

NASA Contractor Report 181790

**Noise Produced by Turbulent Flow
Into a Rotor:
Users Manual for Noise Calculation**

R. K. Amiet, C. G. Egolf, and J. C. Simonich

**United Technologies Research Center
East Hartford, CT**

Contract NAS1-17763

June 1989



**National Aeronautics and
Space Administration**

**Langley Research Center
Hampton, Virginia 23665-5225**

**(NASA-CR-181790) NOISE PRODUCED BY
TURBULENT FLOW INTO A ROTOR: USERS MANUAL
FOR NOISE CALCULATION Final Report (United
Technologies Research Center) 38 p CSCL 20A**

N89-29152

**Unclas
0225002
G3/71**

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* ROUTINE - NOPMAN

* PURPOSE - The main program which begins the calculation.
* It also does the summation over radius.

* AUTHOR - Roy K. Amiet

* INPUT

* COMMON BLOCKS

* COMMON /ROTCA/

Name	Type	Description
CL	RD	Chord/turbulence length scale
BN	RD	Number of blades
COC	RD	Sound speed / chord
RC	RD	Blade radius/chord
R1C	RD	Far-field distance / chord
RPS	RD	Rotational speed revolutions / sec
DXDZ	RD	Deformation tensor
ALPHA	RD	Tip path plane angle of attack
A0	RD	Speed of sound
TMIN	RD	Minimum observer polar angle in degrees (theta=0 along rotor axis in thrust direction)
TMAX	RD	Maximum observer polar angle in degrees
D	RD	Diameter of rotor
DELT	RD	Desired increment in polar angle between successive calculations
PMIN	RD	Minimum observer azimuthal angle in degrees (phi=0 in direction of mean wind)
PMAX	RD	Maximum observer azimuthal angle in degrees
DELP	RD	Desired increment in azimuthal angle between successive calculations
ZM	RD	Axial Mach number
FM	RD	Flow Mach numbr in rotor plane
UU	RD	Rms turbulence velocity / axial velocity
GWS	RD	Geostrophic wind speed (m/s)
WUINF	RD	Vertical component of the rms turbulence normalized by the stream velocity

* COMMON /NOPCB/

Name	Type	Description
J	I	Number of azimuthal integration points
HF	I	First harmonic
HL	I	Last harmonic
NUM	I	Number of points
IH	I	Homogenous or nonhomogenous indicator 0 homogenous case 1 nonhomogenous
NR	I	Number of radial points

LOCAL VARIABLES

Name	Type	Description
DH	RD	Fractional harmonic spacing between frequency calculations
DR	RD	Increment between radial points
H	RD	Frequency of sound in multiples of blade passage harmonics
HOLD	RD	Last harmonic calculated
IARRAY	I	Array containing integer words from a data member record
I2	I	Do loop index
II	I	Do loop index
IP	I	Number of P values
ISTAT	I	Status of calls to data member routines
JJ	I	Do loop index
K	I	Do loop index
LPOUT	I	Logical unit to write
NOPIN2	RD	Array containing data member name of NOP input file
NP	I	Do loop index
NR	I	Number of radial points
NT	I	Do loop index
NWRDS	I	Number of words read in from data member record
P2	RD	Pressure averaged around azimuth
P22	RD	Previous P2 value
PH	RD	Angle of flight Mach number
RARRAY	RD	Array containing the real words from a data member record
RCP	RD	Radial point
RCP1	RD	Previous radial point
SUM	RD	Sum of pressure squared contributions to noise
TH	RD	Polar angle of observer

OUTPUT

Name	Type	Description
H	RD	Frequency of sound in multiples of blade passage harmonic
F1	RD	Frequency of sound in Hz
PSD	RD	Spectrum level in dB (per unit Hz)
NP1	RD	Summation counter
NM1	RD	Summation counter
N	RD	Summation counter

FUNCTIONS

1. To call subprogram to read in input values
2. To call subprogram giving spectrum integrated over azimuth
3. To perform integration of spectrum over radius

SUBPROGRAMS CALLED

MMCLOS MMGETR MMOPRD NOPINP PX XFETCH XSTORE

```

*
* CALLING PROGRAMS
* ANOP EXEC
*
* ERRORS
* NON-FATAL
* 1. Error opening data member for input
* FATAL
* none
*
* ENTRY
* Print the input quantities for checking
* Write the values of the deformation tensor
* If beginning harmonic is negative, return to matrix input
* If harmonic spacing is negative, return to previous input
* If number of steps is negative, return to first input
* Calculate frequency step size
* Print headings for the eventual output
* Initialize the frequency variable
* Input of zero for L2 defaults to a single frequency step
* DO 60 K=1,L2
* Increment frequency
* Initialize radius
* Initialize sum
* DO 22 I2=1,19
* Increment blade radial position
* Calculate tip Mach number at this radius
* Call subroutine giving azimuthally averaged spectrum at this
* radius
* Halve first value in trapezoidal integral over radius
* Add to integrated spectrum
* END DO
* Calculate PSD
* Calculate harmonic
* Write results
* END DO
* EXIT
***

```

* ROUTINE - NOPINP

* PURPOSE - To read in input variables and calculate the mean
* and turbulence properties for an atmospheric boundary
* layer

* AUTHOR - J. C. Simonich

* INPUT

* USER PARAMETERS

Name	Type	Description
AO	RD	Speed of sound (m/s)
D	RD	Diameter of rotor (m)
C	RD	Blade chord (m)
BN	RD	Number of blades
FF	RD	Distance from rotor to observer (m)
RPS	RD	Rotational speed in rev/sec
HF	I	First harmonic
HL	I	Last harmonic
NUM	I	Number of frequency points
TMIN	RD	Minimum observer polar angle in degrees (theta=0 along rotor axis in thrust direction)
TMAX	RD	Maximum observer polar angle in degrees
DELT	RD	Desired increment in polar angle between success calculations
PMIN	RD	Minimum observer azimuthal angle in degrees (phi=0 in direction of mean wind)
PMAX	RD	Maximum observer azimuthal angle in degrees
DELP	RD	Desired increment in azimuthal angle between successive calculations

* DATA MEMBER ROTNOP(ABLOT1) - This is the output from the FM ABL

* GWS, LWX, WUINF

Name	Type	Description
GWS	RD	Geostrophic wind speed (m/s)
LWX	RD	Correlation length scale
WUINF	RD	Vertical component of the rms turbulence normalized by the velocity

* DATA MEMBER ROTNOP(ROTOT1) - This is the output from the FM ROT

* TITLE

* NR, J, IH

* R2, ALPHA, R

* STRENG

* If IH=0 (homogenous case) read in following:

* T, U, V, W, X, Y, Z

* XSL1, YSL1, ZSL1, XSL2, YSL2, ZSL2

* USAV, VSAV, WSAV

```

*      XA11, XA21, XA31
*      XA12, XA22, XA32
*      XA13, XA23, XA33
*

```

```

*      Name      Type      Description
*      .....
*      TITLE     A          Title of case run
*      NR        I          Number of radial points
*      J         I          Number of azimuthal points
*      IH        I          Indicator of homogenous or nonhomogenous case
*      R2        RD         Maximum radius
*      ALPHA     RD         Rotor tip path plane angle of attack
*      R         RD         Radius of rotor
*      STRENG    RD         Vortex circulation strength
*      For homogenous case (IH=0) the following input is read, otherwise
*      the rest of the data member is read in the subroutine NOPPX
*      T         RD         Streamline drift time
*      U         RD         U velocity component in radii/sec
*      V         RD         V velocity component in radii/sec
*      W         RD         W velocity component in radii/sec
*      X         RD         Downstream X coordinate of streamline in
*                          rotor plane
*      Y         RD         Downstream Y coordinate of streamline in
*                          rotor plane
*      Z         RD         Downstream Z coordinate of streamline in
*                          rotor plane
*      XSL1      RD         Downstream X coordinate of streamline in
*                          standard coordinate system
*      YSL1      RD         Downstream Y coordinate of streamline in
*                          standard coordinate system
*      ZSL1      RD         Downstream Z coordinate of streamline in
*                          standard coordinate system
*      XSL2      RD         Upstream X coordinate of streamline in
*                          standard coordinate system
*      YSL2      RD         Upstream Y coordinate of streamline in
*                          standard coordinate system
*      ZSL2      RD         Upstream Z coordinate of streamline in
*                          standard coordinate system
*      USAV      RD         Upstream U velocity component in radii/sec
*      VSAV      RD         Upstream V velocity component in radii/sec
*      ZSAV      RD         Upstream Z velocity component in radii/sec
*      XA12,...  RD         Deformation tensor
*

```

LOCAL VARIABLES

```

*      Name      Type      Description
*      .....
*      IARRAY    I          Array to store a data member record
*      IHDR      I          Array containing the length of the largest
*                          record and the number of records written
*      II        I          Do loop index
*      ISTAT     I          Status of calls to data member routines
*      ITYPE     I          Indicator of user parameter type
*      JJ        I          Do loop index
*      LPOUT     I          Logical unit to write
*

```

```

*      MEXIST      I      Indicator of existance of data member
*      NEL         I      Indicator of number of elements in user
*                      parameter
*      NOPIN1      RD      Array containing data member name of ABL output
*                      file
*      NOPIN2      RD      Array containing data member name of ROT output
*                      file
*      NWRDS       I      Number of words read in from data member record
*      PI          RD      3.14159...
*      RARRAY      RD      Storage area for real variables being read in fr
*                      data member record

```

OUTPUT

COMMON BLOCKS

NOPCA - see NOPMAN

NOPCB - see NOPMAN

FUNCTIONS

1. To input variables for NOP.
2. To input variables from FM ROT.
3. For homogenous case read in deformation tensor and calculate axial mach number, flow mach number and rms turbulence velocity.

SUBPROGRAMS CALLED

MMCLOS, MMGETR, MMOPRD, MMVUM, NEUTRAL, STABLE, UNSTAB, XFETCH, XSTORE, XGETP, XASKP

CALLING SUBPROGRAM

NOPMAN

ERRORS

NON-FATAL

1. Error finding user parameter in table
2. Error in opening data member
3. Error reading in record from data member

FATAL

none

ENTRY

Input values from data member ROTNOP(NOPIN1)

If L > 0 call STABLE

If L < 0 call UNSTAB

If L = 0 call NEUTRL

Calculate vertical component of the rms turbulence normalized by the stream velocity

Input data member ROTNOP(ROTOT1)

If IH=0 read in deformation tensor

EXIT

* ROUTINE - NOPPX

* PURPOSE - To take the cross product of column vectors N2 and N3
* of E and place the result in column N1.

* AUTHOR - Roy K. Amiet

* INPUT

* ARGUMENTS

Name	Type	Description
NOPIN2	RD	Array containing data member name
F1	RD	Observer frequency
RCP	RD	Radial point
TH	RD	Polar angle of observer
PH	RD	Angle of flight Mach number

* COMMON BLOCK

* NOPCA

Name	Type	Description
CL	RD	Chord/turbulence integral length scale
BN	RD	Blade number
COC	RD	Sound speed/chord
R1C	RD	Far-field distance/chord
RPS	RD	Revolutions/second
DXDZ	RD	Deformation tensor
ZM	RD	Axial Mach number
FM	RD	Flight Mach number in rotor plane
UU	RD	RMS turbulence velocity/axial velocity

* COMMON BLOCK

* NOPCB

Name	Type	Description
J	I	Number of azimuthal integration points
IH	I	Specifies homogenous or inhomogenous calculation

* OUTPUT

* ARGUMENT

Name	Type	Description
P2	RD	Pressure averaged around azimuth
NP1	I	Counter for upward summation in NTITRB subroutine
NM1	I	Counter for downward summation in NTITRB

```

*
*           N           I           subroutine
*           Counter for rescaling of CVT in NTITRB
*           subroutine

```

LOCAL VARIABLES

Name	Type	Description
TM	RD	Local tip Mach number
AJ	RD	Float J
DEL	RD	Azimuthal step size
C	RD	Cosine theta
S	RD	Sine theta
C4	RD	Cosine psi
S4	RD	Sine psi
QM	RD	Expression in analysis
BFZ2	RD	Expression in analysis
SQ1	RD	Expression in analysis
RER	RD	Retarded radius/actual radius
SUM	RD	Sum of azimuthal spectral contributions
G	RD	Azimuthal angle gamma
I	I	DO loop counter
C2	RD	Cosine gamma
S2	RD	Sine gamma
C5	RD	Cosine (gamma + psi)
S5	RD	Sine (gamma + psi)
ALP	RD	Angle alpha
C1	RD	Cosine alpha
S1	RD	Sine alpha
RM	RD	Mach number component along chord
C3	RD	Cosine of angle phi in analysis
X	RD	Observer coordinate
Y	RD	Observer coordinate
Z	RD	Observer coordinate
SG	RD	Modified radius
FP	RD	Frequency measured on blade
XK	RD	Value of x wavenumber
YK	RD	Value of y wavenumber
T	RD	Blade passage time
T1	RD	Time between eddy chops
XX	RD	Specific value of x in analysis
YY	RD	Specific value of y in analysis
ZZ	RD	Specific value of z in analysis
T2	RD	Time T1 plus propagation time difference
CVT	RD	Step size for summation over wavenumber
ZK0	RD	Initial value of wavenumber in summation
AD	RD	Contribution to sum of particular azimuthal station

SUBPROGRAMS CALLED

NOPNI NOPLFT

CALLING PROGRAMS

NOPMAN

ERRORS

```

*      NON-FATAL
*      1. Error reading in data member record
*      FATAL
*      none
*
*      ENTRY
*      Calculate TM, the local tip Mach number
*      Float J
*      Calculate DEL, the azimuthal step size
*      C, S and C4, S4, are the cosine and sine of theta and psi
*      respectively
*      QM is a factor appearing in the analysis
*      BFZ2 is a Prandtl-Glauert factor
*      SQ1 is a factor appearing in the analysis
*      RER is the observer retarded distance/actual distance
*      Initialize NP1,....G
*      DO 50 I=1,J      Integration over azimuthal angle gamma
*      Increment gamma
*      Find cosine and sine of gamma and gamma + psi respectively
*      Calculate ALP, the angle of the rotor blade wrt the rotor plane
*      Calculate C1 and S1, the cosine and sine of alpha
*      Calculate RM, the Mach number of rotor segment wrt to fluid
*      Calculate C3, the cosine of an angle in the analysis
*      Calculate observer coordinates in rotor fixed coordinates
*      Calculate sigma, a modified observer distance
*      Calculate FP, the frequency on the blade
*      Calculate XK and YK, the x and y wavenumbers
*      Calculate T, the time between blade passes
*      Calculate T1, the time between eddy intersections
*      Calculate XX, YY, ZZ which are X, Y, Z values
*      Calculate CVT which is 2*P1/eddy passing distance Z
*      Calculate ZK0, the initial radian frequency in the summation
*      Call turbulence summation subroutine
*      Call airfoil response subroutine
*      Increment counters
*      Contribution to spectrum from azimuthal integration
*      Summation over azimuthal spectrum
*      End DO
*      Multiply by remaining factors
*      EXIT

```

*

ROUTINE - NOPCRS

*

*

PURPOSE - To take the cross product of column vectors N2 and N3 of E and place the result in column N1.

*

*

AUTHOR - Roy K. Amiet

*

*

INPUT

*

*

ARGUMENT

*

Name	Type	Description
------	------	-------------

*

*

*

E	RD	3x3 rotation matrix.
N1	I	Column into which the cross product is to be placed.

*

*

OUTPUT

*

*

ARGUMENT

*

Name	Type	Description
------	------	-------------

*

*

E	RD	Unit vectors along coordinates
---	----	--------------------------------

*

*

*

LOCAL VARIABLES

*

*

Name	Type	Description
------	------	-------------

*

*

N2,N3	I	Column vectors for which the cross product is found.
-------	---	--

*

EM1M	RD	Normalizes the output to a magnitude of 1.
------	----	--

*

*

SUBPROGRAMS CALLED

*

None

*

*

CALLING PROGRAMS

*

NOPKVC

*

*

ERRORS

*

None

*

*

ENTRY

*

*

Calculate N2 and N3 so that N1, N2, N3 are in cyclic permutation. Calculate cross product of column vectors N2 and N3; place result in column N1.

*

Find the magnitude of vector N1.

*

Normalize vector N1.

*

EXIT

```

*      ROUTINE - NOPKVC
*
*      PURPOSE - To calculate effect of rapid distortion on turbulence
*                spectrum.
*
*      AUTHOR - Roy K. Amiet
*
*      INPUT
*
*      ARGUMENT
*
*      Name      Type      Description
*      .....
*      DK         RD         Wavevector
*      DXDZ       RD         Deformation tensor
*      VN         RD         Unit vector normal to blade
*
*      OUTPUT
*
*      ARGUMENT
*
*      Name      Type      Description
*      .....
*      ED         RD         Three coordinate vectors downstream of
*                            contraction.
*      EU         RD         Three coordinate vectors upstream of
*                            contraction.
*      DKM        RD         Magnitude of downstream wavevector.
*      DKUK       RD         Ratio of downstream to upstream wavevectors.
*      UQDQ       RD         Ratio of upstream to downstream turbulent
*                            velocities.
*
*      LOCAL VARIABLES
*
*      Name      Type      Description
*      .....
*      F(I)      RD         For temporary storage of EU(I,3).
*      AFI       RD         Magnitude of wavevector, to be used for
*                            normalization.
*
*      FUNCTIONS
*      1. To calculate the effect of rapid distortion on the wavevector
*         and Fourier component amplitude
*
*      SUBPROGRAMS CALLED
*      NOPCRS
*
*      CALLING PROGRAMS
*      MOPNI
*
*      ERRORS
*      NONE
*
*      ENTRY
*      Find magnitude of wavevector.

```

```

*      DO I = 1,3
*          Set third column of ED equal to wavevector direction.
*          Set second column of ED equal to blade normal.
*      END DO
*      Find cross product of first two vectors
*      Find cross product of previous result with third vector of ED.
*      DO I=1,3
*          DO J=1,3
*              Initialize EU
*              DO K=1,3
*                  Take product of ED with deformation matrix to find EU.
*              END DO
*          END DO
*      END DO
*      Store third column of EU in F.
*      Find the magnitude of first column of EU.
*      Normalize the first column of EU
*      Find the cross-product of columns 1 and 2 of EU.
*      Find cross-product of previous result with third vector of EU.
*      Calculate ration of downstream to upstream wavevector magnitude.
*      Calculate ratio of upstream to downstream turbulent velocities.
*      EXIT
***

```

```

*
* ROUTINE - NOPFNL
*
* PURPOSE - To calculate the Fresnel integrals C and S. Ref. Abromovitz
* and Stegun, p 302.
*
* AUTHOR - Roy K. Amiet
*
* INPUT
*
* ARGUMENT
*
* Name Type Description
* .....
* X RD Fresnel integral argument
*
* OUTPUT
*
* ARGUMENT
*
* Name Type Description
* .....
* E C Fresnel integrals in form C - iS
*
* LOCAL VARIABLES
*
* Name Type Description
* .....
* G C Intermediate variables from Abromovitz and Stegun.
* H C To rotate G in complex plane.
*
* FUNCTIONS
* 1. To calculate a value for the Fresnel integrals
*
* SUBPROGRAMS CALLED
* None
*
* CALLING PROGRAMS
* NOPLFT
*
* ERRORS
* NONE
*
* ENTRY
* Calculate G from Abromovitz and Stegun equations p 302.
* Calculate H.
* Calculate E = C - iS following Abromovitz and Stegun.
* EXIT
***

```

* ROUTINE - NOPLFT

* PURPOSE - To calculate the airfoil gust response function.

* AUTHOR - Roy K. Amiet

* INPUT

* ARGUMENT

Name	Type	Description
X	RD	Chordwise distance
SG	RD	Far-field distance modified by Prandtl-Glauert factor
RM	RD	Chordwise Mach number component
XK	RD	Chordwise wavenumber
YK	RD	Spanwise wavenumber

* OUTPUT

* ARGUMENT

Name	Type	Description
GL2	RD	Square of effective lift, including noncompactness

* LOCAL VARIABLES

Name	Type	Description
B2	RD	Column vectors for which the cross product is found.
UM	RD	Normalizes the output to a magnitude of 1.
RMI	RD	Similarity Mach number for skewed gusts
UMI	RD	Specifies use of low or high frequency solution.
T2	RD	Intermediate dummy variable.
CM	RD	Magnitude of E.
E	RD	Complex representation of Fresnel integrals; $C - iS$

* FUNCTIONS

* 1. To calculate the airfoil response function for given values of the wavenumbers

* SUBPROGRAMS CALLED

* NOPFNL

* CALLING PROGRAMS

* NOPPY

* ENTRY

* Calculate Prandtl-Glauert factor B2.

* UM is proportional to airfoil chord/acoustic wavelength.

* RMI is Graham's similarity Mach number for skewed gusts.


```
*      UMI used in following line for branching test.
*      Case of (UMI -.75) NEG, ZERO, POS
*      NEG: Use modified Sears function
*      ZERO: Use modified Sears function
*      POS: Use high reduced frequency solution
*           Call Fresnel integrals
*           Find absolute value
*           Calculate square of effective lift
*      End case.
*      EXIT
***
```

*
*
* ROUTINE - NCPNI
*

* PURPOSE - To take the cross product of column vectors N2 and N3 of
* E and place the result in column M1
*

* AUTHOR - Roy K. Amiet
*

*
* INPUT
*

* ARGUMENT
*

Name	Type	Description
CL	RD	Chord/turbulence integral length scale
CVT	RD	Step size for summation over wavenumber
XK	RD	X wavenumber component
YK	RD	Y wavenumber component
ZK	RD	Z wavenumber component
ALP	RD	Angle alpha
G	RD	Gamma
DXDZ	RD	Deformation tensor; 9 components

*
* OUTPUT
*

* ARGUMENT
*

Name	Type	Description
SVV	RD	Pressure averaged around azimuth
NP	I	Counter for upward summation in NTITRB subroutine
NM	I	Counter for downward summation in NTITRB subroutine
N	I	Counter for rescaling of CVT in NTITRB subroutine

* LOCAL VARIABLES
*

Name	Type	Description
EK	RD	Constant in Karman spectrum
DK	RD	Wavevector; 3 components
C1	RD	Cosine alpha
S1	RD	Sine alpha
C2	RD	Cosine gamma
S2	RD	Sine gamma
VN	RD	Normal to blade
ROT	RD	Expression in analysis
DXDZR1	RD	Intermediate deformation matrix
DXDZR	RD	Final deformation matrix after rotation
CVT1	RD	Dummy for CVT
ED	RD	Downstream unit vectors parallel to axes
EU	RD	Upstream unit vectors parallel to axes
DKM	RD	Wavevector amplitude downstream at rotor face
DKUK	RD	Ratio of downstream to upstream wavevector amplitudes

```

*          UQDQ      RD      Ratio of upstream to downstream velocity
*          amplitudes
*          XKUO      RD      Upstream x value of wavevector; initial value
*          YKUO      RD      Upstream y value of wavevector; initial value
*          XYO       RD      Expression in Karman spectrum; initial value
*          DKM1      RD      Wavevector amplitude downstream at rotor face
*          DKUK1     RD      Ratio of downstream to upstream wavevector
*          amplitudes
*          UQDQ1     RD      Ratio of upstream to downstream velocity
*          amplitudes
*          XKU       RD      Upstream x value of wavevector
*          YKU       RD      Upstream y value of wavevector
*          ZKU       RD      Upstream z value of wavevector
*          XY        RD      Expression in Karman spectrum
*          DN        RD      Denominator in Karman spectrum
*          DEL1      RD      Temporary variable for testing end of iteration
*          AN        RD      Float N
*          ZK1       RD      Value of x wavenumber
*          ZK2       RD      Value of y wavenumber

```

SUBPROGRAMS CALLED

NOPKVC

CALLING PROGRAM

NOPPX

ERRORS

NONE

ENTRY

```

* Calculate ke which equals  $0.7468342/L$  equals  $0.373417(c/L)/b$ ;
* Define wavevector in airfoil fixed coordinate system; x along
* chord, y along span, and z along normal.
* Sine and cosine of angles alpha and gamma.
* Calculate normal to airfoil in same coordinate system as for DK.
* Calculate rotation matrix. The first three components give the
* chord direction, the second three give the spanwise
* direction and the third three give the normal direction.

```

```

* DO 50 I=1,3

```

```

*   DO 30 J=1,3

```

```

*     Initialize DXDZR1

```

```

*     DO 90 K=1,3

```

```

*       Calculate DXDZR1

```

```

*     END DO

```

```

*   END DO

```

```

* END DO

```

```

* DO 70 I=1,3

```

```

*   DO 60 J=1,3

```

```

*     Initialize DXDZR

```

```

*     DO 91 K=1,3

```

```

*       Calculate DXDZR

```

```

*     END DO

```

```

*   END DO

```

```

* END DO

```

```

* Introduce dummy for CVT

```

```

*      Call deformation program WOPKVC
*      Calculate denominator for upstream turbulence with  $kz = 0$ .
*          This will be used for comparison later in program.
*      Make CVT as large as possible without losing accuracy. Increase
*          by factors of two and test size of DELI.
*      Initialize sum variable, SVV.
*      Begin summation with minimum but still positive value of ZK after
*          subtracting integer number of CVT values.
*      Initialize counters NP and NM for number of steps up and down in kz.
*      Sum over increasing values of ZK.
*          Increment upward summation counter
*          Set third wavevector component
*          Call deformation program WOPKVC
*          Calculate upstream values of three wavevector components
*          Calculate XY, an intermediate variable
*          Calculate DN, the denominator of the Karman spectrum
*          Add to summation, SVV
*          Check for excessive summations
*          Increment z wavevector component
*          Check to see how large the denominator has become.
*      End upward summation
*      Sum over decreasing values of ZK.
*          Increment downward summation counter
*          Decrement z wavevector component
*          Set third wavevector component
*          Call deformation program WOPKVC
*          Calculate upstream values of three wavevector components
*          Calculate XY, an intermediate variable
*          Calculate DN, the denominator of the Karman spectrum
*          Add to summation, SVV
*          Check for excessive summations
*          Check to see how large the denominator has become.
*      End downward summation
*      Multiply SVV by remaining factors
*      EXIT
***

```

Appendix A: Computer Program for Noise Produced by Rotor-Turbulence Interaction

A computer program implementing the algorithm discussed in the Theory Manual for Noise Calculation is given in the Computer Listings to follow. Computer Listing 1 is the main executive portion of the program; it prompts for inputs and prints the output. It also performs the integration over the rotor span.

The inputs to the program, including the symbols used in the program, are:

CL	c/L = chord/turbulence length scale
BN	Blade number
C0C	c ₀ /c = sound speed/chord
RC	Blade radius/chord
R1C	r/c = far-field distance/chord
RPS	Revolutions/sec
ZM	M _z = axial Mach number
FM	Flow Mach number in rotor plane
UU	$\sqrt{u^2/V_z}$
TH	θ = observer angle wrt z axis; observer in x,y plane
SUMS	Number of terms in azimuthal summation; N in equation (B3)
PSI	ψ = angle of M _f wrt z axis; M _f is positive inward as in figure 1
DH	Frequency step size in fractions of a harmonic
AL1	Initial harmonic number
L2	Number of frequency steps

The numerical constant 203.95 occurring in the expression for PSD is obtained by introducing equation (82) into equation (63) and multiplying by the blade number. This gives

$$S_{pp}(\omega_0, \underline{x}) = \frac{B}{2\pi} \int_0^{2\pi} \overline{u^2} \left(\frac{\omega}{\omega_0}\right)^2 \left(\frac{\omega z_3 \rho_0 b}{c_0 \sigma_3^2}\right)^2 \pi U_b d |\underline{L}|^2 b^2 F dy \quad (A1)$$

where

$$F \equiv \frac{2\pi}{b^2 u^2 z} \sum_{n=-\infty}^{\infty} \Phi_{ww}(K_x, K_y, K_z^{(n)})$$

Atmospheric pressure P₀ = 10⁶/0.987 dynes/cm² and reference pressure P_r = 0.0002 dynes/cm².

S_{pp} must be multiplied by 4π to convert from a two sided -∞ < ω < ∞ to a one sided 0 < ω < ∞ spectrum and to convert to a unit Hertz rather than a unit radian frequency of measurement. Using the relations

$$\bar{K}_x = \omega b / U_b \quad c_0^2 = \gamma P_0 / \rho_0 \quad (A2)$$

this can be written (where γ = 2πn/N)

$$G_{pp}(f_0)/P_r^2 = \frac{1}{2} \left(\frac{\gamma \pi P_0}{P_r} \right)^2 \left\{ B \frac{s}{c} \frac{\overline{u^2}}{V_z^2} M_z^2 \frac{c}{c_0 N} \sum_{n=1}^N M_b^3 \left(\frac{z_3 c \omega_0}{\sigma_3^2 \omega} \right)^2 (bK_x)^2 |L|^2 F \right\} \quad (A3)$$

Converting to dB,

$$10 \log_{10} \left[\frac{1}{2} \left(\frac{\gamma \pi P_0}{P_r} \right)^2 \right] = 203.95 \quad (A4)$$

The outputs of the program are:

H Frequency of sound expressed in multiple of blade passage harmonic
 F1 Frequency of sound in Hz
 PSD Spectrum level in dB (per unit Hz)
 NP1,NM1,N Counters for certain of the summations for use in diagnosis of output

The programs in the following appendices are standard Fortran code with added line numbers for reference in the documentation. This allows more detailed comments to be used without deleteriously affecting the ability to easily read the code.

The program listing here is for an homogenous turbulence in the rotor plane. This can be easily extended to the nonisotropic case by inputting the deformation tensor at each point of the rotor plane rather than just once. The turbulence spectrum at each point of the rotor plane is then calculated from a rapid contraction of an isotropic turbulence using this deformation tensor. The changes to the main program and one subroutine for this generalization to the nonhomogeneous case are listed below.

Changes to main program:

<u>Line #</u>	<u>Code</u>
12	1 'RADIUS/C, FAR-FIELD/C, RPS, IH' /)
24	IF (IH .EQ. 0) READ(1,*) ((DXDZ(I,J), I=1,3), J=1,3)
25	IF (IH .EQ. 0) WRITE(*,200) ((DXDZ(I,J), J=1,3), I=1,3)
26	IF (IH .EQ. 0) WRITE(2,200) ((DXDZ(I,J), J=1,3), I=1,3)
28	IF (IH .EQ. 0) CLOSE(1)
59	1 P2,NP1,NM1,N,IH)

In the subroutine SPX, change the first line of the subroutine to accept the new variable IH and add the following line between lines 46 and 47:

```

1            SUBROUTINE PX(F1,ZM,CL,BN,C0C,UU,RC,R1C,RPS,FM,TH,J,PSI,DXDZ,
46a            IF (IH .EQ. 1) READ(1,*) ((DXDZ(I,J), J=1,3), I=1,3)

```

In the above code the parameter IH is an input designating whether a homogeneous or inhomogeneous calculation should be performed. If IH = 0 is input, homogeneous turbulence is assumed. If IH = 1 is input, inhomogeneous turbulence is assumed, and the above read and write statements are deferred to the subroutine SPX.

```

*      PXFINI 12/3/84 R. K. Amiet Integrates over span.
1      DIMENSION DXDZ(3,3)
2      CHARACTER*10 FNAME
3      CHARACTER*10 FNAME1
4      WRITE(*,500)
5      500  FORMAT(' Turbulence ingestion program with integration over'
6            1  ' span'/' and nonisotropic turbulence. R. K. Amiet 12/84'/)
7      WRITE(*,'(A\)' ) ' OUTPUT FILE NAME - '
8      READ(*,'(A)' ) FNAME1
9      OPEN(2,FILE=FNAME1,STATUS='NEW')
10     30  WRITE(*,100)
11     100  FORMAT('/' INPUT C/L, BLADE NO., C0/C,
12           1  ' RADIUS/C, FAR-FIELD/C, RPS'/)
13     READ(*,*) CL, BN, C0C, RC, R1C, RPS
14     TM1 = 2.*3.141593*RPS*RC/C0C
15     WRITE(*,300) TM1, CL, BN, C0C, RC, R1C, RPS
16     WRITE(2,300) TM1, CL, BN, C0C, RC, R1C, RPS
17     300  FORMAT('/' M TIP = ',F4.3,'          CHORD/TURB SCALE = ',F7.4/
18           1  ' BLADE NO. = ',F4.0,'          SOUND SPEED/CHORD = ',F7.1/
19           1  ' RADIUS/CHORD = ',F5.1,' FAR-FIELD/CHORD = ',
20           1  ' F6.1/' REV/SEC = ',F5.1/)
21     10  WRITE(*,'(A\)' ) ' INPUT FILE NAME - '
22     READ(*,'(A)' ) FNAME
23     OPEN(1,FILE=FNAME,STATUS='OLD')
24     READ(1,*) ((DXDZ(I,J), I=1,3), J=1,3)
25     WRITE(*,200) ((DXDZ(I,J), J=1,3), I=1,3)
26     WRITE(2,200) ((DXDZ(I,J), J=1,3), I=1,3)
27     200  FORMAT(1X,3F5.2)
28     CLOSE(1)
29     20  WRITE(*,400)
30     400  FORMAT('/' INPUT MZ, FM, UU, THETA, SUMS, PHI'/)
31     READ(*,*) ZM, FM, UU, TH, J, PH
32     WRITE(*,900) ZM, UU, TH, FM, J, PH
33     WRITE(2,900) ZM, UU, TH, FM, J, PH
34     900  FORMAT(' MZ = ',F4.3,' UU = ',F6.3,' THETA = ',F5.0/
35           1  ' MF = ',F4.3,' SUMS = ',I4,' PSI = ',F5.1/)
36     70  WRITE(*,700)
37     700  FORMAT('/' INPUT' /
38           1  ' BEGINNING HARMONIC:           If < 0, go to matrix input.'/
39           1  ' FRACTIONAL HARMONIC SPACING: If < 0, go to previous input.'/
40           1  ' NUMBER STEPS:                 If < 0, go to first input.'/)
41     READ(*,*) AL1, DH, L2
42     IF (AL1 .LT. 0.) GO TO 10
43     IF (DH .LT. 0.) GO TO 20
44     IF (L2 .LT. 0) GO TO 30
45     DF = RPS*BN*DH
46     WRITE(*,800)
47     WRITE(2,800)
48     800  FORMAT(/2X,'HRMNC',5X,'FREQ',6X,'PSD',4X,'SM P',1X,'SM M'/)
49     F1 = (AL1/DH-1.)*DF
50     IF (L2 .EQ. 0) L2=1

```

Computer Listing 1: Executive program for turbulence ingestion.

```

51      DO 60 K=1,L2
52      F1 = F1 + DF
53      RCP = RC*1.05
54      SUM = 0.
55      DO 22 I2=0,19
56      RCP = RCP - .05*RC
57      TM = TM1*RCP/RC
58      CALL PX(F1,ZM,CL,BN,C0C,UU,RCP,R1C,RPS,FM,TH,J,PH,DXDZ,
59          1          P2,NP1,NM1,N)
60      IF (I2 .EQ. 0) P2 = P2/2.
61      SUM = SUM + P2
62      22 CONTINUE
63      PSD = 10.*ALOG10(SUM*RC*.05)
64      H = F1/(RPS*BN)
65      WRITE(*,600) H, F1, PSD, NP1, NM1, N
66      WRITE(2,600) H, F1, PSD, NP1, NM1, N
67      600 FORMAT(1X,F6.1,1X,F8.1,1X,F9.2,1X,I5,2I6)
68      60 CONTINUE
69      GO TO 70
70      END

```

<u>Line #</u>	<u>Comment</u>
7-9	Prompt for a filename into which to write the calculated results
10-13	Prompts for inputs
14	Calculation of tip Mach number
15-20	Prints the input quantities for checking
21-23	Prompt for input containing the deformation tensor values
24-28	Read and write the values for the deformation tensor
29-35	Prompt for more input parameters; writes out values to file
36-44	Prompt for final input values; if any are negative the program returns to one of the previous input prompts
45	DF = frequency step size
46-48	Prints headings for the eventual printout
49	Initialize the frequency variable
50	Input of zero for L2 gives one iteration with this line
51-69	Stepping through frequency range
52	Increment frequency variable
53-54	Initialize radius and summation variables
55-63	Integration over radius
56	RCP = local radius
57	TM = M_t local tip Mach number
58-59	Call routine for summation over γ
60	Divide the first term in the summation by 2; the last term also should halved, but since it approaches zero, it needn't be explicitly set to zero.
61	Perform radial summation
63	Introduce remaining factors in equation (69)
64	Calculate harmonic number
65-67	Write outputs

Computer Listing 1: Executive program for turbulence ingestion.

Appendix B: Subroutine Calculating the Main Problem Parameters and Integrating over Azimuth

This subroutine is called by the main turbulence ingestion program in Appendix A. It calculates geometry and integrates over azimuthal angle. The inputs to the subroutine are:

F1	Observer frequency
ZM	Axial Mach number; see figure 1
CL	Chord/turbulence integral length scale
BN	Blade number
COC	Sound speed/chord
UU	RMS turbulence intensity/axial velocity
FC	Local blade radius/chord
R1C	Far-field distance/chord
RPS	Revolutions per second
FM	Flight Mach number in rotor plane; see figure 1
TH	Polar angle of observer; see figure 1
J	Number of azimuthal integration points
PSI	Angle of flight Mach number with the y axis; see figure 1
DXDZ	Deformation tensor

The outputs are:

P2	Sound level from a radial blade segment
NP1,NM1,N	Counters used in the summations; used for diagnostic purposes

The program calls the subroutines TRBNI and LEFF, the turbulence and the airfoil response calculations. The subroutine performs the azimuthal integration over θ in Eq. (63).

```

• Subroutine SPX
• Program written by R. K. Amiet.
1 SUBROUTINE PX(F1,ZM,CL,BN,C0C,UU,RC,R1C,RPS,FM,TH,J,PSI,DXDZ,
2 P2,NP1,NM1,N)
3 DIMENSION DXDZ(3,3)
4 PI = 3.14159
5 TM = 2.*PI*RPS*RC/C0C
6 AJ = J
7 DEL = 360./AJ
8 C = COS(TH/57.2958)
9 S = SIN(TH/57.2958)
10 C4 = COS(PSI/57.2958)
11 S4 = SIN(PSI/57.2958)
12 QM = FM*S*S4+ZM*C
13 BFZ2 = 1.-FM**2-ZM**2
14 SQ1 = SQRT(QM**2+BFZ2)
15 RER = (SQ1+QM)/BFZ2
16 NP1 = 0
17 NM1 = 0
18 SUM = 0.
19 G = 90. - DEL
20 DO 50 I=1,J
21 G = G + DEL
22 C2 = COS(G/57.2958)
23 S2 = SIN(G/57.2958)
24 C5 = COS((G+PSI)/57.2958)
25 S5 = SIN((G+PSI)/57.2958)
26 ALP = 57.2958*ATAN2(ZM, TM+FM*C5)
27 C1 = COS(ALP/57.2958)
28 S1 = SIN(ALP/57.2958)
29 RM = SQRT(ZM**2 + (TM + FM*C5)**2)
30 C3 = C*S1 - S*C1*S2
31 X = R1C*(TM*RER*C1 - C3)
32 Y = R1C*(S*C2 + FM*RER*S5)
33 Z = R1C*(C*C1 + S*S1*S2 + TM*RER*S1)
34 SG = SQRT(X**2+(1.-RM**2)*(Y**2+Z**2))
35 FP = F1*(1.+TM*(S2*S-FM*RER*C5)/SQ1)
36 XK = PI*FP/(C0C*RM)
37 YK = PI*FP*Y/(SG*C0C)
38 T = 2.*PI*RC/(TM*C0C*BN)
39 T1 = T*TM*S1*C1/ZM
• Next line added to make peaks occur at bpf when ZM = 0.
40 T1 = T/(1.+ MF*C5/TM)
41 XX = TM*(T-T1)
42 YY = T1*FM*S5
43 ZZ = T*TM*C0C*S1
44 T2 = T1 + XX*(RM-X/SG)/(1.- RM**2) + YY*Y/SG
45 CVT = PI/ZZ
46 ZK0 = PI*T2*F1/ZZ
47 CALL TRBNI(CL,CVT,XK,YK,ZK0,ALP,G,DXDZ,SVV,NP,NM,N)

```

Computer Listing 2: Subroutine for calculating principle parameters in problem

```

48      CALL LFT(X,SG,RM,XK,YK,GL2)
49      NP1 = NP1 + NP
50      NM1 = NM1 + NM
51      AD = GL2*SVV*RM*(RM*Z*FP*XK/(F1*SG**2))**2
52      SUM = SUM + AD
53      50 CONTINUE
54      P2 = 2.48E20*SUM*BN*(UU*ZM)**2/(C0C*AJ)
55      RETURN
56      END

```

<u>Line #</u>	<u>Comment</u>
1-2	Inputs
5	$TM = M_t =$ local tip Mach number
6	Float J
7	DEL = azimuthal step size
8-11	C, S and C4, S4 = cosine and sine of θ and ψ respectively
12	$QM = M_s \cos \theta$; Eq. (43)
13	$BFZ2 = 1 - M_s^2$; Eq. (43)
14	$SQ1 = (1 - M_s^2 \sin^2 \theta)^{1/2}$
15	$RER = r_e/r$; Eq. (42)
16-19	Initialize variables
20-53	Integration over azimuthal angle γ
21	Increment γ
22-25	C2, S2 and C5, S5 = cosine and sine of γ and $\gamma + \psi$ respectively
26	$ALP = \alpha$; Eq. (34)
27-28	C1, S1 = cosine and sine of α
29	$RM = M_b$; Eq. (36)
30	$C3 = \cos \phi$; Eq. (49)
31-33	X, Y, Z = x_3, y_3, z_3 ; Eq. (48)
34	$SG = \sigma$
35	FP = frequency on blade; Eq. (55)
36-37	XK, YK = specific wavenumbers \bar{K}_x, \bar{K}_y ; Eqs. (9), (14)
38	T = time between blade passes
39-40	T1 = time between eddy intersections; Eq. (62) for line 39. Equation (32) is not appropriate for eddies stretched in axial direction; for this case the diagonal distance in figure 3 is not appropriate; given here is the result for an eddy of infinite axial length corresponding to the limit $M_z \rightarrow 0$; Eq. (62).
41-43	XX, YY, ZZ = X, Y, Z in Eqs. (62), (64)
44	$CVT = 2\pi/Z =$ step size in Eq. (70)
45	$ZK0 = \omega_0 T_2/Z =$ initial radian frequency in Eq. (70)
46	$T2 = T_2$; Eq. (65)
47	Call turbulence summation subroutine
48	Call airfoil response subroutine
49-50	Increment counters
51	Contribution to spectrum from azimuthal integration; Eqs. (50) and (69)
52	Summation over azimuthal spectrum
54	Multiplication by remaining factors in Eq. (69)

Computer Listing 2: Subroutine for calculating principle parameters in problem

Appendix C: Subroutine for Summing over the Turbulence Spectrum for Blade to Blade Correlation

This subroutine calculates the summation in Eq. (69) over the turbulence spectrum. The output SVV of this program is

$$SVV = \frac{2\pi}{b^2 u^2 Z} \sum_{n=-\infty}^{\infty} \Phi_{ww}(\lambda, K_y, K_z^{(n)}) \quad (E1)$$

The inputs to the program and the equivalent symbols used in the report are

$$\begin{aligned} CL &= c/L & CVT &= 2\pi b/Z \\ XK &= K_x & YK &= K_y \\ ZK0 &= \omega_0 T_2/Z & DXDZ(I,J) &= \partial x_i / \partial \xi_j \quad (x_i = \text{precontraction coordinate}; \xi_j = \text{post contraction coordinate}) \end{aligned}$$

Other parameters in the program are: $EK = k_e b$ where k_e is given in Eq. (32). CVT is the step size in the summation. Since the spectrum is written in a form with the wavenumbers k_x and k_y normalized by k_e , CVT must also be so normalized. Note that this changes CVT in the main program, but this is of no concern since CVT is used only in this subroutine.

The summation over n is over the range $\pm\infty$. In numerically carrying out this summation it is easiest to begin where the individual terms are maximum and sum to either side of this point until the terms become negligible. Thus, the integer N is the optimum value of n at which to begin the summation. The optimum value would be $n = 0$ except for the offset $\omega_0 T_2/Z$ occurring in $K_z^{(n)}$ (see Eq. (69)).

If the step size CVT is too small, very many terms in the summation would be required. For this case, the summation can be replaced by an integral. For the case of an isotropic turbulence the integral can be carried out in closed form as in Eq. (31).

The parameters ZK1 and ZK2 represent $K_z^{(n)}/k_e$. ZK1 is used for increasing values of n and ZK2 for decreasing values.

The integers NP and NM count the number of summation steps in the upward and downward directions respectively. If either goes over 100 the summation is terminated, although this case has never been encountered. If the output specifies that NP or NM reached the value of 100, further checking should be done to ensure that a sufficient number of steps were taken. Generally the summation is terminated when the term DN (denoting the denominator in Eq. (32)) becomes greater than 200 times the initial value of the denominator.

Finally, the coefficient $0.11561 = 55 \Gamma(5/6) / [9\sqrt{\pi} \Gamma(1/3) 4\pi]$. The factor 4π comes from Eq. (30) and the remaining factors come from the expression for I.

```

• EDDYNI.FTN; Summation over turbulence spectrum.
* Written by R. K. Amiet; final version 1985
1 SUBROUTINE TRBNI(CL,CVT,XK,YK,ZK,ALP,G,DXDZ,SVV,NP,NM,N)
2 DIMENSION EU(3,3), ED(3,3), VN(3), DK(3), DXDZ(3,3),
3 1 DXDZR(3,3), ROT(3,3), DXDZR1(3,3)
4 EK = .373417*CL
5 DK(1) = XK
6 DK(2) = YK
7 DK(3) = 0.
8 C1 = COS(ALP/57.2958)
9 S1 = SIN(ALP/57.2958)
10 C2 = COS(G/57.2958)
11 S2 = SIN(G/57.2958)
12 VN(1) = 0.
13 VN(2) = 0.
14 VN(3) = 1.
15 ROT(1,1) = C1*S2
16 ROT(2,1) = C2
17 ROT(3,1) = S1*S2
18 ROT(1,2) = -C1*C2
19 ROT(2,2) = S2
20 ROT(3,2) = -S1*C2
21 ROT(1,3) = -S1
22 ROT(2,3) = 0.
23 ROT(3,3) = C1
24 DO 50 I=1,3
25 DO 30 J=1,3
26 DXDZR1(I,J) = 0.
27 DO 90 K=1,3
28 DXDZR1(I,J) = DXDZ(I,K)*ROT(J,K) + DXDZR1(I,J)
29 90 CONTINUE
30 30 CONTINUE
31 50 CONTINUE
32 DO 70 I=1,3
33 DO 60 J=1,3
34 DXDZR(I,J) = 0.
35 DO 91 K=1,3
36 DXDZR(I,J) = DXDZR1(K,J)*ROT(I,K) + DXDZR(I,J)
37 91 CONTINUE
38 60 CONTINUE
39 70 CONTINUE
40 CVT1 = CVT
41 CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
42 XKU0 = EU(1,3)*DKM/DKUK
43 YKU0 = EU(2,3)*DKM/DKUK
44 XY0 = EK**2 + XKU0**2 + YKU0**2
45 D0 = XY0**2.83333
46 N = 0
47 10 N = N + 1
48 CVT = CVT1

```

Computer Listing 3: Subroutine for calculating summation over turbulence spectrum.

```

49      IF (N .GT. 1) CVT1 = 2.*CVT1
50      DK(3) = CVT1
51      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM1,DKUK1,UQDQ1)
52      XKU = EU(1,3)*DKM1/DKUK1
53      YKU = EU(2,3)*DKM1/DKUK1
54      ZKU = EU(3,3)*DKM1/DKUK1
55      XY = EK**2 + XKU**2 + YKU**2
56      DN = (XY + ZKU**2)**2.83333
57      DEL1 = ABS(1.- DN/D0)
58      IF (DEL1 .LT. .01) GO TO 10
59      SVV = 0.
60      N = ZK/CVT
61      AN = N
62      ZK1 = ZK - AN*CVT
63      ZK2 = ZK1
64      NP = 0
65      NM = 0
66      20 NP = NP + 1
67      DK(3) = ZK1
68      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
69      XKU = EU(1,3)*DKM/DKUK
70      YKU = EU(2,3)*DKM/DKUK
71      ZKU = EU(3,3)*DKM/DKUK
72      XY = EK**2 + XKU**2 + YKU**2
73      DN = (XY + ZKU**2)**2.83333
74      SVV = SVV + (XY - EK**2)/(UQDQ**2*DN)
75      IF (NP .GT. 100) GO TO 40
76      ZK1 = ZK1 + CVT
77      IF (DN .LT. D0*200.) GO TO 20
78      40 NM = NM + 1
79      ZK2 = ZK2 - CVT
80      DK(3) = ZK2
81      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
82      XKU = EU(1,3)*DKM/DKUK
83      YKU = EU(2,3)*DKM/DKUK
84      ZKU = EU(3,3)*DKM/DKUK
85      XY = EK**2 + XKU**2 + YKU**2
86      DN = (XY + ZKU**2)**2.83333
87      SVV = SVV + (XY - EK**2)/(UQDQ**2*DN)
88      IF (NM .GT. 100) GO TO 80
89      IF (DN .LT. D0*200.) GO TO 40
90      80 SVV = .11561*SVV*CVT*EK**.666667
91      RETURN
92      END

```

Computer Listing 3: Subroutine for calculating summation over turbulence spectrum.

<u>Line #</u>	<u>Comment</u>
1	Inputs
4	$k_e = 0.7468342/L = 0.373417(c/L)/b; 0.7468342 = \Gamma(5/6)\sqrt{\pi}/\Gamma(1/3).$
5-7	Define wavevector \underline{k} in coordinate system fixed to airfoil; x along chord, y along span, and z along normal. k_z will take different values.
8-11	Sine and cosine of angles α and γ .
12-14	Normal to airfoil in same coordinate system as in lines 5-7.
15-23	Rotation matrix; $\partial\underline{x}_1/\partial\underline{x}_3$ with the definitions in Eq.(47). The first three components give the chord direction, the second three give the spanwise direction and the third three give the normal direction. 21 VN(1) written in the unrotated \underline{x}_1 system. 22 VN(2) written in the unrotated \underline{x}_1 system. 23 VN(3) written in the unrotated \underline{x}_1 system.
24-39	Calculate deformation tensor in coordinate system defined in lines 5-7. First premultiply, then postmultiply, DXDZ by ROT.
40-45	Denominator for upstream turbulence with $k_z = 0$. Used for comparison in lines 77 and 89.
46-58	If CVT is too small, will take too many summations. Make CVT larger until start getting significant variation in either the ratio of wavevectors between downstream and upstream.
59	Initialize sum variable.
60-63	Begin with minimum but still positive value after subtracting integer number of CVT values.
64-65	Initialize counters for number of steps up and down in k_z .
66-77	Sum over increasing values of k_z . Lines 69-71 calculate upstream values of wavevector. These expressions are placed into isotropic turbulence in 72-83. Line 75: check on number of iterations. Line 76: increment k_z . Line 77: check to see how large the denominator has become.
78-89	Same comments as lines 53-64 except summation is in downward direction.
90	Factors multiply sum. Note that CVT is included in the product so that it is o'k to increase CVT in lines 46-58 making the summation step size bigger. $0.11561 = 55\Gamma(5/6)/[36\pi^{3/2}\Gamma(1/3)]$

Computer Listing 3: Subroutine for calculating summation over turbulence spectrum.

Appendix D: Program for Calculating Airfoil Response Function, L , for Leading Edge Noise

Computer Listing 4 gives the subroutine for calculating the effective lift $|L|$ for noise produced by airfoil-turbulence interaction. The inputs to the subroutine and the equivalent notation used in this report are:

Program	Text
X	x_3
SG	σ
RM	M_b ; equation (36)
XK	k_x ; x wavenumber component
YK	k_y ; y wavenumber component

The output GL2 is the effective lift $|L|^2$ and is calculated in a low frequency and a high frequency regime. The low frequency result is given by equation (27) and the high frequency result by Eqs. (28).

```

*      Lift function subroutine
*      Written by R. K. Amiet; final version 1978
1      SUBROUTINE LFT(X,SG,RM,XK,YK,GL2)
2      COMPLEX E
3      B2 = 1.-RM**2
4      UM = RM*XK/B2
5      RMI = SQRT(RM**2-B2*(YK/XK)**2)
6      UMI = UM*RMI/RM
7      IF (UMI-.75) 10, 10, 20
8      10  GL2 = 1./(B2*(1./(1.+2.4*XK/B2)+6.28319*XK/B2))
9      GO TO 30
10     20  T1 = ABS(UM*(X/SG-RMI/RM))
11     CALL FRNL(SQRT(1.27324*T1),E)
12     CM = CABS(E)
13     GL2 = .20264*CM**2/(XK*T1*(1.+RMI))
14     30  RETURN
15     END

```

Line #	Comments
1	Inputs and output
3	$B2 = \beta_b^2$
4	$UM = \mu$
5	$RMI = M_{\infty}$; equation (24)
6	$UMI = \mu_{\infty}$; equation (24)
7	Check whether to use low or high frequency solution.
8	Low frequency solution; equation (27)
10-13	High frequency solution; equation (28a)
10	$T1 = \Theta_1$; equation (29)
13	Equation (28a); $.20264 = 2/\pi^2$

Computer Listing 4: Subroutine for calculating lift response for leading edge noise

Appendix E: Program for Calculating the Effect of Contraction on the Turbulence Spectrum

Computer Listing 5 gives the subroutine for calculating the effect of a contraction of a turbulence spectrum. This subroutine has as input a 3x3 deformation matrix representing a flow contraction. The program then accepts a flow direction \underline{v}_n and a wavevector \underline{k} both for the downstream flow, and calculates the upstream wavevector and flow vector. The inputs to the subroutine and the equivalent notation used in this report are:

<u>Program</u>	<u>Text</u>
DK	\underline{k}^d = downstream wavevector components
DXDZ	$\partial x_i / \partial \xi_j$ = deformation tensor; equation (71)
VN	Upwash velocity component normal to the air foil
ED, EU	Tensors representing the three vector components of the upstream and downstream coordinate systems. Each such vector is represented by a column of the matrix.

The outputs are:

DKM	Wavevector amplitude downstream at the rotor face
DKUK	Ratio of downstream to upstream wavevector amplitudes
UQDQ	Ratio of upstream to downstream velocity amplitudes

```

*      Turbulence contraction calculation.
*      Written by R. K. Amiet 9/7/83
1      SUBROUTINE KVEC(DK,DXDZ,VN,ED,EU,DKM,DKUK,UQDQ)
2      DIMENSION ED(3,3), EU(3,3), VN(3), F3(3), DK(3), DXDZ(3,3)
3      DKM = SQRT(DK(1)**2 + DK(2)**2 + DK(3)**2)
4      DO 10 I=1,3
5          ED(I,3) = DK(I)/DKM
6          ED(I,2) = VN(I)
7      10  CONTINUE
8          CALL CROSS(ED,1)
9          CALL CROSS(ED,2)
10     DO 20 I=1,3
11         DO 30 J=1,3
12             EU(I,J) = 0.
13     30  CONTINUE
14     20  CONTINUE
15         DO 40 I=1,3
16             DO 50 J=1,3
17                 DO 60 K=1,3
18                     EU(I,J) = EU(I,J) + DXDZ(K,I)*ED(K,J)
19     60  CONTINUE
20     50  CONTINUE
21     40  CONTINUE
22         F3(1) = EU(1,3)
23         F3(2) = EU(2,3)
24         F3(3) = EU(3,3)
25         AF1 = SQRT(EU(1,1)**2 + EU(2,1)**2 + EU(3,1)**2)

```

Computer Listing 5: Subroutine for calculating effect of contraction on turbulence spectrum

```

26      EU(1,1) = EU(1,1)/AF1
27      EU(2,1) = EU(2,1)/AF1
28      EU(3,1) = EU(3,1)/AF1
29      CALL CROSS(EU,3)
30      CALL CROSS(EU,2)
31      DKUK = EU(1,3)*F3(1) + EU(2,3)*F3(2) + EU(3,3)*F3(3)
32      UQDQ = AF1*DKUK
33      RETURN
34      END

```

<u>line #</u>	<u>Comments</u>
3	Calculates the magnitude of the downstream wavevector k^d .
4-7	Reads V_n into the 2'nd column of e^d and a unit vector along k^d into the 3'rd column.
8	Calculates the direction of the vorticity determined by the specified wavevector k and velocity V_n directions.
9	Calculates the direction of the velocity produced by the wavevector. V_n is a component of this velocity.
10-14	Initialize matrix e^u .
15-21	Calculates the values of e^u from the downstream values e^d by using equation(71) on each of the 3 column vectors making up e^d . This is not the final form for e^u . The vector \hat{e}_1^u representing the vorticity direction will keep its direction but be normalized to a unit vector. \hat{e}_3^u will be found by taking the cross product of vectors 1 and 2, and \hat{e}_2^u is then determined by taking the cross product of \hat{e}_3^u and \hat{e}_1^u .
22-24	\underline{f} represents a vector found by taking a unit vector along k^d and transforming according to equation(B 11b). This is used to determine k^d/k^u using equation(72).
25	The magnitude of the transformed value of the vorticity, needed in equation(73).
26-28	Unit vector in the direction of the upstream vorticity.
29	Determines the unit vector \hat{e}_3^u from the cross product of \hat{e}_1^u and \underline{f}_2^u .
30	Determines the unit vector \hat{e}_2^u from the cross product of \hat{e}_3^u and \hat{e}_1^u .
31	Determines k^d/k^u using equation(72).

Computer Listing 5: Subroutine for calculating effect of contraction on turbulence spectrum

Appendix F: Subroutine for Calculating the Cross Product of Two Vectors

Computer Listing 6 gives the subroutine for calculating the cross product of two vectors. The subroutine takes a 3x3 matrix $E(i,j)$ composed of 3 column vectors \hat{e}_i and replaces the $N1$ 'th vector by the normalized cross product of the other two in proper cyclic order. The inputs to the subroutine and the equivalent notation used in this report are:

<u>Program</u>	<u>Text</u>
$E(i,j)$	Tensor with columns composed of vectors; also represents the output
$N1$	Column not involved in the cross product

```
* Subroutine for calculating cross product of two vectors
* Written by R. K. Amiet 9/1/83
1  SUBROUTINE CROSS(E,N1)
2  DIMENSION E(3,3)
3  N2 = N1 + 1
4  N3 = N1 + 2
5  IF (N2 .GT. 3) N2 = N2 - 3
6  IF (N3 .GT. 3) N3 = N3 - 3
7  E(1,N1) = E(2,N2)*E(3,N3) - E(3,N2)*E(2,N3)
8  E(2,N1) = E(3,N2)*E(1,N3) - E(1,N2)*E(3,N3)
9  E(3,N1) = E(1,N2)*E(2,N3) - E(2,N2)*E(1,N3)
10 EN1M = SQRT(E(1,N1)**2 + E(2,N1)**2 + E(3,N1)**2)
11 E(1,N1) = E(1,N1)/EN1M
12 E(2,N1) = E(2,N1)/EN1M
13 E(3,N1) = E(3,N1)/EN1M
14 RETURN
15 END
```

<u>Line #</u>	<u>Comment</u>
2-6	Defines the cyclic sequence 1,2,3 or 2,3,1 or 3,1,2 where $N1$ is the first number of the sequence.
7-9	Replaces the $N1$ 'th vector by the cross product of the other two.
10-13	Normalizes the $N1$ 'th vector to have a magnitude of 1.

Computer Listing 6: Subroutine for calculating cross product of two vectors

Appendix G: Subroutine for Calculating the Fresnel Integral

Computer Listing 7 gives the subroutine for calculating the Fresnel integrals. The program uses the algorithm given by equations 7.3.9, 7.3.32, 7.3.33 of Abramowitz and Stegun, Handbook of Mathematical Functions, Dover Publications, New York, 1968.

```
*      FRNL.FOR Subroutine for calculation of Fresnel integrals
*      Written by R. K. Amiet 1976
1      SUBROUTINE FRNL(X,E)
2      COMPLEX E, G, H
3      G = CMPLX((1.+926*X)/(2.+ 1.792*X + 3.104*X**2),
4      1      1./(2.+ 4.142*X + 3.492*X**2 + 6.67*X**3))
5      H = CMPLX(SIN(1.5708*X**2),COS(1.5708*X**2))
6      E = G*H + CMPLX(.5,-.5)
7      RETURN
8      END
```

Computer Listing 7: Subroutine for calculating the Fresnel integrals.

Appendix H: Sample Calculation

These two test cases use the same inputs, listed below. The only difference between the cases is the deformation tensor. For the first case the tensor represents no deformation. The second represents a deformation by a factor of 4 in the axial direction.

Rev/sec = 10.

Chord/Turb scale = .01

Mach no. $M_f = 0$.

Blade # = 2.

Sound speed/Chord = 1000.

Far field/chord = 100.

Radius/chord = 10.

rms turb vel/U = .010

Theta $\theta = 0$.

Axial Mach no. = $M_z = 0.1$

Case 1

Deformation tensor =

```
1.00 .00 .00
 .00 1.00 .00
 .00 .00 1.00
```

HRMNC	FREQ	PSD	HRMNC	FREQ	PSD
.5	10.0	31.94	5.5	110.0	45.62
1.0	20.0	62.82	6.0	120.0	45.58
1.5	30.0	44.56	6.5	130.0	44.66
2.0	40.0	56.06	7.0	140.0	44.39
2.5	50.0	47.12	7.5	150.0	43.73
3.0	60.0	51.93	8.0	160.0	43.36
3.5	70.0	47.24	8.5	170.0	42.84
4.0	80.0	49.11	9.0	180.0	42.45
4.5	90.0	46.55	9.5	190.0	42.00
5.0	100.0	47.09	10.0	200.0	41.62

Case 2

Deformation tensor =

```
2.00 .00 .00
 .00 2.00 .00
 .00 .00 .25
```

HRMNC	FREQ	PSD	HRMNC	FREQ	PSD
.5	10.0	12.34	5.5	110.0	39.34
1.0	20.0	62.08	6.0	120.0	43.53
1.5	30.0	28.14	6.5	130.0	40.56
2.0	40.0	55.32	7.0	140.0	41.88
2.5	50.0	33.18	7.5	150.0	41.56
3.0	60.0	51.06	8.0	160.0	40.45
3.5	70.0	35.89	8.5	170.0	42.34
4.0	80.0	47.95	9.0	180.0	39.26
4.5	90.0	37.82	9.5	190.0	42.91
5.0	100.0	45.51	10.0	200.0	38.29



Report Documentation Page

1. Report No. NASA CR-181790	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Noise Produced by Turbulent Flow Into a Rotor: User Manual for Noise Calculation	5. Report Date June 1989	6. Performing Organization Code	
	7. Author(s) R. K. Amiet, C.G. Egolf and J.C. Simonich	8. Performing Organization Report No.	
9. Performing Organization Name and Address United Technologies Research Center East Hartford, CT 06108	10. Work Unit No. 505-63-51	11. Contract or Grant No. NAS1-17763	
	12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225	13. Type of Report and Period Covered Contractor Report	14. Sponsoring Agency Code
15. Supplementary Notes Langley Technical Monitor: Thomas F. Brooks Final Report			
16. Abstract <p>This document describes a users manual for a computer program for the calculation of noise produced by turbulent flow into a helicopter rotor. This inputs to the program are obtained from the atmospheric turbulence model and mean flow distortion calculation, described in another volume of this set of reports. This report includes descriptions of the various program modules and subroutines, their function, programming structure, and the required input and output variables. This routine is incorporated as one module of NASA's ROTONET helicopter noise prediction program.</p>			
17. Key Words (Suggested by Author(s)) noise prediction helicopter noise, turbulence ingestion noise, rotor noise	18. Distribution Statement Unclassified - Unlimited Subject Category 71		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 37	22. Price A03