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

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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      Minumum observer polar angle in degrees
*                             (theta=0 along rotor axis in thrust direction)
*           TMAX      RD      Maximum observer polor 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 memb
*                                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
*            ..............................................................
*            A0          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      Uptsream 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 vords 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
```

```
*                               subroutine
*       N         I             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
*
*     SUBPROGARAMS 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*Pi/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.
*          EN1M         RD      Normalizes the output to a magnitude of 1.
*
*        SUBPROGARAMS 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
*          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).
*            AF1        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
*
*        SUBPROGARAMS CALLED
*          NOPCRS
*
*        CALLING PROGRAMS
*          NOPNI
*
*        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 previious 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
*
*        SUBPROGARAMS 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    Decsription
*            ...................................................................
*            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
*
*        SUBPROGARAMS CALLED
*          NOPFNL
*
*        CALLING PROGRAMS
*          NOPPX
*
*        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 - NOPNI
*
*        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
*            ..........................................................
*            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
*          XKU0       RD      Upstream x value of wavevector; initial value
*          YKU0       RD      Upstream y value of wavevector; initial value
*          XY0        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
*
*      SUBPROGARAMS 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 NOPKVC
*          Calculate denominator for upstream turbulence with kz = 0.
*               This will be used for comparisonlater 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 NOPKVC
*               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 NOPKVC
*               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	$\sqrt{\overline{u^2}}/V_z$
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

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

where

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

Atmospheric pressure $P_0 = 10^6/0.987$ dynes/cm^2 and reference pressure $P_r = 0.0002$ dynes/cm^2. S_{pp} must be multiplied by 4π to convert from a two sided $-\infty < \omega < \infty$ to a one sided $0 < \omega < \infty$ spectrum and to convert to a unit Hertz rather than a unit radian frequency of measurement. Using the relations

$$\bar{K}_x = \omega b/U_b \qquad c_0^2 = \gamma P_0/\rho_0 \tag{A2}$$

this can be written (where $\gamma = 2\pi n/N$)

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

Converting to dB,

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

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.
         DIMENSION DXDZ(3,3)
         CHARACTER*10 FNAME
         CHARACTER*10 FNAME1
         WRITE(*,500)
  500    FORMAT(' Turbulence ingestion program with integration over'
     1     ' span'/' and nonisotropic turbulence.  R. K. Amiet 12/84'/)
         WRITE(*,'(A\)') ' OUTPUT FILE NAME -'
         READ(*,'(A)') FNAME1
         OPEN(2,FILE=FNAME1,STATUS='NEW')
   30    WRITE(*,100)
  100    FORMAT(//' INPUT C/L, BLADE NO., C0/C, '
     1          'RADIUS/C, FAR-FIELD/C, RPS'/)
         READ(*,*) CL, BN, C0C, RC, R1C, RPS
         TM1 = 2.*3.141593*RPS*RC/C0C
         WRITE(*,300) TM1, CL, BN, C0C, RC, R1C, RPS
         WRITE(2,300) TM1, CL, BN, C0C, RC, R1C, RPS
  300    FORMAT(//' M TIP = ',F4.3,'          CHORD/TURB SCALE =',F7.4/
     1                     ' BLADE NO. =',F4.0,'       SOUND SPEED/CHORD =',F7.1/
     1                     ' RADIUS/CHORD =',F5.1,'   FAR-FIELD/CHORD =',
     1                     F6.1/' REV/SEC =',F5.1/)
   10    WRITE(*,'(A\)') ' INPUT FILE NAME -'
         READ(*,'(A)') FNAME
         OPEN(1,FILE=FNAME,STATUS='OLD')
         READ(1,*) ((DXDZ(I,J), I=1,3), J=1,3)
         WRITE(*,200) ((DXDZ(I,J), J=1,3), I=1,3)
         WRITE(2,200) ((DXDZ(I,J), J=1,3), I=1,3)
  200    FORMAT(1X,3F5.2)
         CLOSE(1)
   20    WRITE(*,400)
  400    FORMAT(/' INPUT MZ, FM, UU, THETA, SUMS, PHI'/)
         READ(*,*) ZM, FM, UU, TH, J, PH
         WRITE(*,900) ZM, UU, TH, FM, J, PH
         WRITE(2,900) ZM, UU, TH, FM, J, PH
  900    FORMAT(' MZ =',F4.3,'  UU =',F6.3,'  THETA =',F5.0/
     1                     ' MF =',F4.3,'  SUMS =',I4,'  PSI =',F5.1/)
   70    WRITE(*,700)
  700    FORMAT(/' INPUT'/
     1 '     BEGINNING HARMONIC:           If < 0, go to matrix input.'/
     1 '     FRACTIONAL HARMONIC SPACING: If < 0, go to previous input.'/
     1 '     NUMBER STEPS:                 If < 0, go to first input.'/)
         READ(*,*) AL1, DH, L2
         IF (AL1 .LT. 0.) GO TO 10
         IF (DH .LT. 0.) GO TO 20
         IF (L2 .LT. 0) GO TO 30
         DF = RPS*BN*DH
         WRITE(*,800)
         WRITE(2,800)
  800    FORMAT(/2X,'HRMNC',5X,'FREQ',6X,'PSD',4X,'SM P',1X,'SM M'/)
         F1 = (AL1/DH-1.)*DF
         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
```

Line #	Comment
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
RC	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 © in Eq. (63).

```
•       Subroutine SPX
•       Program written by R. K. Amiet.
        SUBROUTINE PX(F1,ZM,CL,BN,C0C,UU,RC,R1C,RPS,FM,TH,J,PSI,DXDZ,
      1                 P2,NP1,NM1,N)
        DIMENSION DXDZ(3,3)
        PI = 3.14159
        TM = 2.*PI*RPS*RC/C0C
        AJ = J
        DEL = 360./AJ
        C = COS(TH/57.2958)
        S = SIN(TH/57.2958)
        C4 = COS(PSI/57.2958)
        S4 = SIN(PSI/57.2958)
        QM = FM*S*S4+ZM*C
        BFZ2 = 1.-FM**2-ZM**2
        SQ1 = SQRT(QM**2+BFZ2)
        RER = (SQ1+QM)/BFZ2
        NP1 = 0
        NM1 = 0
        SUM = 0.
        G = 90. - DEL
        DO 50 I=1,J
        G = G + DEL
        C2 = COS(G/57.2958)
        S2 = SIN(G/57.2958)
        C5 = COS((G+PSI)/57.2958)
        S5 = SIN((G+PSI)/57.2958)
        ALP = 57.2958*ATAN2(ZM,TM+FM*C5)
        C1 = COS(ALP/57.2958)
        S1 = SIN(ALP/57.2958)
        RM = SQRT(ZM**2 + (TM + FM*C5)**2)
        C3 = C*S1 - S*C1*S2
        X = R1C*(TM*RER*C1 - C3)
        Y = R1C*(S*C2 + FM*RER*S5)
        Z = R1C*(C*C1 + S*S1*S2 + TM*RER*S1)
        SG = SQRT(X**2+(1.-RM**2)*(Y**2+Z**2))
        FP = F1*(1.+TM*(S2*S-FM*RER*C5)/SQ1)
        XK = PI*FP/(C0C*RM)
        YK = PI*FP*Y/(SG*C0C)
        T = 2.*PI*RC/(TM*C0C*BN)
        T1 = T*TM*S1*C1/ZM
• Next line added to make peaks occur at bpf when ZM = 0.
        T1 = T/(1.+ MF*C5/TM)
        XX = TM*(T-T1)
        YY = T1*FM*S5
        ZZ = T*TM*C0C*S1
        T2 = T1 + XX*(RM-X/SG)/(1.- RM**2) + YY*Y/SG
        CVT = PI/ZZ
        ZK0 = PI*T2*F1/ZZ
        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 = α; 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 = σ
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

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

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

$CL = c/L$ $\quad$ $CVT = 2\pi b/Z$

$XK = K_x$ $\quad$ $YK = K_y$

$ZK0 = \omega_0 T_2/Z$ $\quad$ $DXDZ(I,J) = \partial x_i/\partial \xi_j$ $\quad$ (x_i = precontraction coordinate; ξ_j = post contraction coordinate)

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
      SUBROUTINE TRBNI(CL,CVT,XK,YK,ZK,ALP,G,DXDZ,SVV,NP,NM,N)
      DIMENSION EU(3,3), ED(3,3), VN(3), DK(3), DXDZ(3,3),
     1                 DXDZR(3,3), ROT(3,3), DXDZR1(3,3)
      EK = .373417*CL
      DK(1) = XK
      DK(2) = YK
      DK(3) = 0.
      C1 = COS(ALP/57.2958)
      S1 = SIN(ALP/57.2958)
      C2 = COS(G/57.2958)
      S2 = SIN(G/57.2958)
      VN(1) = 0.
      VN(2) = 0.
      VN(3) = 1.
      ROT(1,1) = C1*S2
      ROT(2,1) = C2
      ROT(3,1) = S1*S2
      ROT(1,2) = -C1*C2
      ROT(2,2) = S2
      ROT(3,2) = -S1*C2
      ROT(1,3) = -S1
      ROT(2,3) = 0.
      ROT(3,3) = C1
      DO 50 I=1,3
      DO 30 J=1,3
      DXDZR1(I,J) = 0.
      DO 90 K=1,3
      DXDZR1(I,J) = DXDZ(I,K)*ROT(J,K) + DXDZR1(I,J)
   90 CONTINUE
   30 CONTINUE
   50 CONTINUE
      DO 70 I=1,3
      DO 60 J=1,3
      DXDZR(I,J) = 0.
      DO 91 K=1,3
      DXDZR(I,J) = DXDZR1(K,J)*ROT(I,K) + DXDZR(I,J)
   91 CONTINUE
   60 CONTINUE
   70 CONTINUE
      CVT1 = CVT
      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
      XKU0 = EU(1,3)*DKM/DKUK
      YKU0 = EU(2,3)*DKM/DKUK
      XY0 = EK**2 + XKU0**2 + YKU0**2
      D0 = XY0**2.83333
      N = 0
   10 N = N + 1
      CVT = CVT1
```

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

```
      IF (N .GT. 1) CVT1 = 2.*CVT1
      DK(3) = CVT1
      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM1,DKUK1,UQDQ1)
      XKU = EU(1,3)*DKM1/DKUK1
      YKU = EU(2,3)*DKM1/DKUK1
      ZKU = EU(3,3)*DKM1/DKUK1
      XY = EK**2 + XKU**2 + YKU**2
      DN = (XY + ZKU**2)**2.83333
      DEL1 = ABS(1.- DN/D0)
      IF (DEL1 .LT. .01) GO TO 10
      SVV = 0.
      N = ZK/CVT
      AN = N
      ZK1 = ZK - AN*CVT
      ZK2 = ZK1
      NP = 0
      NM = 0
   20 NP = NP + 1
      DK(3) = ZK1
      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
      XKU = EU(1,3)*DKM/DKUK
      YKU = EU(2,3)*DKM/DKUK
      ZKU = EU(3,3)*DKM/DKUK
      XY = EK**2 + XKU**2 + YKU**2
      DN = (XY + ZKU**2)**2.83333
      SVV = SVV + (XY - EK**2)/(UQDQ**2*DN)
      IF (NP .GT. 100) GO TO 40
      ZK1 = ZK1 + CVT
      IF (DN .LT. D0*200.) GO TO 20
   40 NM = NM + 1
      ZK2 = ZK2 - CVT
      DK(3) = ZK2
      CALL KVEC(DK,DXDZR,VN,ED,EU,DKM,DKUK,UQDQ)
      XKU = EU(1,3)*DKM/DKUK
      YKU = EU(2,3)*DKM/DKUK
      ZKU = EU(3,3)*DKM/DKUK
      XY = EK**2 + XKU**2 + YKU**2
      DN = (XY + ZKU**2)**2.83333
      SVV = SVV + (XY - EK**2)/(UQDQ**2*DN)
      IF (NM .GT. 100) GO TO 80
      IF (DN .LT. D0*200.) GO TO 40
   80 SVV = .11561*SVV*CVT*EK**.666667
      RETURN
      END
```

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

Line #	Comment
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, $\mathcal{L}$, for Leading Edge Noise

Computer Listing 4 gives the subroutine for calculating the effective lift $|\mathcal{L}|$ 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 $|\mathcal{L}|^2$ 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:

Program	Text
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 airfoil
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
        SUBROUTINE KVEC(DK,DXDZ,VN,ED,EU,DKM,DKUK,UQDQ)
        DIMENSION ED(3,3), EU(3,3), VN(3), F3(3), DK(3), DXDZ(3,3)
        DKM = SQRT(DK(1)**2 + DK(2)**2 + DK(3)**2)
        DO 10 I=1,3
        ED(I,3) = DK(I)/DKM
        ED(I,2) = VN(I)
     10 CONTINUE
        CALL CROSS(ED,1)
        CALL CROSS(ED,2)
        DO 20 I=1,3
        DO 30 J=1,3
        EU(I,J) = 0.
     30 CONTINUE
     20 CONTINUE
        DO 40 I=1,3
        DO 50 J=1,3
        DO 60 K=1,3
        EU(I,J) = EU(I,J) + DXDZ(K,I)*ED(K,J)
     60 CONTINUE
     50 CONTINUE
     40 CONTINUE
        F3(1) = EU(1,3)
        F3(2) = EU(2,3)
        F3(3) = EU(3,3)
        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
```

Line #	Comments
3	Calculates the magnitude of the downstream wavevector $\underline{k}^d$.
4-7	Reads $\underline{V}_n$ into the 2'nd column of e^d and a unit vector along $\underline{k}^d$ into the 3'rd column.
8	Calculates the direction of the vorticity determined by the specified wavevector $\underline{k}$ and velocity V_n directions.
9	Calculates the direction of the velocity produced by the wavevector. $\underline{V}_n$ 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 $\underline{k}^d$ and transforming according to equation(B11b). 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:

Program	Text
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
```

Line #	Comment
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 Abromowitz 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
        SUBROUTINE FRNL(X,E)
        COMPLEX E, G, H
        G = CMPLX((1.+.926*X)/(2.+ 1.792*X + 3.104*X**2),
     1          1./(2.+ 4.142*X + 3.492*X**2 + 6.67*X**3))
        H = CMPLX(SIN(1.5708*X**2),COS(1.5708*X**2))
        E = G*H + CMPLX(.5,-.5)
        RETURN
        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.
Blade # = 2.
Radius/chord = 10.
Axial Mach no. = M_z = 0.1

Chord/Turb scale = .01
Sound speed/Chord = 1000.
rms turb vel/U = .010

Mach no. M_f = 0.
Far field/chord = 100.
Theta θ = 0.

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

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16. Abstract

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.

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