)*ORDER**2))
    CTRATB = SQRT((FREQ-ORDER*MS)**2/((ID0-MXB**2)*ORDER**2))
    CTRATC = SQRT((ABC*FREQ)**2/((ID0-MXC**2)*ORDER**2))
ENDIF

C.. Output only waves with cutoff ratios > 0.2 in up or downstream region
IF (CTRATA .GT. 0.2D0) GOTO 51
IF (CTRATC .LE. 0.2D0) GOTO 52
51 A4 = ALF(4,N,K)  ! axial wavenumber upstream
    A8 = ALF(8,N,K)  ! axial wavenumber downstream
    G4 = - (ABA*FREQ + MXA*A4)  ! eq. 81
    G8 = - (ABC*FREQ + MXC*A8)  ! eq. 93
    CALL GETW(L(CTRATA,MXA,A4,G4,LUP(N,K),-I, PWRA, PWLA)
    CALL GETWL(CTRATC,MXC,A8,G8,LDN(N,K), I, PWRC, PWLC)
    PWLAT = PWRA + PWRA
    PWLCT = PWRC + PWRC
C.. Compute pressures at phi=0 and x = xa and xc
    PUP = G4*LUP(N,K)*EXP(AI*A4*XA)
    PDN = G8*LDN(N,K)*EXP(AI*A8*(XC-XE))
    WRITE(*,1) N, K, FREQ, ORDER, DEBEL(PUP,POPSA), DEBEL(PDN,POPSB),
                      PWLA, PWLC, CTRATA, CTRATB, CTRATC
 1 FORMAT(1X, 2I5, F7.2, I6, 4F8.1, 1X, 2F8.1)
52 CONTINUE
    PWLAT(N) = MAX(0D0, 10D0*LOG10(|PWRA*1.0D1+1.0D-30|))
    PWLCT(N) = MAX(0D0, 10D0*LOG10(|PWRC*1.0D3+1.0D-30|))
    WRITE(*,3) N, PWLAT(N), PWLCT(N)
 3 FORMAT(1X,'-------------------  Total power for Nz=',I2, ' ', 2F8.1)
    WRITE(*,*) ''
50 CONTINUE
RETURN
END
SUBROUTINE GETPWL(CTRAT, MX, A, G, L, IX, POWER, PWL)
   c.. Computes sound power level according to theory in Eqs. 98-116.
   c.. Checks that power is real (within numerical accuracy) and that real part
   c.. has the correct sign for flux away from blades.
   IMPLICIT DOUBLE PRECISION (A-H,O-Z)
   DOUBLE PRECISION MX
   DOUBLE COMPLEX A, G, L, PWR
   c.. No power for waves that are cut off.
   IF (CTRAT .LE. 1.0) THEN
      POWER = 0.0D0
      PWL = 0.0D0
      RETURN
   ENDIF
   c.. Treat power as complex to verify correct behavior. See Eqs. 112 & 115.
   c.. SIGN function below is needed because derivation was for power flux in the
   c.. +x direction. The expression below must be real and > 0 for regions A & C.
   PWR = ((1.0D0+MX**2)*A*G + MX*(A**2+G**2))*ABS(L)**2 *SIGN(1,IX)
   c.. Check that PWR is real.
   TEST = ABS( IMAG(PWR)/(REAL(PWR)+1.0D-20) )
   IF (TEST .LT. .001DO) THEN
      STOP 'Execution terminated because power flux is complex'
   ENDIF
   c.. Check that power flux is outgoing on either side of the source.
   IF (REAL(PWR) .LT. 0.) THEN
      WRITE(*,*)'IX = ', IX
      STOP 'Execution terminated because power flux is negative'
   ENDIF
   POWER = REAL(PWR)
   IF (POWER .LT. 1.0D-13) THEN
      PWL = 0.0D0
   ELSE
      PWL = 10.0D0*LOG10(POWER*1.0D13) ! eq. 113
   ENDIF
   RETURN
END

DOUBLE PRECISION FUNCTION DBEL(X, POPS)
   c.. Computes SPL dB from harmonic peak value normalized by ambient rho*c**2.
   c.. Uses POPS, the ratio of local ambient pressure to 2116 psf.
   IMPLICIT DOUBLE PRECISION (A-H,O-Z)
   DOUBLE COMPLEX X
   TEMP=20.0D0*LOG10(.707110651D9+1.0D35)
   DBEL=MAX(TEMP,0.0D0)
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE DSWK(KR,KI,NP, IW)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MACH,LAM,MACH2,MACH4,MACH6,KR(51,51),KI(51,51)
COMMON /WHEAD/ SC,STAG,MACH,LAM,PHASE,DEG,PI,COSST, SINST,
> MACH2,B,B2,BC,BC2
COMMON/WAVEC/ XU,APU,APD,ANU,AND,PUR,PDR,PUI,VU,VD
DIMENSION ICHECK(51,51),ZE(51),ZP(51)
C.... CONSTANTS FOR VORTEX SHEET CALCULATION
X = LAM*SC*COSST
Y = LAM*SC*SINST + PHASE
VORT = 0.5*LAM*SINH(X)/(COSH(X) - COS(Y))
C.... CONSTANTS FOR LOG SINGULARITY CORRECTION
MACH4 = MACH2*MACH2
MACH6 = MACH4*MACH4
B4 = B2*B2
B6 = B2*B4
A1 = 1.0 - 0.5*MACH2/B2
A2 = 1.0 - 0.5/B2 + 0.9*MACH2/B4
A3 = 0.5*(1.0 - 1.0/B2 + MACH2/(6.0*B4) + 1.0/(3.0*B4))
> - 0.375*MACH4/B6 + MACH6/(6.0*B6))
C.... MATCHING AND VORTEX POINTS:
DO I = I,NP
EPSIL = PI*FLOAT(2*I - I)/FLOAT(2*NP)
ZE(I) = 0.5*(1.0 - COS(EPSIL))
PSI = PI*FLOAT(I - I)/FLOAT(NP)
ZP(I) = 0.5*(1.0 - COS(PSI))
ENDDO
C.... ZERO COUNTS AND ARRAYS:
IR = 0
ICOUNT = 0
IW = 0
NP2 = NP*NP
DO I = I,NP
DO J = I,NP
ICHECK(I,J) = 0
KR(I,J) = 0.0
KI(I,J) = 0.0
ENDDO
ENDDO
C ASSEMBLE MATRIX
C I{ = M + 1 IN PAPER) GIVES VORTEX POSITION
C.... J( = L + 1 IN PAPER) GIVES MATCHING POINT
C 30 CALL WAVE(IR, IW)
IF(IW.EQ.I) RETURN
DO I = I,NP
DO J = I,NP
IF(ICHECK(I,J).EQ.1) GO TO 131
POS = ZE(I) - ZP(J)
IF(POS.GT.0.0) GO TO 90
C....... UPSTREAM POINT
XP = EXP(XU*POS)
YP = APD*POS
QR = XI*COS(YF)
QI = XI*SIN(YF)
TERM = (PUR*QR - PUI*QI)/SC
TERMi = (PUR*QI + FUI*QR)/SC
GO TO 100

C ........ DOWNSTREAM POINT
90 XP = EXP(- XU*POS)
YP = APO*POS
QR = XP*COS(YP)
QI = XP*SIN(YP)
TERMr = (PDR*QR - PUI*QI)/SC
TERMi = (PDR*QI + PUI*QR)/SC

C ........ ADD TO MATRIX
100 KR(I,J) = KR(I,J) + TERMr
KI(I,J) = KI(I,J) + TERMi

C ........ CHECK CONVERGENCE OF SERIES
C.. The next 3 lines modified from Smith's code on 8/19/91 by DBH

X = ABS(TERMr) + ABS(TERMi)
Y = ABS(KR(I,J)) + ABS(KI(I,J))
IF((X/Y) .GT. 1.0D - 7) GO TO 131

C X = TERMr*TERMr + TERMi*TERMi
C Y = KR(I,J)*KR(I,J) + KI(I,J)*KI(I,J)
C IF((X/Y) .GT. 1.0D - 11) GO TO 131

ICHECK(I,J) = 1
ICOUNT = ICONT + 1

C ........ CORRECT FOR LOG::SINGULARITY (LAST TIME THROUGH)
SUM = 0.0
EPSIL = PI*FLOAT(2*I - 1)/FLOAT(2*NP)
PSI = PI*FLOAT(J - 1)/FLOAT(NP)
NPM1 = NP - 1
DO JR = I,NPM1
FJR = FLOAT(JR)
SUM = SUM + COS(FJR*EPSIL)*COS(FJR*PSI)/FJR
ENDDO
SUM = 2.0*SUM + LOG(4.0*ABS(POS))
SUM = SUM*LAM/(2.0*PI*B)
PLAM = LAM*POS
PLAM2 = PLAM*PLAM
PLAM3 = PLAM2*PLAM
KR(I,J) = KR(I,J) + SUM*(AI*PLAM - A2*PLAM2)
KI(I,J) = KI(I,J) + SUM*(1.0 - A2*PLAM2)

C ........ ADD VORTICITY WAVE
IF(POS.LE.0.0) GO TO 131
KR(I,J) = KR(I,J) + VORT*COS(PLAM)
KI(I,J) = KI(I,J) - VORT*SIN(PLAM)
131 CONTINUE
ENDDO
ENDDO

C .... CHECK FOR COMPLETION
IF(ICONT.EQ.NP2) RETURN
IF(IR.GT.0) THEN
IR = -IR
ELSE
IR = -IR + 1
ENDIF
GO TO 30
END

Figure 4. (continued) Source code for CUP2D.
CALCULATION OF ACOUSTIC WAVE PROPERTIES

SUBROUTINE WAVE(IR, IW)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MACH, LAM, MACH2
COMMON /WHEAD/ SC, STAG, MACH, LAM, PHASE, DEG, PI, COSST, SINST,
> MACH2, B, B2, BC, BC2
COMMON/WAVEC/ XU, APU, APD, ANU, AND, PUR, PDR, PUI, VU, VD

BETAH=(PHASE-2.0*PI*FLOAT(IR))/SC
BETAH2=BETAH*BETAH
A=LAM*LAM+BETAH2+2.0*LAM*BETAH*SINST
D=MACH2*(LAM+BETAH*SINST)*COSST/BC2
E=BETAH2-MACH2*A
IF(E .NE. 0.0) GO TO 32
WRITE(*,31) IR
FORMAT(' Resonance at IR=',I4) IW=1
GO TO 60
F=SQR(T(ABS(E))
FB=F/BC2
H=(BETAH+LAM*SINST)/(2.0*A)
P=BETAH*LAM*COSST/(F*2.0*A)
IF(E .GT. 0.0) GO TO 50
WAVE NUMBERS, PROPAGATING CASE

ACUI=D+FB
ACDI=D-FB
APU=ACUI*COSST+BETAH*SINST
APD=ACDI*COSST+BETAH*SINST
ANU=BETAH*COSST-ACUI*SINST
AND=BETAH*COSST-ACDI*SINST
PUR=ANU*(P-H)
PDR=AND*(P+H)
PUI=0.0
XU=0.0
VU=(P-H)*(LAM+APU)/SC
VD=(P+H)*(LAM+APD)/SC
GO TO 60

WAVE NUMBERS, DECAYING CASE

50 APU=D*COSST+BETAH*SINST
APD=APU
ANU=BETAH*COSST-D*SINST
AND=ANU
PUR=-ANU*H-FB*SINST*P
PDR=-PUR
PUI=ANU*P-FB*SINST*H
XU=FB*COSST
GO TO 60
RETURN
END

Figure 4. (continued) Source code for CUP2D.
SUBROUTINE MATINV(A,N)
C.. This routine written by D.B. Hanson to call the LINPACK routines for
C.. inversion of real matrices. Call for matrix A. Inverse returned in
C.. same array.

DOUBLE PRECISION A(1020,1020),WORK(1020),DET(2),RCOND,Z(1020)
INTEGER  IPVT(1020)

WRITE(*,*) 'Entering MATINV'
CALL GEEO(A,1020,N,IPVT,RCOND,Z)
WRITE(*,*) 'Condition number of KMATRIX = ', RCOND
CALL GEDI(A,1020,N,IPVT,DET,WORK,1)
RETURN
END

Figure 4. (continued) Source code for CUP2D.
Section 5
Array Dimensions

This section shows how the arrays are dimensioned in case they need to be changed to accommodate more harmonics or panels on the blades. Interpret $N_h$ and $N_p$ below to be the maximum permitted values of number of harmonic and number of panels.

\begin{align*}
\text{ALF}(9, -N_h:N_h, -N_h:N_h) \\
\text{BETA}(-N_h:N_h, -N_h:N_h) \\
\text{KRUP, KRDN, KSUP, KSDN}(N_h, -N_h:N_h, N_p) \\
\text{R12, R21, R13, R31, T14, T28, T38}(-N_h:N_h, -N_h:N_h) \\
\text{WREXT, WSEXT}(N_h, N_p) \\
\text{LR, LS}(N_h, N_p) \\
\text{KMATRIX}(4*N_h*N_p, 4*N_h*N_p) \\
\text{FW}(N_h) \\
\text{KR, KI}(N_p, N_p) \\
\text{WR, WS}(N_h, N_p) \\
\text{LOAD, WASH}(4*N_h*N_p) \\
\text{LUP, LDN}(N_h, -N_h:N_h) \\
\text{LRUP, LRDN, LSUP, LSDN}(N_h, -N_h:N_h)
\end{align*}
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A 2D linear aeroacoustic theory for rotor/stator interaction with unsteady coupling was derived and explored in Volume 1 of this report. Computer program CUP2D has been written in FORTRAN embodying the theoretical equations. This volume (Volume 2) describes the structure of the code, installation and running, preparation of the input file, and interpretation of the output. A sample case is provided with printouts of the input and output. The source code is included with comments linking it closely to the theoretical equations in Volume 1.

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