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A Model For Simulating Rotational Data For Wind Turbine Applications

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SUMMARY

This document describes a wind simulation model to be used in relation to wind turbine operations. The model is a computer code written in FORTRAN 77. The model simulates turbulence and mean wind effects as they are experienced at a rotating point on the blade of either a horizontal-axis wind turbine (HAWT) or a vertical-axis wind turbine (VAWT). The model is fast, requiring 15 to 120 seconds of VAX execution time to produce a simulation and related statistics.

The model allows the user to set a number of wind parameters so that he may evaluate the uncertainty of model results as well as their typical values. When this capability is combined with short execution time, the user can quickly produce a number of simulations based on reasonable variation of input parameters and can use these simulations to obtain a range of wind turbine responses to the turbulence. This ability is important because some of the wind parameters that cannot be precisely evaluated should be prescribed over a range of values.

The model has its limitations: it does not model any machine-induced modifications to the turbulence, it does not model any kind of meteorological event, and it simulates only the neutrally stable atmospheric boundary layer.

This document is essentially a user's guide. Its features include theoretical derivations, samples of output, comparisons of measured and modeled results, a listing of the FORTRAN code, a glossary for the code, and the input and output of a sample run.

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1.0 INTRODUCTION

In the past few years, a theoretical method has been developed for modeling turbulence as it would be experienced at a point rotating in a circle in a plane perpendicular to the mean wind direction. Thus turbulence as experienced just ahead of a point on the rotating blade of a horizontal-axis wind turbine (HAWT) is simulated. The theory (called the PNL theory) was developed by Connell (1982). Other applications are described by George (1984), George and Connell (1984), and Powell et al. (1985).

Prior to the development of the PNL theory, a so-called disk-averaging theory was invoked, e.g., by Frost et al. (1978). The underlying assumption of that theory was that turbulence features of smaller dimension than the rotational disk did not contribute significantly to the effects of turbulence on wind turbine operation; thus frequencies of fluctuation faster than the rotation rate of the blade could be ignored. Mathematically, this is accomplished by appropriate low-pass filtering of single-point turbulence data. Larger scale turbulence was treated as a time-varying wind that was the same throughout the disk.

But Connell's work theoretically and experimentally showed that turbulence as experienced at a rotating point on a wind turbine blade contributes significantly to the flap-wise bending moment fluctuations on the blade and the drive train at higher frequencies. The physical effect of the rotational motion is that energy is transferred from low and middle frequencies to that high frequency domain that includes the rotational frequency of the blade and harmonics of the rotational frequency. These frequencies are sometimes called 1P, 2P, and so on.

In this report, the previous spectral work is expanded to simulate rotational wind speed time series, with the mean wind effect either included or excluded. Also the theoretical work is extended to apply to a vertical-axis wind turbine (VAWT), such as a Darrieus wind turbine. Four different turbulence components are modeled. These are defined in Section 2. An additional objective of this report is to make the simulation technique more broadly usable, by providing a user's manual describing the computer program, which is written in FORTRAN 77 for a VAX 11/780 computer.

Section 2 presents the mathematical derivations of the HAWT and VAWT rotational turbulence and explains their physical significance. Section 3 is the user's guide proper, discussing the program from an operational point of view. Section 4 compares modeled and measured results. Section 5 presents our conclusions and recommendations.

There are four appendices. Appendix A provides a listing of the code, a glossary of important variables, and the input and output of a test case. Appendix B discusses the rotational spectra produced by the model as conditions approach the Eulerian, i.e., as the rate and the radius of rotation approach zero. Appendix C presents theoretical definitions of autocorrelations, of spatial correlations, and of length scales. Appendix D is a sample of model results from input parameters different from those used in the experiment modeled in Section 4.

2.0 THE BASIC SPECTRAL THEORY

The basic spectral theory consists of derivations of autocorrelation functions (acf's) for turbulence as experienced at a rotating point. The point rotates either in a vertical plane, as on a HAWT blade, or in a horizontal plane, as on a VAWT blade.

2.1 FOR THE HAWT

The autocorrelation function u-component (R_{11}) turbulence at a point rotating in a vertical plane perpendicular to the mean wind direction in the wind turbine layer has been given by Connell (1982). The equation is

$$R_{11}(r) = \frac{2 \sigma^2}{\Gamma(1/3)} \left(\frac{r}{2L} \right)^{1/3} \left\{ K_{1/3} \left(\frac{r}{L} \right) - \frac{r}{2L} \left[1 - \frac{x^2}{r^2} \right] K_{2/3} \left(\frac{r}{L} \right) \right\} \quad (1)$$

where:

Γ is the gamma function

σ^2 is the turbulence variance

r is the separation distance

L is a length characteristic of the turbulence

$K_{1/3}$ is the modified Bessel function of the second kind, of fractional order 1/3 ($K_{2/3}$ is the same function, of fractional order 2/3)

x is the alongwind component of the separation distance.

To physically understand the r , one must visualize the two ends of the segment defining r as follows (see Figure 1): One end is fixed to an arbitrary point on the blade and thus describes a circular path in the disk of rotation, perpendicular to the mean wind direction, as the blade rotates. The other end is downstream of its original position (P_0 on Figure 1) on the blade at a distance x , or Ut where U is mean wind speed and t is travel time. Mathematically, this is expressed

$$r^2 = \left[2\rho \sin \frac{\Omega t}{2} \right]^2 + (Ut)^2 \quad (2)$$

P_0 is position of P at initial time

$\Omega t = \theta + 2 n \pi$ where n is number of revolutions in time t

FIGURE 1. Geometry of r in Equation (1)

where ρ is the radius of rotation of the one end and Ω is the rotation rate. These two terms express the rotational and translation effects, respectively. The second term dominates the first as t becomes large.

By setting x equal to r in Equation (1), we model Eulerian motion. The $K_{2/3}$ term vanishes. The L in the correlation is defined by the fact that when this Eulerian acf is integrated over time (substituting Ut for R) and then multiplied by the mean wind speed, the result is a length scale L/1.34.

The expression for r in Equation (2) must be introduced into Equation (1). But first, we divide both sides of Equation (2) by $(2L)^2$. This yields

$$\left(\frac{r}{2L}\right)^2 = \left[\frac{\rho}{L} \sin \frac{\Omega t}{2}\right]^2 + \left(\frac{Ut}{2L}\right)^2, \quad (3)$$

which is substituted into (1).

We notice in Equation (3) that the same length scale is used as a denominator for both the alongwind length, Ut, and the crosswind length, ρ .

Accordingly, we now effectively redefine the L on the left by introducing two new scales on the right, to correspond to the essential physics. The result is

$$\left(\frac{r}{2L}\right)^2 = \left[\left(\frac{\rho}{L_y}\right) \sin \frac{\Omega t}{2}\right]^2 + \left(\frac{Ut}{2L_x}\right)^2 \quad (4)$$

where L_y is some lateral scale of turbulence, and L_x is the corresponding longitudinal scale. They could be the lateral and longitudinal integral length scales of turbulence, or possibly 3/4 of each, respectively. Here, L must be some weighted average of L_x and L_y .

The essential physics of interaction between machine and atmosphere imposes two non-turbulence length scales. One, ρ , is the radius of the wind turbine, and the other is the length U/Ω , the length of a column of air advected through the plane of the rotor during one rotor revolution.

The ratios of corresponding variables are expressed by the following dimensionless parameters:

$$\alpha = \rho/L_y \quad (5)$$

and

$$\beta = U/(\Omega L_x) \quad (6)$$

Also, a dimensionless time was defined:

$$\tau = \Omega t/2 \quad (7)$$

We note that

$$x/L_x = 2\beta\tau \quad (8)$$

We define a dimensionless autocorrelation function

$$P(\tau) = R_{11}/\sigma^2 \quad (9)$$

Substitution of Equations (4), (5), (6), and (7) into (1), and then into Equation (9) yields

$$P(\tau) = 2/\Gamma(1/3) \left(\alpha^2 \sin^2(\tau) + \beta^2 \tau^2 \right)^{1/6} \quad (D-E) \quad (10)$$

where

$$D = K_{1/3} \left[2 \left(\alpha^2 \sin^2(\tau) + \beta^2 \tau^2 \right)^{1/2} \right]$$

and

$$E = \frac{(\alpha^2 \sin^2(\tau))}{(\alpha^2 \sin^2(\tau) + \beta^2 \tau^2)^{1/2}} K_{2/3} \left[2 \left(\alpha^2 \sin^2(\tau) + \beta^2 \tau^2 \right)^{1/2} \right] .$$

$P(\tau)$ is a correlation in the dimensionless time variable τ in terms of the dimensionless parameters α and β . Because of this construction, changing the uncertain value of L_y is equivalent to changing the certain value of ρ ; and changing the uncertain value of L_x is equivalent to changing the value of U/Ω .

This correlation function is then Fourier-transformed into a power spectrum that is converted to dimensional form. We have not found any theoretical guarantee that the spectrum so calculated will be positive at every value.

2.2 FOR THE VAWT

The correlation distance r involved in VAWT rotational motion has an expression somewhat different from that given by Connell (1982) for the r involved in HAWT rotational motion. The reason is seen in the different geometry illustrated in Figure 2, where rotation is in the horizontal (x,y) plane. The circle represents the maximum horizontal projection of a VAWT. Applying some algebra and trigonometry, we find that

$$r^2 = (Ut)^2 + 4\rho^2 \left(1 + \frac{UT}{\rho} \right) \sin^2\left(\frac{\theta}{2}\right) . \quad (11)$$

FIGURE 2. Radius Definition for VAWT Rotational Movement

The autocorrelations of turbulence at the moving point may be derived using the theory of isotropic turbulence for the cross correlation of turbulence at two points, in this case, the two ends of the radius, r . Consider the most general case, where we are interested in the cross correlation of turbulence components at any two points in any two specified directions. We will call these two turbulence functions $(u_a)_A$ and $(u_b)_B$, which are the turbulence component in direction a at point A and the turbulence component in direction b at point B . This concept is illustrated in Figure 3.

The vectors U_a and U_b are the instantaneous turbulence vectors. The directions a and b in the figure are shown specialized in the four diagrams so that both are the directions of

1. the u -component,
2. the v -component,
3. the component in the plane of the disk and tangential to the VAWT circumference, or
4. the component in the radial direction.

FIGURE 3. Turbulence Components at Points and in Two Arbitrary Directions
a. u-Component; b. v-Component; c. Tangential Component;
d. Radial Component

Restricting attention to the two horizontal dimensions, the correlation of turbulence in direction a at point A with that in direction b at point B is the sum of components multiplied by direction cosines according to the equation

$$Q_{ab}(AB) = Q_{11} e_{a1} e_{b1} + Q_{12} (e_{a1} e_{b2} + e_{a2} e_{b1}) + Q_{22} e_{a2} e_{b2} \quad (12)$$

where

Q_{11} = the correlation of u-component turbulence at points A and B

Q_{12} = the correlation of u at A with v at B, which is the same as the correlation of v at A with u at B in homogeneous, isotropic turbulence

Q_{22} = the correlation of v at A with v at B. (See Hinze (1959) for a fuller discussion.)

These are all dimensional correlations, the dimension being velocity-squared. The direction cosines, as illustrated by Figure 4, are

$$e_{a1} = \cos \theta_{a1}$$

$$e_{a2} = \cos \theta_{a2} = \sin \theta_{a1}$$

$$e_{b1} = \cos \theta_{b1}$$

$$e_{b2} = \cos \theta_{b2} = \sin \theta_{b1}$$

Hereafter in this discussion we will use only the angles with subscript 1, and so we will drop the subscript.

FIGURE 4. Direction Cosine Illustrated in Two Dimensions
a. Direction a; b. Direction b

In all cases, the point A is placed on the diameter that is perpendicular to the mean wind direction and on the downwind side of the turbine. Therefore, the following statements hold.

When $(u_a)A$ and $(u_b)B$ are both the u-component, θ_a and θ_b are both zero and

$$Q_{ab}(AB) = Q_{11} \quad . \quad (13)$$

Define this as $Q_{uu}(AB)$. Likewise, when $u_a(A)$ and $(u_b)B$ are both the v-component, θ_a and θ_b are both 90 degrees and

$$Q_{ab}(AB) = Q_{22} \quad . \quad (14)$$

Define this as $Q_{vv}(AB)$.

When $u_a(A)$ and $u_b(B)$ are the tangential component, $\cos \theta_a$ is zero, $\sin \theta_a$ is one, and we have

$$Q_{ab}(AB) = Q_{12} \cos \theta_b + Q_{22} \sin \theta_b \quad (15)$$

Define this as $Q_{tt}(AB)$.

When $u_a(A)$ and $u_b(B)$ are the radial component, $\cos \theta_a$ is one and $\sin \theta_a$ is zero, and we have

$$Q_{ab}(AB) = Q_{11} \cos \theta_b + Q_{12} \sin \theta_b \quad (16)$$

Define this as $Q_{nn}(AB)$.

The functions Q_{11} , Q_{12} , and Q_{22} are given by Hinze (1959) as functions of the dimensionless correlations $f(r)$, the two-point longitudinal correlation of isotropic turbulence, and $g(r)$, the two-point lateral correlation of isotropic turbulence.

Von Karman (1948) has derived expressions of these in terms of the radius, r , the longitudinal and lateral components of r , x and y , and an unspecified length scale, L , characteristic of the turbulence. These expressions are

$$f(r) = C K_{1/3}(r/L) \quad (17)$$

and

$$g(r) = C \left[K_{1/3}(r/L) - (r/2L) K_{2/3}(r/L) \right] \quad (18)$$

where

$$C = \frac{2}{\Gamma_{1/3}} \left(\frac{r}{2L} \right)^{1/3} \quad (19)$$

Letting σ^2 represent the isotropic turbulence variance, the expressions for Q_{11} , Q_{12} , and Q_{22} are

$$Q_{11}/\sigma^2 = (x/r)^2 [f(r) - g(r)] + g(r) , \quad (20)$$

$$Q_{12}/\sigma^2 = (xy/r)^2 [f(r) - g(r)] , \quad (21)$$

$$Q_{22}/\sigma^2 = (y/r)^2 [f(r) - g(r)] + g(r) . \quad (22)$$

The final expressions for these correlations are given in dimensionless variables similar to those used in (10). However, α must be defined because rotation is now in the horizontal plane; in the horizontal plane, the radial direction may be either longitudinal or lateral with respect to the mean wind. Therefore, if a single value has to be assigned to an effective length scale, this value would be somewhere between those of L_x and L_y . We call it L_h and define

$$\alpha_h = \rho/L_h .$$

Then the final dimensionless correlations in terms of α , β , and τ are

$$Q_{uu}(AB)(\tau) = C \left[K_{1/3}(2Z) - Z \left(1 - \frac{\beta^2 \tau^2}{Z^2} \right) K_{2/3}(2Z) \right] , \quad (23)$$

$$Q_{vv}(AB)(\tau) = C \left[K_{1/3}(2Z) - Z \left(1 - \frac{\alpha_h^2}{4Z^2} \sin^2(2\tau) \right) K_{2/3}(2Z) \right] , \quad (24)$$

$$\begin{aligned} Q_{tt}(AB)(\tau) = & C \left[\frac{\alpha_h \beta \tau}{2Z} \sin(2\tau) K_{2/3}(2Z) \right] \cos \theta_b \\ & + C \left[K_{1/3}(2Z) - Z \left(1 - \frac{\alpha_h^2}{4Z^2} \sin^2(2\tau) \right) K_{2/3}(2Z) \right] \sin \theta_b , \end{aligned} \quad (25)$$

$$Q_{nn}(AB)(\tau) = C \left[K_{1/3}(2Z) - Z \left(1 - \frac{\beta^2 \tau^2}{Z^2} \right) K_{2/3}(2Z) \right] \cos \theta_b$$

$$+ C \left[K_{1/3}(2Z) - Z \left(1 - \frac{\alpha_h^2}{4Z^2} \sin^2(2\tau) \right) K_{2/3}(2Z) \right] \sin \theta_b, \quad (26)$$

where

$$Z = r/2L$$

and

$$Z^2 = (\beta\tau)^2 + \alpha_h^2 \left(1 + \frac{2\beta\tau}{\alpha} \right) \sin^2(\tau).$$

2.3 TURBULENCE SIMULATION

Under the principle of simulation used, the power spectrum derived from one of the above correlation functions supplies half of the degrees of freedom (that is, the amplitude information) of the simulated data, while the other half is supplied by the assumption of a random phase structure from one harmonic to the next in the simulated data.

Let Q stand for any of the correlations derived just above. Theoretically, the spectrum of the same correlations is given as the Fourier transformation of Q . That is,

$$S(N) = 4\sigma^2 \int_0^\infty Q(\tau) \cos(2\pi N\tau) d\tau \quad (27)$$

where N is dimensionless frequency. This can be transformed to a spectrum of dimensional frequency n by using the transformation

$$S(n) = 2 S(N)/\Omega \quad (28)$$

where $n = \Omega N/2$. N is related to n as t is to τ (see Equation (7)).

The actual procedure consists of computing $S(N)$ by submitting $Q(\tau)$ to a fast Fourier routine. This routine requires that 2^m , where m is an integer, members of $Q(\tau)$ be submitted. The $S(N)$ that is transformed to $S(n)$ has values at 2^m frequencies such that

$$S_j = S(n), \quad n = j/T \quad (29)$$

where T is the length of the data series to be simulated, given by

$$T = 2^{m+1} \Delta\tau \quad (30)$$

Let $M = 2^m$. Then the simulated data series is given by

$$u(k\Delta t) = \sum_{j=1-M/2}^{M/2} c_j \exp(i 2\pi jk/M), \quad K = 1, M, \quad (31)$$

where the c_j are complex Fourier coefficients such that

$$S_j = 2T c_j^* c_j \quad (c_j^* \text{ is the complex conjugate of } c(j))$$

and such that the phase angle

$$\text{phase}_j = \text{Arctan} (\text{Imaginary } c_j / \text{Real } c_j)$$

is evenly distributed between zero and 2π for $j = 1, 2, \dots, M/2$.

2.3.1 Simulation of Mean Wind Effects and Adding to Turbulence

The mean wind effects are very different for HAWT and VAWT, both analytically and in magnitude. In either case, it is sufficiently accurate to assign the entire variational effect to the rotational frequency of the blade. In fact, for the VAWT, the entire mean wind effect is theoretically at the rotational frequency.

2.3.1.1 HAWT Mean Wind Effects

In the neutrally stable atmospheric boundary layer, the relation between the wind at two heights z_1 and z_2 is

$$U(z_2) = U(z_1) \ln(z_2/z_0)/\ln(z_1/z_0) \quad (32)$$

where z_0 is the surface roughness length (discussed in Section 3.1.2). In Figure 5, z_1 is the HAWT hub height; $U(z_1)$ is the hub height wind speed (called U in the description so far); z_2 is the current blade position height, and $U(z_2)$ is the mean wind speed at that height. The mean wind effect then is $U(z_2)$, which is a function of time at the varying heights z_2 , where z_2 is given by

$$z_2 = z_1 + \rho \sin(\Omega t) \quad (33)$$

where (Ωt) is the angle θ in Figure 5.

Thus, $U(z_2)$ is a period function whose period is the inverse of the rotational frequency. It approaches but does not become a sinusoid because the logarithm of z_2 is used. The spectral content of $U(z_2)$ at the overtone frequencies is slight (Powell et al. 1985).

2.3.1.2 VAWT Mean Wind Effects

The mean wind effects for the four VAWT simulations are caused by the blade moving in and out of the mean wind without height change. For the u- and v-components, the problem is trivial. If we let $U(t)$ be the mean wind effect (mwe), we can write:

$$\text{VAWT u-simulation: } U(t) = U(z) - \text{a constant}$$

$$\text{VAWT v-simulation: } U(t) = 0.$$

For the tangential and radial simulations, the mwe is

$$U(\text{tangential}) = U \sin[\pi(\Omega t + 1)] + 2\pi\Omega\rho \quad (34)$$

$$U(\text{radial}) = U \cos[\pi(\Omega t + 1)] \quad (35)$$

FIGURE 5. HAWT Geometry for Mean Wind Effects

The offset 1 makes the equations agree with Figure 3, parts c and d. The mwe energy contribution is

$$\text{Energy}(\text{mwe}, 1P) = 1/2 U^2 \quad (36)$$

and occurs at the rotational frequency, as the notation indicates.

3.0 DESCRIPTION OF PROGRAM AND USER'S GUIDE

The computer program is executed by submitting a prepared command file. This command file specifies numerous variables and options set by the user. The variables include both wind turbine and meteorological parameters. The read-in parameters are defined and discussed in the first section. The following section summarizes the operation of the program. The main program is treated first, and then the subroutines. Appendix A lists the code and provides a more complete glossary of program variables.

3.1 PARAMETERS TO BE READ IN

The parameters to be read in are organized in five groups, referred to as records. Each parameter has several optional values, described below. Units of the input physical parameters are mks.

3.1.1 First Record

KAWT: The option KAWT directs which of the following simulations will be performed:

- KAWT = 1: HAWT u
- 2: VAWT u
- 3: VAWT v
- 4: VAWT tangential (VAWT t)
- 5: VAWT radial (VAWT r).

MWIND: The program has the option of simulating either the total wind component, including the mean wind effect, or turbulence only, as determined by the value of MWIND.

- MWIND = 0: simulate turbulence only
- 1: simulate turbulence and mean wind effect.

DELAY: This is the phase delay, in degrees, imposed on the mean wind effect (mwe), modeled at the rotational frequency 1P. If DELAY is zero, the program is written so that the 1P harmonics of mwe and turbulence will be in phase. For any other value of DELAY, the mwe is delayed by that angle. Thus, the mwe DELAY would be incorporated as follows

$$U(t, mwe) = \phi(\omega \times t - \pi \times \text{DELAY}/180.)$$

where ϕ is either a sine or a cosine function.

One possible treatment for DELAY is to treat it as a random variable of even distribution. In this case, several runs could be made so that the statistical nature of the interrelation of mean flow and turbulence could be sampled. Another plausible scenario would be to read DELAY in as zero. This is a worst-case scenario for the HAWT u-component and the VAWT tangential component simulations, making the mwe and turbulence 1P effects occur in phase. A lesser variance is produced for the radial simulations when DELAY equals zero, since the radial turbulence is 90 degrees out of phase with the tangential turbulence, and therefore 90 degrees out of phase with the mean wind effect.

3.1.2 Second Record

The second record consists of physical parameters and related options.

RADIUS: This specifies the radius of rotation to be simulated.

ENO: This is the rate of rotation, in Hz, to be simulated.

Z: This is hub height.

U: This is the mean wind speed at height Z. $U(Z)$ will necessarily take on a value between the machine's cut-in and cut-out wind speeds.

Z0: Z0 is a length parameter invented exclusively for meteorological reasons. This is the surface roughness length. Surface roughness consists physically of such things as grasses, bushes, trees, buildings, and terrain features. The rougher the surface, the larger the value of Z0. It corresponds to no single factor that can be measured in nature. Since it cannot be measured, a value must be selected from a table of surface roughness values, such as those given by Chan et al. (1983) and by Panofsky and Dutton (1984). (The first is an engineering report, the second a meteorological book.) For a typical rural setting, gently rolling land with crops and a few trees, setting a Z0 value of 0.1 m is appropriate. The value of Z0 affects only the turbulence variance, not the shape of the spectrum.

KSG: This option determines whether the computer or the user provides values for SIGU and SIGV, the turbulence rms of the u- and v-components, respectively.

KSG = 0: The program calculates SIGU and SIGV.

1: The program accepts values of SIGU and SIGV as the next numbers read in.

There are uncertainties and inconsistencies to be recognized whether SIGU and SIGV are calculated or read in. The uncertainties arise from the fact that not all the physics necessary to model the low frequency part of the u and v turbulence spectra are known. Therefore, when these parameters are estimated using existing models, measured and modeled values may differ significantly. Since the rms is the square root of the frequency integral of the spectrum, these uncertainties are part of the calculated rms. In addition and for the same reason, a measured value may not be typical for the site at which it was measured.

The inconsistency comes from the fact that the von Karman theory on which this model is based assumes that SIGU equals SIGV. Actually, the von Karman theory is based on the theory of isotropic turbulence, which assumes that all variances of turbulence-directional components are equal. In the atmosphere, this is not true. It is more reasonable to assume that SIGV is about 0.8 SIGU. But if such values are used in the program, the high frequency portions of the spectra, which are well-known, will be out of the proper relationship to each other. This higher frequency range of the spectrum is where the harmonic spikes occur.

If the program is allowed to calculate SIGU and SIGV, it takes a conservative approach by setting them equal to each other. Thus, SIGV is set at the higher value appropriate for SIGU.

If measured values are supplied by the user, the values should be based on Eulerian data samples at least 10 minutes long and sampled at a discretization rate of no less than 5 samples per second. Otherwise the calculated variance will be too low. It can be corrected, but the correction depends on the current height and mean wind speed and requires good understanding of meteorological dimensionless turbulence spectra.

KEL: This option can have the following values:

KEL = 0: Program calculates EL1 and EL2.

= 1: Program accepts values of EL1 and EL2 as the next numbers read in.

The parameters EL1 and EL2 are the integral scales of u-component turbulence in the longitudinal and lateral directions, L_x and L_y , respectively. Numerically, they are of more uncertain evaluation than the rms values. These integral scales are more fully defined and described in Appendix C.

The character of the rotational spectra may be adjusted by manipulating values of EL1 and EL2 (Powell et al. 1985). In general, increasing L_y decreases the portion of the energy transferred to the spikes and decreases the peakedness. Increasing L_x increases the peakedness without significantly affecting the amount of energy transferred to the peaks. Therefore, increasing both length scales proportionally lowers the amount of energy transferred into the spikes without significantly changing the peakedness.

This completes the information on the second record. A simple procedure for determining values for this record is as follows:

Set RADIUS, ENO, and Z according to the machine specifications.

Set U at the assumed mean wind speed.

Set Z0 at 0.1 if terrain and building feature are of "average rural roughness." Make comparisons by setting Z0 at 0.3 and at 1.0 if greater roughness is estimated; make comparisons by setting Z0 at 0.03 and 0.01 if less roughness is estimated. Obtaining a table of surface roughness values will help in estimating Z0. Because individual runs with this model are very cheap, it is economical to try several alternatives to achieve the greatest accuracy.

For HAWT analysis, set KSG and KEL at zero.

For VAWT analysis, set KSG at zero and KEL at 1. Then set EL1 and EL2 at about 3.3 Z.

Remember that all units are mks.

3.1.3 Third Record

The parameters of the third read-in record are more manipulable. Before choosing values, the user must decide how many data he wants to simulate and at what discretization interval. The discretization interval is most easily specified indirectly, by specifying the number of samples per revolution. The following suggestions are made:

KNDOPT: This is an option that allows the user to specify the discretization interval either in angular units or in seconds.

KNDOPT = 0: This is the easiest option, because the program rather than the user makes the calculations.

KNDOPT must be set at zero if **MWIND** does not equal zero. That is, if the mwe is to be simulated, the model requires an integral number of samples about the rotational circle, specified by the integer **NANGLE**.

KNDOPT = 1: Discretization interval (DT) is read in directly. If this option is used, DT should be no greater than $1.0/(12. * ENO)$.

NANGLE: This is the number of sectors the sampling (discretization) divides the rotational circle into. Note that **NANGLE** is an integer. The minimum allowable value of **NANGLE** is twice the number of harmonics the analyst wishes to model, which would be at least four or five. Therefore, **NANGLE** must be at least eight or ten. Actually, a value of twelve or greater is recommended. If the value is twelve, sampling positions 30 degrees apart are simulated. The discretization interval in seconds (DT) is calculated from **NANGLE** and **ENO**. That is, DT equals $1/(\text{NANGLE} \times \text{ENO})$. **NANGLE** is used directly in the calculation of the autocorrelation function only if **KAWT** is four or five, i.e., if the simulation is of either the **VAWT** tangential component or the **VAWT** radial component. **NANGLE** is used only if **KNDOPT** equals zero.

DT: DT is the discretization, or sampling, interval in seconds. A read-in value of DT is used only if **KNDOPT** equals one. If **KNDOPT** equals zero, **NANGLE** is used.

MMT: This is the number of simulated data. It must be 2^N , where N is an integer. This is because the FFT method cannot handle any number of data other than 2^N . A problem arises because the number of rotational cycles simulated is more likely to be fractional than integral. Thus, when the spectrum of these data is computed, the energy that physically belongs to certain frequencies is diffused upward and downward among all frequencies. However, if enough rotational cycles are simulated, the fraction of energy diffused out of the 1P rotational band by this mathematical artifice will be small. Twenty cycles seem to be sufficient for this purpose. Therefore, we recommend that the product (MMT x DT x ENO), or, equivalently, the quotient MMT/NANGLE, should at least equal 20. Thus, MMT must be greater than $20/(DT \times ENO)$ or greater than $20 \times NANGLE$. The program requires the user to perform these calculations.

There are other considerations in setting MMT. Usually the spectrum $S(n)$ should be calculated to a minimum frequency on the order of 0.01 Hz to adequately model the low frequency part of the spectrum. To do so requires that MMT be no less than the order of $(100/DT)$.

A minimum value of 1024 is recommended for MMT (these considerations may indicate the need for a higher minimum). The speed of the model means that the greater economy resulting from selecting smaller values is not important. In addition, the product MMT x ILIAS, the next parameter, must not exceed 16384.

ILIAS: This parameter removes the high-frequency part of the spectrum calculated by Fourier transform of the autocorrelation function (acf). The low frequency portion of the spectrum remaining equals $1/ILIAS$. Thus:

ILIAS = 1: none of the spectrum is removed. The high-frequency end will be severely aliased.

= 2: the upper half of the spectrum is removed, leaving the lower frequency half.

= 4: three-fourths of the spectrum is removed.

A value of 4 is recommended for ILIAS. The program will accordingly use a discretization interval DTA one-fourth of the original and will allow calculation of an acf four times as long as the maximum allowance specification. After the

spectral transform of this acf has been calculated, three-fourths of it will be discarded and the relatively unaliased remainder will be used for data simulation.

KWINDOW: This is an option allowing the use of the Hamming window (Blackman and Tukey 1958) to taper the end of the autocorrelation function. The tapered autocorrelation function is given by:

$$\begin{aligned} R(t) \text{ tapered} &= 0.5 R(t) + 0.5 R(t) \cos(\pi t/T), t \leq T, \\ &= 0, t > T. \end{aligned}$$

T is the time length of the function at the point where it converges according to the convergence criterion CHK, the next parameter read in. If this criterion is not met, T is the maximum time allowed for the acf. The limit on the number of members of R(t) is (MMT x ILIAS/2). Therefore, the limit on T is (DT x MMT x ILIAS/2). The algorithm uses the value of CHK such that the acf is deemed convergent when the the sum of the absolute values of the last three computed values of the function does not exceed 3 x CHK. KWINDOW values are as follows:

KWINDOW = 0: Hanning window is not used.

= 1: Hanning window is used whether acf was terminated by the convergence criterion or not. Otherwise the spectral transform may have a "beard" (a rapid frequency oscillation in the spectrum).

CHK: This is the convergence criterion discussed above. A reasonable value range for CHK is 0.001 to 0.01.

NP: This is the number of degrees of freedom used in the impulse response function when the simulated data are calculated by the convolution of Gaussian white noise with an impulse response function. NP may not exceed MMT/2. It may very well be about one-tenth that amount. As will be explained in Section 3.1.5, the method of calculation using Gaussian white noise is one of two options for calculating the final simulated data. Since the other option, based on harmonic analysis, is the preferred one, we have had little experience setting NP. When the other option is used, NP is ignored.

This completes the information on the third record. A reasonable set of values would be:

```
KNDOPT = 0
NANGLE = 24
MMT     = 1024
ILIAS   = 4
KWINDOW = 1
CHK     = 0.001
NP      (irrelevant if KBR in the fifth record has the recommended
        nonzero value).
```

Such a simulation requires about 20 to 45 seconds on the VAX 11/780, if an executable image of the code already exists.

3.1.4 Fourth Record

All of the options on this record govern writing to output files that are suitable for plotting by some other program. When they are set at any value other than zero, the specified task is done. Normally K8 and K14 are not used.

- K8: Write the entire calculated impulse response function to disk.
- K9: Write the following $S(n)$ spectra to disk:
 - * the FFT transform of the autocorrelation function
 - * the spectrum calculated from the simulated data.
- K11: Write the $S(n)$ from cosine integration of the autocorrelation function to disk.
- K12: Write the simulated data to disk.
- K13: Write both the original and the altered von Karman $S(n)$ spectra to disk. (These alternatives will be explained below.)
- K14: Write the complex Fourier coefficients of the transform of simulated data to disk.
- K15: Calculate the logarithmically banded $nS(n)$ spectrum of simulated data and write it to disk, preceded by the unbanded $nS(n)$ values for the lowest three frequencies. (Banding is a smoothing procedure.)

3.1.5 Fifth Record

The last read-in record consists of further options.

KSERIAL: This is a five-character alphameric array used for naming a run.

KBR: This option governs the analytical method by which the simulated data are computed.

KBR = 0: Use convolution integral of Gaussian white noise and impulse response function.

= 1: Use spectrum for Fourier amplitudes and use random number generator to compute phases. This method is recommended.

KXIFPR, KVKPR: These are printing options for the unbanded estimates of the spectrum, as calculated by transformation of the autocorrelation function and for the von Karman spectrum, respectively. These spectra are not those of 80 frequencies from 0.1P to 8P. Rather, these are the 2^N harmonic estimates, where N may be 10 or 11. Therefore, the printouts can be quite large. Usually there is no need of them, as is explained below. Any nonzero value for these options results in printing.

3.2 FLOW CHART OF MAIN PROGRAM

Figure 6 is a flow chart of the main program. Subroutines are identified by names written in capital letters, in boxes having probes extending to other boxes. The abbreviation WDO stands for "written to disk by option." The option is usually one of the K* variables, such as K9. If the variable does not equal zero, the writing occurs.

3.3 SUMMARY OF PROGRAM OPERATION

Operation of the main program is summarized first, followed by the operations of specific routines.

3.3.1 Main Program

The user initiates the program by entering the parameters and variables as described in Section 3.1. The program then calculates autocorrelation functions, spectra and harmonic spike variances, and produces simulated data.

Flow Chart for Main Program RODASIM7

FIGURE 6. Flow Chart Illustrating Operation of the Main Program. $S(n)_d$ refers to the spectrum of the simulated data, it is numerically equivalent to $S(n)_r$.

3.3.1.1 Entering Parameters and Variables

First, the necessary parameter values are read in or determined internally. Then the two limit frequencies for certain of the calculated spectra are determined. The lowest frequency, EN1, is the inverse of the total time period of the simulated data. The highest frequency, EN2, is one-half the reciprocal of the sampling interval, DT.

At this point, other variables are identified by adding the letters A, ND, or AND to variable names already defined. The meanings are best illustrated by examples. Consider the variable DT, the discretization interval. The most direct way to create a spectrum reasonably free of aliasing is to create one with an extended high frequency range that is not needed and which is later disregarded. This is done by using a reduced discretization interval to compute the autocorrelation function of the rotational data. This reduced discretization interval is called DTA. It is computed by dividing DT by the alias reduction factor, ALIAS (the floating point version of ILIAS). Because the autocorrelation function is first computed in terms of dimensionless variables, we also need dimensionless equivalents of DT and DTA. These are DTND and DTAND, obtained by multiplying the corresponding dimensional variable by $(\pi \times \text{ENO})$. Other modified variables exist in some or all of these forms for MMT, EN1, EN2, and NANGLE. Some of these additional values are defined for printing only. Others have an analytical role.

Once the initial variables are defined, Subroutine RODAPRINT is called to print out the initial variables.

3.3.1.2 Calculation of Autocorrelation Functions and of Several Spectra

The next section of the program calculates the autocorrelation function of the simulated data according to the specifications just read in and those just calculated. It calls on Subroutine BESSEL to calculate the modified Bessel functions of the second kind, $K(1/3)$ and $K(2/3)$. Then the logic in the main program uses the Bessel function values to determine the particular acf that corresponds to the value of KAWT read in, that is, HAWT u, VAWT u, etc. The discretization interval of the acf is DTAND.

If KAWT equals one (HAWT u-simulation), all of the acf calculation is done in the main program except the part done by Subroutine BESSEL. If KAWT is greater than 1, setting up one of the VAWT simulations, the entire acf calculation is performed in subroutines. Specifically,

if KAWT equals two or three (VAWT u or v simulation), Subroutine VAWTUV is used;

if KAWT equals four or five (VAWT tangential or radial simulation), Subroutine VAWTTN is used.

Subroutines VAWTUV and VAWTTN call Subroutine BESSEL at the appropriate point. The Hanning window adjustment is done in each of the VAWT subroutines as well as in the main program.

The next section of the program calculates several spectral functions. They may be easily confused with each other unless they are defined at the outset. These spectra are defined and described as follows:

$$S(n)_f, \text{ in } (m/s)^2/Hz.$$

This is the full spectrum calculated by submitting the acf to the fast Fourier transforms, FFT. These are performed by the Cooley-Tukey subroutine, called Subroutine COOLEY. The lowest value of n is EN1. The highest value is EN2A, or EN2 x ALIAS. The number of frequencies is MMT x ILIAS/2.

$$S(n)_r, \text{ in } (m/s)^2/Hz.$$

This is the reduced, relatively unaliased spectrum. It can be defined as

$$\begin{aligned} S(n)_r &= S(n)_f, \text{ if } n \text{ is not greater than the original EN2.} \\ &= 0, \text{ if } n \text{ is greater than the original EN2.} \end{aligned}$$

The lowest frequency is EN1; the highest frequency is EN2. The number of frequencies is MMT/2. $S(n)_f$ is never used after $S(n)_r$ is determined. $S(n)_r$ is the spectrum used as the basis for later data simulation.

$$S(n)_c, \text{ in } (m/s)^2/Hz.$$

This spectrum is computed by direct cosine integration of the acf for frequencies 0.1P, 0.2P,.....8.0P or EN2, whichever is lower. The maximum number of frequencies is 80.

$$S(n)_{c1}, \text{ in } (m/s)^2/Hz.$$

A detailed low frequency description analogous to $S(n)_c$, at 20 frequencies, is 0.005P, 0.010P....., 0.100P.

The following corresponding von Karman spectra are computed.

$$\begin{aligned} Svk(n)_r, & \text{ in } (m/s)^2/Hz - \text{ original von Karman spectrum analog of } S(n)_r, \\ Svk(n)_{ra}, & \text{ in } (m/s)^2/Hz - \text{ altered von Karman spectrum analog of } S(n)_r, \\ Svk(n)_{ca}, & \text{ in } (m/s)^2/Hz - \text{ altered von Karman spectrum analog of } S(n)_c. \end{aligned}$$

The term "ra" stands for the altered u- or v-spectra that were found to be the limit spectra of the rotational spectra, as rotational rate and radius (or rate alone) approach zero. This finding was not expected. More details and the analytical forms of the original and altered spectra are given in Appendix B. Both original and altered versions of the spectra are computed at this point and can be written to disk.

The von Karman spectra are computed according to which component simulation is being performed. The u-spectra are computed if the simulation is of HAWT u, VAWT u or VAWT t. The v-spectra are computed if the simulation is VAWT v or VAWT r. Most of these spectral functions can also be written to disk.

The spectra $S(n)_c$ and von Karman $Svk(n)_{ca}$ are printed out, along with the variance computed by integrating $S(n)_c$. At the bottom of the page, just above the variance, is a print-out of $S(n)_{c1}$ that was calculated for 20 divisions of the lowest frequency band, that is, from 0.005P to 0.100P. The reason for computing $S(n)_c$ is that both its numerical print-out and its plot make for very easy visual assessment of the rotational effect. $S(n)_c$ is a handy spectrum in this respect. The von Karman analogs, $Svk(n)_c$ and $Svk(n)_{ca}$, are printed and plotted for comparison of the rotational and corresponding Eulerian spectra.

3.3.1.3 Calculation of Harmonic Spike Variances

The next section of the program computes variances for the first six harmonic spikes of the rotational spectrum. This is the amount of energy per unit mass in each spike. The amount of energy in the von Karman spectrum in each of these frequency bands is also computed for comparison. These results are printed out. The spectra used in these computations are $S(n)_c$, $S(n)_r$, and $Svk(n)_{ca}$.

The reader should note at this point that since the $S(n)_r$ spectrum is used for data simulation, the $S(n)_c$ and its von Karman analogs $Svk(n)_c$ and $Svk(n)_{ca}$ are no longer necessary for the central purpose of the program. However, the $S(n)_c$ and $Svk(n)_{ca}$ spectra were the basis of earlier reported material (Powell et al. 1985) before the simulation capability was added to the code. For this reason, and because these spectra could conceivably be used to generate simulated data by the Gaussian white noise method, they have been retained.

3.3.1.4 Data Simulation

The remainder of the program performs the wind-speed time-series simulation by one of two alternative methods, according to the value given for the option KBR. The first method, used when KBR equals zero, calculates the simulated data by a convolution integration of Gaussian white noise with an impulse response function. The impulse response function is calculated from the spectrum $S(n)_r$ and can be written to disk. The result depends on an additional arbitrary input by the user, namely the number of degrees of freedom (members or NP), to be used in the calculated impulse response function. Increasing the number of members gets more of the spectral characteristics into the simulated data, at a cost of greater running expense. Experience is needed to determine what is an optimal number of members to use.

The computations we made by this method used about 50 members in the impulse response function. The spectrum of the simulated data differed somewhat from the original spectrum, and more than 20% of the original variance was lost. In contrast, when the second simulation alternative is used, the spectrum of the simulated data is identical with the original rotational spectrum, $S(n)_r$. Therefore, the two variances are also identical. There is no choice

to be made corresponding to what number of members of an impulse response function to use. For these reasons, we recommend the second alternative.

The second alternative, chosen when KBR equals one, uses the spectral estimates to calculate the amplitudes of the Fourier harmonics of the simulated data and to add the phase as an uncorrelated random variable from harmonic to harmonic. The random phase is provided by calling a routine that generates an evenly distributed random variable over the range 0 to 1 and scaling this over the range 0 to 2π .

Following either kind of simulation, several statistical calculations are made based on the simulated data. The variance, skewness and kurtosis of the simulated data are computed. Then the simulated data may be written to disk. Next, the power spectrum of the simulated data is computed. This is identical to the original power spectrum if the second simulation alternative was used or if the mwe has not yet been added in (see Figure 6). The computation of variance in the first half-P and in the harmonic spikes is repeated, this time using the spectrum of the simulated data. The spectrum and the Fourier coefficients it was computed from may be written to disk. The last computation, also optional, is a conversion of the $S(n)$ spectrum of the simulated data at evenly spaced frequencies to an $nS(n)$ spectrum at logarithmically spaced frequencies. There are ten bands per frequency decade. The $nS(n)$ estimates for the lowest frequencies are left unbanded. This is because banding has no advantages when the ratio between successive frequencies of the unbanded spectrum is greater than the frequency ratio within the specified band width. The $nS(n)$ version of the von Karman spectrum is also computed if the original version was written to disk.

The program terminates here if MWIND is zero, i.e., if no mwe simulation is to be made. Otherwise, the following operations are performed:

First, Subroutine FOURALTER is called to find the phase angle of the 1P harmonic in the simulated data D1. The ANGLE is identified by

ANGLE = Arctan (B, A), in degrees, where the equation of the mwe is

$$U[mwe](t) = A \cos(\omega \times t) + B \sin(\omega \times t)$$

or

$$U[mwe](t) = C \cos(\omega \times t - \pi \times \text{ANGLE}/180.),$$

where

$$C = \sqrt{A^2 + B^2}$$

and ω is the rotational rate in radians per second.

The calculated variables OFFSET and IFFSET are a combination designed to bring $U[mwe](t)$ into phase with the 1P turbulence harmonic when DELAY is zero, and when the mwe equations are written as they are in Subroutines HAWTMEAN and VAWTTNMEAN. The program calls up the appropriate subroutine to calculate one cycle of mwe for the particular HAWT or VAWT component simulation being calculated. This does not occur for either the VAWT u- or VAWT v-component simulations.

The one cycle of mwe is returned to the main program. It is extended through as many cycles as are needed to cover the turbulence. It is then added to the turbulence.

With this done, the program goes back to the moment-calculating routine and recalculates all the statistics of the simulated data. These include the moments, spectrum and harmonic spike integrations of the spectrum of the simulated data including mwe.

3.3.2 Specific Subroutine Operations

A selection of the following subroutines is called by each run. Figure 6 illustrates where the subroutines fit in the operation of the whole program.

3.3.2.1 Subroutine BESSEL

Subroutine BESSEL computes a summation for each of the Bessel functions until both addends are reduced below a certain tolerance. At this point, the

computed sums become the two Bessel function values, and control returns to the main program. The argument going into the summation begins near zero. When the argument exceeds eight, the sums diverge. Therefore, if the argument reaches eight, control is returned to the main program, and a warning message is printed out. Fortunately, this potential problem does not seem to exist in actual computations.

Of the four arguments in the call list, three are essential. The fourth applies only in the so-called D-line output used for checking the subroutine. The three essential arguments are the single input argument for the two Bessel functions and the two output values.

3.3.2.2 Subroutines VAWTUV and VAWTTN

These subroutines are alternate routes for the main program, depending on the value of KAWT, that is, on what kind of simulation is being executed. If the simulation is any of the VAWT simulations, the part of the main program that computes the acf for the HAWT simulation is bypassed and one of these subroutines is called. Subroutine VAWTUV is used for a VAWT u- or v-component simulation and Subroutine VAWTTN is used for a VAWT tangential or radial component simulation. Both of these subroutines have the same call to Subroutine BESSEL and the same windowing option as the main program has for the HAWT simulation. The call lists are somewhat long. Most of the variables therein are defined in the glossary in Appendix A. Ordinarily, the user need not be concerned with them.

3.3.2.3 Subroutine COOLEY

This FFT subroutine was authored by Winkelman and Smith before 1970. It accepts two real data series as the real and imaginary parts of a complex series and performs the FFT of the complex series. Certain additional logic is necessary to sort out the values for the two power spectra and the cross spectra when two sets of original data are entered, filling both the real and the imaginary parts of the complex series seen by the subroutine. In the present operations, we filled only the real slots.

The subroutine is called three times to effect the transform. There are two input variables. The first is the complex data series. The second is an indicator that differs on each of the three submissions:

1. the negative of the number of members in the complex data vector
2. the positive of the same number
3. zero.

The output Fourier transform values occupy the same slots the original data occupied.

3.3.2.4 Subroutine LOGBAND

This subroutine reads in a number of evenly banded $S(n)$ spectra over the same frequency range and converts them to $nS(n)$ spectra logarithmically banded. This operation is performed on $S(n)_r$, and on the von Karman spectra $Svk(n)_r$ and $Svk(n)_{ra}$, if they have been calculated and written to disk. The call list for the subroutine consists of

BPSD	number of logarithmically-spaced frequency bands per spectral decade. The recommended value of BPSD is 10.
K13	the option governing whether the von Karman spectra are written to disk.
MWF	a flag telling the subroutine whether or not to read a third record of $S(n)$ values. This third spectrum is of simulated data including mwe.

After the subroutine reads the $S(n)$ input spectra, it constructs the bounds of the logarithmically spaced bands. The highest frequency band has the Nyquist frequency ($0.5/DT$) for its upper bound. Upper bounds of the successively lower frequency bands are all related by the same ratio, which is

$$RATIO = 10.0^{(1.0/BPSD)}.$$

That is, if the upper bound of the highest band is FQQ , the Nyquist frequency, the lower bound of this band is $FQQ/RATIO$, and the central frequency is the geometric mean of those two. The second highest band has $FQQ/RATIO$ for its upper frequency bound and $FQQ/RATIO^2$ for its lower bound. This formation of frequency bands continues until the frequency band width becomes less than the

fundamental frequency, thus leaving some of the lowest frequency values of $S(n)$ unbanded. Once the band limits are established, the $nS(n)$ values are computed by straightforward arithmetic. The subroutine prints out a table of the banded estimates and, below these, the unbanded $nS(n)$ values are also printed out.

This feature was used to generate the spectra shown in Appendix B. Genuine rotational spectra would be distorted by this type of banding. Therefore, operation of Subroutine LOGBAND is not essential.

3.3.2.5 Subroutine FOURALTER

Given a frequency ENO, Subroutine FOURALTER computes the A and the B of the 1P wave:

$$S(1P)\text{turbulence} = A \cos(2\pi \times \text{ENO} \times t) + B \sin(2\pi \times \text{ENO} \times t) .$$

These are printed out, and the phase angle

$$\text{ANGLE} = \text{Arctan} (B, A)$$

is computed and returned to the main program so that the mean wind effect, which is a wave with frequency 1P, can be adjusted to the proper phase relation with the 1P wave of the turbulence.

3.3.2.6 Subroutines HAWTMEAN and VAWTTNMEAN

These subroutines calculate one cycle of simulated mean wind effect. Then this cycle is transferred to the main program and added repeatedly to the turbulence until enough cycles, including partial cycles, have been added to cover the turbulence record. Subroutine HAWTMEAN simulates the mwe for HAWT rotation; Subroutine VAWTTNMEAN simulates the mwe for either the tangential or the radial component of VAWT rotation.

3.4 ON BRACKETING THE ANSWERS BY ENVELOPING INPUT PARAMETERS

As indicated above, turbulence rms and length scales are uncertain. The turbulence rms during unstable conditions may well be 50 percent greater than

the program-calculated value, which applies for neutral conditions. Similarly, the effective surface roughness length may well be anywhere from $2/3$ to $3/2$ that reasonably assumed. Surface roughness length affects model calculations only through the rms. The results described in the next section suggest that both length scales specified by the model may be about 3.5 times the height. However, turbulence length scales do not scale exactly with height. Therefore, a wider range should be considered. The user may wish to submit a series of runs, varying parameter values within these ranges and plotting all results in order to get an envelope.

A reasonable envelope for rms would be 0.8 to 1.5 times the program-calculated values for SIGU. This allows for uncertainty about both atmospheric stability and surface roughness. However, if the stable atmosphere is to be modeled, the rms may well be half the program-calculated values. An envelope of values for rms can be used without running the model again because all simulated wind values are directly proportional to rms and all spectral values are directly proportional to the square of the rms. Other reasonable envelopes would be:

$$L_x: 3Z \text{ to } 6Z.$$

$$L_y: 0.4 L_x \text{ to } 1.0 L_x.$$

For HAWT simulations, a smaller choice of $L_y(u)$ is appropriate. For VAWT simulations, L_y should approximate L_x more closely. Calculating an envelope of values for L_x and L_y requires running the model for each individual pair of specified values.

4.0 MODELING OF SPECTRAL ANALYSIS OBTAINED BY ANALYSIS OF FIELD DATA

The comparison in this section is based on spectral analysis. We use two descriptors. One is the spectrum itself. The spectrum of rotational turbulence data produces a series of spikes at the rotational frequency and at a number of its harmonics, or overtones (see figures in Appendix D). The other descriptor is the energy in the harmonic spikes of the rotational spectrum. The energy is computed by integrating over the frequency range of each harmonic spike. Since the latter descriptor is more important in application, it is presented first.

4.1 MEASURED DATA DESCRIPTION

On June 5, 1984, data were taken by two hotfilm devices mounted on the boom of a vertical-axis rotating boom apparatus located within the Hanford 300 area. The boom, driven by an electric motor, rotated in a horizontal plane in response to the wind. The final hot film analysis data consisted of the components of the wind tangential and radial to the circle of rotation (see Figure 2), recorded at a sampling rate of 25/sec. The rotating boom was mounted at a height of 7.2 m above the ground and the hot films were located at a radius of 4.17 m from the vertical axis of rotation. The mean wind speeds were taken from analysis of data from a Gill anemometer mounted at the same height nearby.

Data were collected for four test periods. Table 1 summarizes the conditions for these test periods, including starting times, mean wind speed and rotational rate of the blade. Starting times are used to identify the test periods.

The final analyses were performed by taking a segment of 8192 rotational data (representing 328 seconds) from each test period and subdividing it into four equal sections. Each section was analyzed separately before the four results were averaged together to arrive at the final characterization for each test case. A sample of the rotating boom hotfilm-measured wind speed is given in Figure 7.

TABLE 1. Conditions for the Four Test Periods, June 5, 1984.
All measurements were taken 7.2 m above ground level, and with a 4.17 m radius of rotation

<u>Starting time (hours, minutes)</u>	<u>Mean wind speed (m/s)</u>	<u>Rotation rate (Hz)</u>
1327	7.3	0.582
1432	6.7	0.591
1502	8.2	0.590
1521	6.6	0.776

FIGURE 7. Tangential and Radial Component Data, Test 1327.
a. Total wind effect, in m/s; b. Turbulence effect, in m/s

Figure 7a shows the total of mean wind and turbulence, while Figure 7b shows the turbulence only. Evidently the mean wind effect dominates the turbulence at the frequency that corresponds to the rotation rate of the blade. It is perhaps this evidence that often leads to the conclusion that turbulence is not important for VAWTs. However, our results show that at higher frequencies of wind fluctuation the turbulence dominates.

4.2 MODELING SCENARIOS

Two modeling scenarios were applied. They were the "MWIND=0" and "MWIND=1" models. In the first case, turbulence alone was handled in the model and the mean wind effect was simulated by adding $0.5 U^2$ at the first harmonic. In the second case, the mean wind effect went directly into the model.

In all cases, the discretization interval was determined by specifying NANGLE. The value specified was calculated by determining the number of samples per rotational cycle from the values of the discretization interval used in measurement and the rotational frequency. Thus a value of 42 was used for NANGLE for Tests 1327, 1432, and 1502, while a value of 33 was used for Test 1521. Both length scales, EL1 and EL2, were set at 3.5 Z, or 25 m.

4.3 ENERGY IN THE HARMONIC SPIKES, COMPARISON BETWEEN MODELED AND MEASURED

Ratios were computed between energy in the harmonic spikes as calculated by the model and as calculated from data analysis. The results, averaged over the second through sixth harmonics (leaving out the mean wind effect, which is in the first harmonic), are given in Table 2. Table 3 breaks these down by harmonic.

TABLE 2. Average Ratio of Modeled/Measured Energy in Harmonic Spikes, Averaging over All Tests, and over Harmonics 2 to 6. Turbulence and mean wind effects are modeled together.

	<u>Tangential Simulation</u>	<u>Radial Simulation</u>
MWIND=0	1.06	0.91
MWIND=1	1.17	0.96

TABLE 3. Average Ratio of Modeled/Measured Energy in Harmonic Spikes, by Harmonic, Averaging over All Tests. Mean wind and turbulence effects are modeled together.

Harmonic	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
MWIND=0						
Tangential	0.82	1.61	1.00	1.06	0.80	0.83
Radial	1.02	0.50	0.99	1.17	1.10	0.78
MWIND=1						
Tangential	0.86	2.03	1.07	1.09	0.80	0.83
Radial	1.02	0.53	1.06	1.18	1.18	0.83

Comparisons should be made for different harmonics separately. We recall that the first harmonic result, combining mwe and turbulence, is primarily a mwe result because the mwe is more than an order of magnitude greater than the turbulence. The higher harmonic results are primarily turbulence and, thus, depend on the length scale and variance choices used in the modeling scenario.

4.3.1 First Harmonic (rotational frequency)

The entire purpose of creating the "MWIND = 1" model was to obtain a better simulation of the first harmonic and of the data by providing for phase adjustment between the mwe 1P harmonic and the turbulence 1P harmonic. In the "MWIND = 1" model, the two harmonics in the tangential analysis are modeled as being in phase. The same modeling renders the two harmonics 90 degrees out of phase in the radial analysis. The results show a small improvement in the tangential analysis at the first harmonic. The energy ratios for the "MWIND = 1" models and "MWIND = 0" models are 0.86 and 0.82, respectively. This difference is not great enough to require that this phase relationship be more accurately modeled (assuming the in-phase modeling for the tangential component is correct). The two results for the radial component also do not differ significantly. Both are just over 1.0, showing that the model slightly overestimates the 1P energy in the radial component.

4.3.2 Second Harmonic

There are significant differences here between modeled and measured results. In both scenarios, the model overestimates 2P energy in the tangential

simulation and underestimates it in the radial simulation. Each error is by a factor of two. We hope this difference can be explained as more examples of wind measurements are analyzed.

4.3.3 Higher Harmonics

At the higher harmonics, the model estimates are all reasonably good. However, as is seen in Figures 8 and 9, the rotational character in the spectra of either model calculation or data analysis is not as strong as for the lower harmonics. Therefore, in these scenarios, the fit of measured and modeled results at these harmonics depends more on fortunate choice of length scale than on anything else, since the program was allowed to calculate the turbulence variance.

FIGURE 8. Spectra of Tangential Component of Rotational Wind - Mean Wind Effect Plus Turbulence. a. Test 1327; b. Test 1432; c. Test 1502; d. Test 1521

FIGURE 9. Spectra of Radial Component of Rotational Wind - Mean Wind Effect Plus Turbulence. a. Test 1327; b. Test 1432; c. Test 1502; d. Test 1521

The overall result obtained by Powell et al. (1985) in their HAWT analysis is better than the VAWT analysis results obtained here, particularly at the second harmonic. The reason is thought to be the longer radius used in the HAWT simulations.

We now turn to comparisons between modeled and measured results for the same component in the same test. The comparisons are shown in Figure 10 for the tangential component and in Figure 11 for the radial component. Most of the pertinent observations that can be made from these graphs have already been made under Table 3, the contents of which are the ratios of modeled to measured results averaged over the four tests, displayed for each harmonic. The results appear to be reasonably consistent among the four test cases in both the tangential and the radial analyses.

FIGURE 10. Harmonic Spike Energy, Tangential Component, Modeled and Measured. a. Test 1327; b. 1432; c. Test 1502; d. Test 1521

4.4 SPECTRAL PLOTS, MODELED VS. MEASURED

The match of $S(n)$ spectra for the tangential and radial components for the four tests are shown in Figures 8 and 9, respectively. These graphs do not add a great deal to the result because neither type of spectrum, whether from the model or from data analysis, shows much of the narrow spike character beyond the second harmonic, except for some of the spectra for the radial analyses in the third harmonic. Note that the modeled and measured results differ in this respect.

The short radius of rotation, coupled with a low rotation rate, accounts for the lack of characterization at higher harmonics. Appendix D provides samples of modeled analysis using a greater radius of rotation. It is also possible that the rotational character would have been more evident if the data had been averaged into a longer discretization interval and the parameter NANGLE correspondingly reduced in the model.

FIGURE 11. Harmonic Spike Energy, Radial Component, Modeled and Measured. a. Test 1327; b. Test 1432; c. Test 1502; d. Test 1521

The difference, mentioned earlier, between modeled and measured results for the second harmonic in the radial analysis is clearly shown in the spectra. We believe that there would be more harmonic spike character in both measured and modeled results if a longer radius had been used in measurement and simulated in modeling.

5.0 CONCLUSIONS AND RECOMMENDATIONS

We conclude that the model offered here is a useful and very economical means of simulating turbulence along a rotational path in the neutrally stable atmospheric boundary layer, i.e., the wind turbine layer, providing that the following limitations are recognized:

1. Meteorological events are not simulated.
2. Modifications of turbulence by the rotating machine are not included.
3. There is some theoretical uncertainty regarding choice of turbulence length scales.

Because execution time is very short for this model, less than 120 seconds on the VAX 11/780, the model is economically rerun using multiple choices of input parameters, so an envelope can be constructed that should include actual conditions. A boundary layer turbulence model must not be presumed to be more precise than this, unless modeling is limited to so-called isotropic scales. These are small scales and do not include most scales significant to wind turbine operations. Key parameters such as turbulence rms and length scales should be enveloped rather than assumed, since they cannot be precisely evaluated.

For future work, it is suggested that the experience gained in constructing this model be used to improve the state of the art of simulating correlated turbulence inputs at two positions on the same blade.

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APPENDIX A

LISTINGS OF THE PROGRAM CODE, A GLOSSARY,
AND A TEST CASE

APPENDIX A

LISTINGS OF THE PROGRAM CODE, A GLOSSARY, AND A TEST CASE

This appendix has three parts. The first is the listing of the program and all its subroutines. The second part is a glossary of code terms. The third part is the input and output of a test case.

A.1 CODE LISTING

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```
*      This program calculates an autocorrelation function of wind speed
*      data that corresponds to wind variation experienced by a point
*      on a rotating wind turbine blade, either HAWT or VAWT. For HAWT
*      the wind direction is perpendicular to the plane of blade rotation.
*      For the VAWT there are four optional definitions for the turbulent
*      wind:
*          u - parallel to mean wind
*          v - perpendicular to mean wind
*          t - tangential to rotating surface
*          n - normal to rotating surface
*              (In the User's guide the n component is called the r
*               component, meaning radial).
*
*      The program then computes several power spectra S(n) as described
*      in the Users's manual. The important one is that called S(n)r, which
*      is used as a basis for later data simulation. There are two optional
*      methods for the simulation. One uses S(n) to generate an impulse
*      response functions and calculates the simulated data by convolving
*      the impulse response function with Gaussian white noise. The other
*      option uses S(n) to generate the amplitudes or a Fourier decomposition.
*      Then phase angles are supplied to each harmonic as an uncorrelated
*      random variable. An inverse Fourier transform yields the simulated
*      data.
*      The 80-member spectrum printed out is the one called S(n)c in the
*      User's manual. It is used for this print out and later to integrate
*      so as to calculate the energy in each harmonic spike of the spectrum.
*      This spectrum is produced by direct cosine integration of the auto-
*      correlation function.
*      This body of comments was written by David Powell, 12/5/85.
```

CCCC

CCCC

```
*      DEFINITIONS:
*      Some of the variables exist in one to three versions in addition to
*      the original, as is shown by the final letters, A, ND, or AND.
*
*      The A final means that this value was needed to compute the complete
*      aliased spectrum. For example if DT, the discretization interval is
*      2., DTA will be (2.*ALIAS).
*      The ND final means that this version of the variable is dimensionless.
*      The AND final means that both effects are combined.
*
```

* DELAY - offset angle between mean wind effect and 1P harmonic
 * of simulated turbulence (degrees)
 * ALFA is the radius of blade radius to turbulence length scale.
 * ANGLE - Phase angle of 1P harmonic in simulated data. Zero value
 * indicates a cosine wave (degrees).
 * ANGLEA - The angle the tangent or normal to the circle at the initial
 * position makes with the mean wind direction (degrees).
 * It is now defined in Subroutine VAWTTN.
 * BETA is the ratio of ALFA to tip speed ratio $\Omega \cdot \text{RADIUS} / U$.
 * CHK is the highest final value that will be accepted in an auto-
 * correlation function without windowing (Hanning).
 * CMMT - number data to be simulated.
 * CMMTA
 * DT - the data discretization interval in seconds.
 * DTA, DTND, DTAND
 *
 * D1() - final simulated data.
 * D1M() - one cycle of mean wind simulation.
 * EL1 is the turbulence length scale in beta, $(L_u)x$.
 * EL2 is the turbulence length scale in alfa, $(L_u)y$.
 * ENL() - frequencies n in Hz. These are linearly spaced and limited in
 * number to 80.
 * ENLND()
 * ENL1() - Frequencies for 20 divisions of the first band of ENL().
 * ENL1ND()
 * ENP() - Cyclic frequency in terms of blade rotation rate (so many P).
 * EN0 is the blade rotation rate in cycles per second.
 * EN1 - lowest frequency for which spectral computation is possible -
 * reciprocal of data length - fundamental frequency - Hz
 * EN1ND
 * EN2 - Nyquist frequency - highest frequency for which spectral
 * computation is possible - Hz.
 * EN2A, EN2ND, EN2AND
 * G1() - white noise
 * HT1() - two-sided impulse response function
 * IPFSET - Number of positions mean wind wave is to be shifted
 * before adding to simulated turbulence.
 * ILIAS is the reciprocal of the fraction of the spectrum that is
 * regarded as fit to retain because aliasing can be ignored.
 * For example: ILIAS = 1 - Retain all of the spectrum.
 * = 2 - Retain the lower frequency half.
 * = 4 - Retain the lower frequency quarter.
 * Recommended values are 2 or 4.
 * KAWT - option: 1 - Do HAWT u analysis and simulation
 * 2 - Do VAWT u
 * 3 - Do VAWT v
 * 4 - Do VAWT t
 * 5 - Do VAWT n
 * KBR - option: 0 - Do Gaussian white noise simulation.
 * 1 - Do random phase simulation. This preferred.
 * KMAX is the maximum number of arguments that may be computed
 * for the autocorrelation function.
 * KSG is an option
 * 0: Calculate SIGU from neutral boundary layer theory.
 * 1: Use SIGU as read in.
 * KWINDOW - additional option to turn off windowing.
 * = 0, windowing is bypassed regardless of character of acf.
 * K8...K15 are options to write to LU 8....15
 * K8 - Write impulse response function to disc.
 * K9 - Write S(n) spectrum to disc
 * a) FFT of original acf
 * b) S(n) of simulated data
 * K11 - Write S(n) from cosine integration of acf to file (needed?)

```

*      K12 - Write simulated data to file.
*      K13 - Write n and von Karman S(n) to file.
*      K14 - Write complex Fourier coefficients of simulated data to file
*      K15 - Write banded nS(n) spectra of simulated data, preceded by
*            unbanded nS(n) for lowest frequencies.
*      MMT is the number of data to be simulated.
*      MMTA
*      NHAR is the number of unbanded spectral estimates S(n) to be
*            written to output file.
*      NP is the number of points to be used on one side of the
*            two-sided symmetrical impulse response function.
*      OMEGA is blade rotational rate (radians/sec).
*      R() - a timelag autocorrelation function generated in SUBROUTINE
*            BESSEL.
*      RADIUS is blade radius (m).
*      SIGU is the rms value for u (u-component turbulence), (m/s).
*      SIGU2 is the corresponding variance (m/s)**2.
*      SIGV, SIGV2 - same for v-component turbulence (m/s).
*      SPECL() - S(n) for linearly spaced frequencies - (m**2/sec)
*      SPECLND()
*      SPECL1() - S(n) for 20 divisions of the first band of SPEC().
*      SPECL1ND()
*      T - running dimensionless time - summation of increments of DTAND.
*      TMAX is dimensional max time for autocorrelation function.
*      U is wind speed (m/s) at height Z.
*      USTAR2 is the square of the corresponding friction velocity (m/s)**2.
*      VKSPEC() - S(n) according to Von Karman - same frequencies as SPECL().
*      XIF1(N) is the power spectral density S(n) (m**2/s**3)
*      Z is nub height (m).
*      Z0 is surface roughness length (m).
C****

```

```

COMPLEX XTEND, AN1, HALF

```

```

DIMENSION R(8192), RP(4097), VKSPEC(80)
DIMENSION ENL(80), ENP(80), SPECL(80), ENL1(20), SPECL1(20)
DIMENSION ENLND(80), SPECLND(80), ENL1ND(20), SPECL1ND(20)
DIMENSION XTEND(16384), XIF1(4097), XVK(4097), XVKA(4097)
DIMENSION G1(12000), D1(8192), HT1(2000), SMOM(4)
DIMENSION DCOS(90), DSIN(90), D1M(90), PVAR2(7)
COMMON MMT, MMTA, DT, DTA, DTND, DTAND, EN1, EN1ND, EN2,
*EN2A, EN2ND, EN2AND, NANGLE, NANGLEA, RADIUS, EN0, Z, U,
*Z0, KSG, SIGU, SIGV, EL1, EL2, ILIAS, KNDOPT,
*KWINDOW, CHK, KMAX, NHAR, USTAR, ALFA, BETA, SIGU2,
*SIGV2, PVAR(7), PRMS(7), PVARVK(7)

```

```

EQUIVALENCE (RP, XVK), (R, D1)

```

```

DOUBLE PRECISION DSEED

```

```

CHARACTER KSERIAL*5

```

```

CHARACTER KAWTER(5)*30

```

```

*      VKU is the Von Karman u-spectrum. VKUD is the denominator of VKU.
VKUD(ENVK) = (1.0 + 70.78 * ENVK**2)**0.833333
VKU(ENVK) = 4.0 * ENVK / VKUD(ENVK)
*      VKUA is the altered Von Karman u-spectrum.
VKUDA(ENVK) = (1.0 + 39.48 * ENVK**2)**0.833333
VKUA(ENVK) = 4.0 * ENVK / (1.339 * VKUDA(ENVK))
*      Following are the corresponding v-spectra.
VKVN(ENVK) = 1.0 + 188.75 * ENVK**2
VKVD(ENVK) = (1.0 + 70.78 * ENVK**2)**1.83333
VKV(ENVK) = 2.0 * ENVK * VKVN(ENVK) / VKVD(ENVK)
*      altered v
VKVNA(ENVK) = 1.0 + 105.28 * ENVK**2
VKVDA(ENVK) = (1.0 + 39.48 * ENVK**2)**1.833333
VKVA(E) = 2.0 * E * VKVNA(E) / (1.339 * VKVDA(E))

```

```

DATA KAWT/ER/'HAWT SIMULATION','VAWT U SIMULATION',
*'VAWT V SIMULATION','VAWT TANGENTIAL SIMULATION',
*'VAWT NORMAL SIMULATION'/
PI = 3.141592654
TWOPI = 2.0 * PI
HALF = (0.5, 0.0)
MWINDFLAG = 0

READ(5,*)
READ(5,*) KAWT, MWIND, DELAY
READ(5,*)
READ(5,*) RADIUS, EN0, Z, U, Z0, KSG, SIGU, SIGV, KEL, EL1, EL2
READ(5,*)
READ(5,*) KNDOPT, NANGLE, DT, MMT, ILIAS, KWINDOW, CHK, NP
READ(5,*)
READ(5,*) K8, K9, K11, K12, K13, K14, K15
READ(5,*)
READ(5,*) KSERIAL, KBR, KXIFPR, KVKPR
IF(MWIND.EQ.0.OR.KNDOPT.EQ.0) GO TO 101
WRITE(7,1001)
1001 FORMAT(1H ,'KNDOPT MUST EQUAL 0 AND NANGLE MUST BE SPECIFIED
* WHEN MWIND.EQ.1')
STOP
101 CONTINUE
IF(KNDOPT.EQ.0) DT = 1.0 / (FLOAT(NANGLE) * EN0)
IF(KNDOPT.NE.0) NANGLE = 0.01 + 1.0 / (DT * EN0)
PIEN0 = PI * EN0
MMTA = MMT * ILIAS
KMAX = MMTA / 2
NHAR = MMT / 2
ALIAS = ILIAS
DTA = DT / ALIAS
DTND = DT * PIEN0
DTAND = DTND / ALIAS
NANGLEA = NANGLE * ILIAS
IF(NANGLEA.GT.MMTA) NANGLEA = MMTA
IF(K15.NE.0) K9 = 1
CMMT = MMT
CMMTA = MMTA
* The fundamental and Nyquist frequencies of the spectrum S(n) before
* removal of high frequency (highly aliased) part.
EN1 = 1.0 / (CMMT * DT)
EN1ND = EN1 / (PIEN0)
EN2 = 0.5 / DT
EN2A = EN2 * ALIAS
EN2ND = EN2 / (PIEN0)
EN2AND = EN2ND * ALIAS
FF = 1.0 / (CMMT * DT)
IF(KSG.GT.0) GO TO 105
SIGU = 0.96 * U / ALOG(Z/Z0)
SIGV = SIGU
105 SIGU2 = SIGU * SIGU
SIGV2 = SIGV * SIGV
UST1 = 0.4 * U / ALOG(Z/Z0)
UST2 = SIGU / 2.4
USTAR2 = UST1 * UST2
USTAR = SQRT (USTAR2)
IF(KEL.GT.0) GO TO 11
EL1 = 4.2 * Z
EL2 = 0.4 * EL1
11 ALFA = RADIUS / EL2
OMEGA = TWOPI * EN0
BETA = U / (EL1 * OMEGA)

```



```

WRITE(7,*) KAWTER(KAWT)
WRITE(10,*) KAWTER(KAWT)
WRITE(7,1201) KSERIAL
WRITE(10,1201) KSERIAL
1201 FORMAT(1H , 'SERIAL NUMBER ', A)

IF(KAWT.EQ.1.OR.KAWT.EQ.2) SIG2 = SIGU2
IF(KAWT.EQ.3) SIG2 = SIGV2
IF(KAWT.EQ.4.OR.KAWT.EQ.5) SIG2 = SIGU2

CALL RODAPRINT(7,1)
CALL RODAPRINT(10,1)

CHKSM = 3.0 * CHK

*      Set linearly spaced dimensionless frequencies.

DO 21 I = 1, 80
  ENP(I) = 0.1 * FLOAT(I)
  ENLND(I) = ENP(I) / PI
21 ENL(I) = ENLND(I) * PIEN0

DO 22 I = 1, 20
  FI = I
  ENLND(I) = 0.05 * FI * ENLND(1)
22 ENL1(I) = ENLND(I) * PIEN0
*      End initial section of program.

C****
*      The steps from here to calculation of R(K) calculate the auto-
*      correlation function for a rotating point according to the memo
*      by J. R. Connell. The autocorrelation is a function of three
*      dimensionless parameters, ALFA, BETA, and T.
C****

*      G43 is the gamma function for 4/3.
G43 = 0.89298
247 G13 = 3.0 * G43
  CONST = 2.0 / G13

***
*      Do VAWT simulation for u or v.
***
  IF(KAWT.EQ.2.OR.KAWT.EQ.3) CALL VAWTUV (R, KMAX, DTAND, ALFA,
*BETA, CHKSM, KWINDOW, TWOARG, CHECK, PI, EN0, KAWT, CONST, TMAX)
***
*      Do VAWT simulation for tangential or normal component.
***
  IF(KAWT.EQ.4.OR.KAWT.EQ.5) CALL VAWTTN (R, KMAX, DTAND, ALFA,
*BETA, CHKSM, KWINDOW, TWOARG, CHECK, PI, EN0, KAWT, CONST,
*NANGLEA, TMAX)
  IF(KAWT.GT.1) GO TO 301

***
*      Do HAWT simulation.
***
      DO KZ = 1, KMAX
        R(KZ) = 0.0
      END DO

```

```
T = 0.0
DO 25 K = 1, KMAX
```

* T is the dimensionless time argument for the autocorrelation function.

```
T = T + DTAND
ARGA = ( ALFA * SIN ( T ) ) ** 2.
ARGB = ( BETA * T ) ** 2
ARG = SQRT ( ARGA + ARGB )
TWOARG = 2.0 * ARG
BK13 = 0.0
BK23 = 0.0
```

```

C****
*      SUBROUTINE BESSEL will calculate a modified Bessel function of the
*      second kind of orders 1/3 and 2/3 provided that the argument is
*      not greater than 8. If the argument is greater than 8, the summation
*      used to calculate the Bessel function will not converge, and calcula-
*      of the autocorrelation function must be terminated. An autocorrela-
*      tion function terminated before it intrinsically converges may
*      transform into a spectrum with some values negative. The printed
*      autocorrelation function should be examined to assess whether
*      it converged or not.
C****
                                IF ( TWOARG .LE. 8.0 ) THEN
                                    CALL BESSEL ( TWOARG,BK13, BK23, T )
                                END IF
                                DIFF = BK13 - ( BK23 * ARG ) / ARG
                                ARG3 = ARG ** .333333333333
                                R ( K ) = CONST * ARG3 * DIFF
if(k.lt.3)go to 25

*      Terminate the autocorelation function if it has converged.

CHECK = ABS(R(K)) + ABS(R(K-1)) + ABS(R(K-2))
IF(CHECK.LT.CHKSM) GO TO 26
25 continue
*      Used only if the above loop runs KMAX times. Printed value of KMAX
*      should be noted.
GO TO 27
26 KMAX = K
27 IF(KWINDOW.EQ.0) GO TO 30
*      Use Hanning window if convergence has not occurred, and if allowed by
*      option.
RK = R(K-1)
FMAX = KMAX
DO 29 K = 1, KMAX
FK = K
29 R(K) = R(K) * (0.50 + 0.50 * COS (PI * FK/FMAX))
WRITE(7,2901) RK
2901 FORMAT (1H0,'Hanning WINDOW USED - LAST R BEFORE USE', F7.4)
30 TMAX = FLOAT(KMAX) * DTA
301 WRITE(7,3011)KMAX, TMAX

3011          FORMAT (1H0,' AUTOCORRELATION FUNCTION', I6,' steps',
*F10.2,' seconds')
IF(KMAX.GT.1000) GO TO 305
WRITE(7, 3012 ) ( R(K),K=1, KMAX)

3012          FORMAT ( 1X, 15F8.4 )
GO TO 31
305 ISK = 1 + KMAX/1000
RP(1) = R(1)
I = 2
K = 1 + ISK
306 RP(I) = R(K)
I = I + 1
K = K + ISK
IF(K.LE.KMAX) GO TO 306
I = I - 1
WRITE(7,3071) ISK

```

```

3071 FORMAT(1H , 'After first value skip interval is', I3)
      WRITE(7,3012) (RP(K), K = 1, I)

*      Determine which warning should be printed out because of manner of
*      termination of acf.

31  IF(KWINDOW.NE.0) GO TO 315
      IFLAG = 0
      IF(TWOARG.GT.8.0) IFLAG = 1
      IF(CHECK.GT.CHKSM) IFLAG = IFLAG + 2
      IF(IFLAG.EQ.0) GO TO 315
      GO TO (311, 312, 313) IFLAG
311  WRITE(7,3111)
3111 FORMAT(1H , 'WARNING - BESSEL FUNCTION DID NOT CONVERGE')
      GO TO 315
312  WRITE(7,3121) CHECK
3121 FORMAT(1H , 'WARNING - ACF DID NOT CONVERGE, CHECK = ', E11.3)
      GO TO 315
313  WRITE(7,3111)
      WRITE(7,3121) CHECK

*      End correlation calculating section of program

```

```

C****
*       Compute spectrum S(n) by Fourier transformation of the
*       autocorrelation function. Here enter the FFT.
C****

315 JTCPL = KMAX + 1
    XTEND(1) = CMPLX (1.0, 0.0)
    DO 32 J = 2, JTCPL
        XTEND(J) = CMPLX (R(J-1), 0.)
        K = MMTA - J + 2
32 XTEND(K) = XTEND(J)

    CALL COOLEY (XTEND,-MMTA)
    CALL COOLEY (XTEND, MMTA)
    CALL COOLEY (XTEND, 0)

    A = REAL(XTEND(1))
    B = AIMAG(XTEND(1))
    XIF1(1) = 2.0 * A * SIG2 * DTA

CCCC
*       This section defines parameter values to removed aliased spectra.
CCCC
NHAR1 = NHAR + 1
C      MMT = 2 * NHAR
      MMTHALF = MMT/2
      JTCPL = MMTHALF + 1
      CMMT = MMT

*       End parameter definitions.

      NSUM = 0
      VSUM = 0.
      DO 33 J = 2, MMTHALF
          XIF1(J) = 2.0 * REAL(XTEND(J)) * SIG2 * DTA
          IF(XIF1(J).LT.0.0) NSUM = NSUM + 1
33 VSUM = VSUM + XIF1(J)
      VSUM = VSUM * FF
      WRITE(7,3301) VSUM
3301 FORMAT(1H0,'VARIANCE FROM INTEGRATION OF ROTATIONAL
* S(M) COMPUTED BY FFT OF ACF', F12.6,' (M/S)**2')
      IF(NSUM.EQ.0) GO TO 34
      WRITE(7,3351) NSUM
      WRITE(6,3351) NSUM
3351 FORMAT(1H ,I5,' NEGATIVE NUMBERS IN REDUCED FFT PRODUCED
* SPECTRUM - S(n)r.')
```

* Write S(n) from FFT of R(t) to disc.

```

34 IF(K9.NE.0) WRITE(9) FF, NHAR, (XIF1(I), I = 1, NHAR)

* Compute S(n) version of Von Karman spectrum.

IF(KAWT.EQ.3.OR.KAWT.EQ.4) GO TO 351
DO 35 N = 1, NHAR
    FN = N
    EN = FN * FF
    ENVK = EN * EL1 / U

    XVK(N) = VKU(ENVK) * SIG2 / EN
    XVKA(N) = VKUA(ENVK) * SIG2 / EN
35 CONTINUE
GO TO 355
```

```

351 DO 352 N = 1, NHAR
    FN = N
    EN = FN * FF
    ENVK = EN * EL1 / U
    XVK(N) = VKV(ENVK) * SIG2 / EN
    XVKA(N) = VKVA(ENVK) * SIG2 / EN
352 CONTINUE
355 IF(KVKPR.EQ.0) GO TO 38
    WRITE(7,3701)(XVKA(N), N = 1, NHAR)
3701 FORMAT(1H1,'VON KARMAN S(N) SPECTRUM',
    */(1H ,5F12.6, F15.6, 4F12.6))

*      Write von Karman spectra and frequencies to disc.

38 CONTINUE
    IF(K13.EQ.0) GO TO 39
    WRITE(13) NHAR, (XVK(N), N = 1, NHAR),
    *(XVKA(N), N = 1, NHAR)
    REWIND 13
C****
*      Compute spectrum S(n) by Fourier transformation of the autocorrelation
*      function at evenly spaced *      Compute the upper limit wave number base
*      and the frequency difference in the frequency vector ENL, which is
*      0.1 * EN0.
C****

39 NEF = 0.001 + 5.0 / (DT * EN0)
    IF(NEF.GT.80) NEF = 80

    DO N = 1, NEF
        A = 0.5
        T = 0.0
        DO K = 1, KMAX
            T = T + DTAND
            A = A + R(K) * COS(TWOPI * ENLND(N) * T)
        END DO
        Dimensional equivalent of DT is DT/PIEN0.
        SPECL(N) = 4.0 * SIG2 * A * DTA
    END DO

*      Compute spectral density within lowest frequency band.

    DO 42 N = 1, 20
        A = 0.5
        T = 0.0
        DO 41 K = 1, KMAX
            T = T + DTAND
41 A = A + R(K) * COS(TWOPI * ENLND(N) * T)
42 SPECL1(N) = 4.0 * SIG2 * A * DTA

*      Calculate length scale by integrating acf.

        A = 0.5
        DO 43 K = 1, KMAX
43 A = A + R(K)
        SCALEL = A * DTA * U

*      Write S(n) spectrum from cosine integration or acf to file.

        IF(K11.NE.0) WRITE(11) NEF, (SPECL1(N), N = 1, 20),
        *(SPECL(N), N = 1, NEF), (ENL1(N), N = 1, 20), (ENL(N), N = 1, NEF)

```

```

*      Calculate S(n) version of von Karman spectrum at NEF evenly spaced
*      frequencies.
      DO 48 N = 1, NEF
      ENVK = ENL(N) * EL1/U
      IF(KAWT.EQ.3.OR.KAWT.EQ.4) GO TO 47
      VKSPEC(N) = SIG2 * VKUA(ENVK) / ENL(N)
      GO TO 48
47 VKSPEC(N) = SIG2 * VKVA(ENVK) / ENL(N)
48 CONTINUE
      IF(K11.NE.0) WRITE(11) (VKSPEC(N), N = 1, NEF)

*      Compute variance of rotational spectrum.

*      Print out S(n) analysis from FFT.
      IF(KXIFPR.EQ.0) GO TO 715
      WRITE(7,7101) (XIF1(I), I = 1, NHAR)
7101 FORMAT(1H0,'S(n) estimates from FFT of ACF',
*/(1H ,5F12.6, F15.6, 4F12.6))

*      Print out S(n) analysis.

715 WRITE(7,8001), NEF
8001 FORMAT(1H1,'S(n) analysis - ',I3,' evenly spaced frequencies')
      WRITE(7,8101)
8101 FORMAT(1H , 'FREQUENCY(HZ)   FREQUENCY(P)           S(N)           VKS(N)'
*11X, 'FREQUENCY(HZ)   FREQUENCY(P)           S(N)           VKS(N)')
      DO 85 I = 1, 40
      IP = I + 40
      85 WRITE(7,8501)ENL(I), ENP(I), SPECL(I), VKSPEC(I), ENL(IP),
*ENP(IP), SPECL(IP), VKSPEC(IP)
8501 FORMAT(1H ,F13.5, F14.1, 2F12.6, F24.5, F14.1, 2F12.6)
      WRITE(7,8601)
8601 FORMAT(1H0,'SPECTRAL DENSITY FOR 20 DIVISIONS OF LOWEST FREQUENCY
* BAND'/' FREQUENCIES')
      WRITE(7,8611)(ENL1(I), I = 1, 20)
8611 FORMAT(1H ,10F12.6)
      WRITE(7,8621)
8621 FORMAT(1H , ' S(N)')
      WRITE(7,8631)(SPECL1(I), I = 1, 20)
8631 FORMAT(1H ,10F12.2)

*      Compute and print out sums needed to compute variance from S(n).

      A = 0.
      DO 87 I = 2, NEF
87 A = A + SPECL(I)
      B = 0.
      DO 88 I = 1, 20
88 B = B + SPECL1(I)
      WRITE(7,8801)A, B

8801 FORMAT(1H , 'SUMS OF S(N) FOR THE TWO SERIES',2F12.2)
      VAR = ENL(1) * (A + 0.05 * B)
      WRITE(7,8811) VAR
      WRITE(10,8811) VAR
8811 FORMAT(1H0,'VARIANCE OF S(N) ON THIS PAGE, S(N)c',
*F10.4,' (M/S)**2')
      WRITE(7,8812) SCALEL
8812 FORMAT(1H0,'LENGTH SCALE FROM INTEGRATION OF ACF IS',F10.1' M')
*      End spectrum computing section of program.

```

* Compute variance (energy) in the 1P, 2P,.....6P bands, where for example,
 * the variance in the 1P band is found by integrating from the 6th through
 * the 15th evenly spaced S(n) harmonics. This is done for both the
 * rotational spectrum SPECL(N) and the von Karman spectrum VKSPEC(N). The
 * first loop ending on Lable 882 performs this integration at frequencies
 * below the 1P band.

```

      K = 1
      SUM = 0.05 * B
      SUMVK = VKSPEC(1)
      DO 882 I = 2, 5
      K = K + 1
      SUM = SUM + SPECL(K)
882  SUMVK = SUMVK + VKSPEC(K)
      PVAR(1) = SUM * 0.1 * EN0
      PRMS(1) = SQRT(PVAR(1))
      PVARVK(1) = SUMVK * 0.1 * EN0
      DO 885 J = 2, 7
      SUM = 0.
      SUMVK = 0.
      DO 883 I = 1, 10
      K = K + 1
      IF(K.GT.NHAR1) GO TO 884
      SUM = SUM + SPECL(K)
883  SUMVK = SUMVK + VKSPEC(K)
      PVAR(J) = SUM * 0.1 * EN0
884  PRMS(J) = SQRT(PVAR(J))
885  PVARVK(J) = SUMVK * 0.1 * EN0

      CALL RODAPRINT(7,2)
      CALL RODAPRINT(10,2)
      WRITE(16,8851), EN0
      WRITE(16,8851) PVAR
      WRITE(16,8851) PVARVK
8851  FORMAT(1H ,F10.4, F15.4, 5F10.4)

```

C BEGIN DATA SIMULATING SECTION OF PROGRAM.
 C Compute impulse reponse function using FFT.

```

896 IF(KBR.NE.0) GO TO 50
      XTEND(1) = (0.0, 1.0)
      DO 90 J = 2, JTCPL
      A = SQRT (0.5 * XIF1(J) / DT)
      B = 0.
      XTEND(J) = CMPLX (A,B)
      K = MMT - J + 2
90  XTEND(K) = XTEND(J)

      CALL COOLEY (XTEND,-MMT)
      CALL COOLEY (XTEND, MMT)
      CALL COOLEY (XTEND, 0)

      DO 91 J = 1, MMTHALF
91  XIF1(J) = REAL(XTEND(J)) / CMMT

```

* Write impulse response function to disc.

```

      IF(K8.NE.0) WRITE(8) MMTHALF, (XIF1(I), I = 1, MMTHALF)
      WRITE(7,9211) (XIF1(I), I = 1, 100)
9211  FORMAT(1H ,5F6.3, F9.3, 4F6.3, F10.3, 4F6.3, F9.3, 4F6.3)
      WRITE(7,9221) NP
9221  FORMAT(1H0,I6,' POINTS USED TO CREATE SIMULATED DATA')
CCCC

```

* This portion executes a convolution of impulse response function Ht1


```

*      with Gaussian white noise.  The originally specified turbulence
*      variance is used.
CCCC
      DO 94 I = 1, NP
      I2 = NP + I - 1
      I1 = NP - I + 1
      HT1(I1) = XIF1(I)
      HT1(I2) = XIF1(I)
      94 CONTINUE
      NP2 = 2 * NP - 1
D      WRITE(7,9401) (HT1(I), I = 1, NP2)
      9401 FORMAT(1H0,'TWO-SIDED IMPULSE RESPONSE FUNCTION',
*/(1H,5F6.3, F9.3, 4F6.3, F10.3, 4F6.3, F9.3, 4F6.3))
      NDG = MMT + NP2
      DSEED = 10.D0
      CALL GGNML (DSEED, NDG, G1)
      DO 95 I = 1, NDG
      95 G1(I) = G1(I) * SIGU
D      WRITE(7,9501) NDG
      9501 FORMAT(1H0,'GAUSSIAN WHITE NOISE' I6,' DATA')
D      WRITE(7,9521) (G1(I), I = 2, NDG)
      9521 FORMAT(1H,20F6.2)
      DO 955 J = 1, MMT
      D1(J) = 0.
      DO 955 I = 1, NP2
      955 D1(J) = D1(J) + G1(I+J) * HT1(I)

*      Return to this point if second alternative was used.

      96 CONTINUE
*      Calculate first four moment of simulated data.

      SUM = 0.
      DO 961 I = 1, MMT
      961 SUM = SUM + D1(I)
      SUM = SUM / CMMT
      DO 962 I = 1, MMT
      962 D1(I) = D1(I) - SUM
      DO 963 I = 1, 4
      963 SMOM(I) = 0.
      DO 964 I = 1, MMT
      A = 1.0
      DO 964 J = 1, 4
      A = A * D1(I)
      964 SMOM(J) = SMOM(J) + A
      DO 965 J = 1, 4
      965 SMOM(J) = SMOM(J) / CMMT
      SMOM(3) = SMOM(3) / SMOM(2)**1.5
      SMOM(4) = SMOM(4) / SMOM(2)**2
      SMOM(1) = SUM
      DO 966 I = 1, MMT
      966 D1(I) = D1(I) + SUM
*      Write simulated data to disc.

      IF(K12.EQ.0) GO TO 969
      WRITE(12) MMT, (D1(I), I = 1, MMT)
      REWIND 12
*      Calculate spectrum of simulated data.

      969 XTEND(1) = CMPLX (D1(1), 0.0)
      DO 97 I = 2, MMT

```

```

97 XTEND(I) = CMPLX (D1(I), 0.0)
CALL COOLEY (XTEND,-MMT)
CALL COOLEY (XTEND, MMT)
CALL COOLEY (XTEND, 0)
FAC = 2.0 * DT / CMMT
XIF1(1) = REAL (XTEND(1)) * FAC
XIF1(JTCPL) = REAL (XTEND(JTCPL)) * REAL (XTEND(JTCPL)) * FAC
9701 FORMAT(1H , 'MMT, MMTHALF, JTCPL, EN0, FF, FAC AT 9701',
*3I6, 2F10.4, E12.4)
VSUM = 0.
DO 971 J = 2, MMTHALF
IJ = MMT - J + 2
AN1 = HALF * (XTEND(J) + CONJG (XTEND(IJ)))
XIF1(J) = AN1 * CONJG(AN1) * FAC
971 VSUM = VSUM + XIF1(J)
VSUM = VSUM * FF
PVAR2(1) = 0.
LDO = 0.5 * EN0 / FF
DO 972 I = 1, LDO
972 PVAR2(1) = PVAR2(1) + XIF1(I)
PVAR2(1) = PVAR2(1) * FF
DO 974 K = 1, 6
I1 = LDO + 1
FK = K
K1 = K + 1
LDO = (FK + 0.5) * EN0 / FF
PVAR2(K1) = 0.
DO 973 I = I1, LDO
973 PVAR2(K1) = PVAR2(K1) + XIF1(I)
974 PVAR2(K1) = PVAR2(K1) * FF
WRITE(7,9751) PVAR2
WRITE(10,9751) PVAR2
9751 FORMAT(1H0,'VARIANCES FOR FIRST HALF-P AND FOR 6P FROM
* SPECTRUM OF SIMULATED DATA, S(n)r',/1H ,F10.4, F15.4,
*5F10.4)
WRITE(17, 8851) EN0
WRITE(17, 8851) PVAR2
LPRXIF1 = 5.0 + 2.0 * EN0 / FF
IF(LPRXIF1.GT.JTCPL) LPRXIF1 = JTCPL
WRITE(7,9801) (XIF1(I), I = 1, LPRXIF1)
9801 FORMAT(1H1,'SPECTRAL ESTIMATES FROM SIMULATED DATA',
*/(1H ,10F12.4))
WRITE(7,9811) VSUM
WRITE(10,9811) VSUM
9811 FORMAT(1H0,'VARIANCE OF S(N)r FROM SIMULATED DATA',F10.4)
WRITE(7,9812) SMOM(1), SMOM(2)
9812 FORMAT(1H , 'SMOM(1), SMOM(2)', 2F10.4)
WRITE(7,9821) SMOM(3), SMOM(4)
WRITE(10,9821) SMOM(3), SMOM(4)
9821 FORMAT(1H , 'SKEWNESS AND KURTOSIS', 2F10.4)
IF(KBR.EQ.0) WRITE(7,9831)
9831 FORMAT(1H0,'FULL RANDOMIZING SIMULAITON - IMPULSE RESPONSE
* FUNCTION')
IF(KBR.NE.0) WRITE(7,9841)
9841 FORMAT(1H0,'HALF-RANDOMIZING SIMULATION - PHASE RANDOMIZED')

* Write S(n) from simulated data to disc.

IF(K9.NE.0) WRITE(9) (XIF1(I), I = 1, NHAR)
REWIND 9

* Write nS(n) from simulated data to disc.

```

```

      IF(K15.NE.0) CALL LOGBAND (10., K13, MWINDFLAG)
      IF(K14.EQ.0) GO TO 986
      DO 985 I = 1, MMT
985  XTEND(I) = XTEND(I) / CMMT

*      Write complex Fourier coefficients from harmonic analysis of
*      simulated data to file.

      WRITE(14) MMT, (XTEND(I), I = 1, MMT)
      REWIND 14
      GO TO 986

*      Calculate simulated data using harmonic analysis.

      50  IGGUWOPT = 1
D      WRITE(7,4901) JTCPL
4901  FORMAT(1H , 'JTCPL', I8)
      DSEED = 10.D0
      CALL GGUW (DSEED, JTCPL, IGGUWOPT, G1)
D      WRITE(7,5011) (G1(I), I = 1, JTCPL)
5011  FORMAT(1H , 'RANDOM DATA', / (1H , 20F6.3))
      DO 51 I = 1, JTCPL
      51  G1(I) = TWOPI * G1(I)
D      WRITE(7,5101) (G1(I), I = 1, JTCPL)
5101  FORMAT(1H0, 'RANDOM PHASE DATA', / (1H , 20F6.3))
      XTEND(1) = (0., 0.)
      DO 52 I = 2, JTCPL
      A = SQRT (0.5 * XIF1(I) * FF)
      THETA = G1(I)
      CR = A * COS(THETA)
      CI = A * SIN(THETA)
      XTEND(I) = CMPLX (CR, CI)
      K = MMT - I + 2
D      IF(I.GT.30) GO TO 52
D      WRITE(7,5191) I, XIF1(I), A, THETA, CR, CI, XTEND(I)
5191  FORMAT(1H , 'I,XIF1,A,THETA,CR,CI,XTEND(I)', I5, 5F10.4, F20.4,
      *F10.4)
      52  XTEND(K) = CONJG(XTEND(I))
D      WRITE(7,5201) (XTEND(J), J = 1, MMT)
5201  FORMAT(1H0, 'XTEND', / (1H , 5(F12.4, F8.4)))
      CALL COOLEY (XTEND, - MMT)
      CALL COOLEY (XTEND, MMT)
      CALL COOLEY (XTEND, 0)

*      These are the simulated data.

      DO 53 J = 1, MMT
      53  D1(J) = REAL (XTEND(J))
D      WRITE(7,5301) (D1(J), J = 1, MMT)
5301  FORMAT(1H , 'SIMULATED DATA', / (1H , 10F12.4))
      GO TO 96
      986 IF(MWIND.EQ.0) GO TO 999
      WRITE(7,9861)
      WRITE(10,9861)
9861  FORMAT(1H1, 'ANALYSIS OF SIMULATED DATA INCLUDING MEAN
      *WIND EFFECT')
      MWINDFLAG = 1
      CALL FOURALTER (D1, DT, EN0, ANGLE)
      WRITE(7,9862) ANGLE, DELAY
9862  FORMAT(1H , 'PHASE ANGLE FOR 1P IN SIMULATED DATA',
      *F10.1, ' DEGREES', / 1H , 'OFFSET ANGLE BETWEEN MEAN WIND
      * AND TURBULENCE AT 1P (DELAY)', F10.1, ' DEGREES')
      FNAN = NANGLE

```

```

FANGLE = ANGLE + DELAY
OFFSET = FANGLE * FNAN / 360.
IFFSET = 0.25 * FNAN - OFFSET
WRITE(7,9863) OFFSET, IFFSET
9863 FORMAT(1H , 'OFFSET, IFFSET, ' F10.1, 16)
DO 987 I = 1, NANGLE
  FI = I - 1
  FQ = 2.0 * PI * FI / FNAN
  DCOS(I) = COS(FQ)
987 DSIN(I) = SIN(FQ)
988 GO TO (989, 990, 992, 993, 993) KAWT
989 CALL HAWTMEAN (D1M, NANGLE, Z, RADIUS, U, Z0, MMT, IFFSET,
  *DSIN)
  GO TO 994
990 DO 991 I = 1, MMT
991 D1(I) = D1(I) + U
  WRITE(7,9911) U
9911 FORMAT(1H , 'THE MEAN WIND VALUE', F10.2, ' M/SEC HAS BEEN ADDED
  * TO ALL SIMULATED WIND VALUES.')
  GO TO 999
992 WRITE(7,9921)
9921 FORMAT(1H , 'THERE IS NO MEAN WIND ADDITION FOR THE V COMPONENT')
  GO TO 999
993 CALL VAWTTNMEAN (D1M, NANGLE, RADIUS, U, MMT, IFFSET, DCOS,
  *DSIN, KAWT, EN0)
994 CONTINUE
  WRITE(7,9941) (D1M(I), I = 1, NANGLE)
9941 FORMAT(1H , 'ONE CYCLE OF MEAN WIND EFFECT - M/S',/(1H ,20F6.2))
  KSET = MMT / NANGLE
  WRITE(7,9942) KSET
9942 FORMAT(1H , 'NUMBER OF COMPLETE MEAN WIND CYCLES IN SIMULATION'
  *I6)
  DO 995 K = 1, KSET
  KN = (K - 1) * NANGLE
  DO 995 I = 1, NANGLE
995 D1(I+KN) = D1(I+KN) + D1M(I)
  NSET1 = NANGLE * KSET + 1
  J = 0
  DO 996 I = NSET1, MMT
  J = J + 1
996 D1(I) = D1(I) + D1M(J)
  MWIND = 0
C   WRITE(7,9961)
9961 FORMAT(1H1, 'FINAL ANALYSIS AFTER MEAN WIND WAS ADDED')
C   WRITE(7,9962) (D1(I), I = 1, MMT)
9962 FORMAT(1H , 'D1',/(1H ,20F6.2))
  GO TO 96
999 STOP
END

```



```

29 ENSN(K,NS) = CBW(K) * ENSN(K,NS) / FLOAT (NTMNL)
30 CONTINUE
    NLOW = NL - 2
    DO 35 N = 1, NLOW
        FN = N
        CBWA(N) = FF * FN
        DO 34 NS = 1, NSPEC
34  ENSNA(N,NS) = CBWA(N) * SN(N+1,NS)
35 CONTINUE
    WRITE(7,4001)
4001 FORMAT(1H , 'BANDED NSN SPECTRA')
    WRITE(7,4002)
4002 FORMAT(1H , 'BAND CENTER, HI, LOW (HZ), NS(N),
    * HARMONIC COUNT PER BAND [NS(N):ORIG',9X,'SIM',
    *10X,'VK',8X,'VKA]')
    DO 50 I = 1, IBN
        I2 = 2*I
        IM = I2 - 1
    50 WRITE(7,5001) CBW(I), BW(IM), BW(I2), IDF(I), NLV(I),
    *NTV(I), (ENSN(I,NS), NS = 1, NSPEC)
5001 FORMAT(1H ,3F12.5, 3I6, F16.5, 3F12.5)
    WRITE(7,5101)
5101 FORMAT(1H0, 'UNBANDED NSN SPECTRA')
    WRITE(15,5501) NLOW
    DO 53 N = 1, NLOW
        WRITE(7,6001) CBWA(N), (ENSNA(N,NS), NS = 1, NSPEC)
    53 WRITE(15,6001) CBWA(N), (ENSNA(N,NS), NS = 1, 4)
    WRITE(15,5501) IBN
5501 FORMAT(1H ,I10)
    DO 60 I = IBN, 1, -1
    60 WRITE(15,6001) CBW(I), (ENSN(I,NS), NS = 1, 4)
6001 FORMAT(1H ,5F12.6)
90 RETURN
END

```

```

SUBROUTINE VAWTUV (R, KMAX, DT, ALFA, BETA, CHKSM, KWINDOW,
* TWOARG, CHECK, PI, ENØ, KAWT, CONST, TMAX)
  DIMENSION R(1)
  UORV = KAWT - 1
      DO KZ = 1, KMAX
          R(KZ) = 0.0
      END DO
  T = 0.0
  DO 25 K = 1, KMAX

```

* T is the dimensionless time argument for the autocorrelation function.

* The following is derived on pages 30 and 31 of the notebook labeled

* "Rotational Spectrum Problem" and written by David Powell.

```

T = T + DT
ARGB = BETA * BETA * T * T
ARG = ARGB
ARG = ARGB + ALFA * (1.0 - COS(2.0*T)) *
      (BETA * T + 0.5 * ALFA)

```

CCC
C The step below defines the "A" on page 31 of my notebook, where
C "A" = $r/2L$. The step above obviously defines "A"², which
C is derived before "A".

```

21      ARG = SQRT(ARG)
D      WRITE(7,2301) T, ARG
2301   FORMAT(1H , 'T, ARG', 2E12.4)
        TWOARG = 2.0 * ARG
        BK13 = 0.0
        BK23 = 0.0
        IF ( TWOARG .LE. 8.0 ) THEN
            CALL BESSEL ( TWOARG,BK13, BK23, T )
        END IF
        GO TO (235, 236) UORV
*      Hinze's normalized Q11 is CONST * ARG3 * DIFF.
235   DIFF = BK13 - BK23 * (ARG*ARG - ARGB)/ARG
        GO TO 24
236   YO2L = 0.5 * ALFA * SIN (2.0*T)
*      Hinze's normalized Q22 is CONST * ARG3 * DIFF.
        DIFF = BK13 - BK23 * (ARG*ARG - YO2L*YO2L)/ARG
24   ARG3 = ARG ** .333333333333
        R ( K ) = CONST * ARG3 * DIFF
        IF(K.LT.3) GO TO 25

```

```

CHECK = ABS(R(K)) + ABS(R(K-1)) + ABS(R(K-2))
IF(CHECK.LT.CHRSM) GO TO 26
25 continue
GO TO 27
26 KMAX = K
27 IF(KWINDOW.EQ.0) GO TO 30
RK = R(K-1)
FMAX = KMAX
DO 29 K = 1, KMAX
FK = K
29 R(K) = R(K) * (0.50 + 0.50 * COS (PI * FK/FMAX))
WRITE(7,2901) RK
2901 FORMAT (1H0,'Hanning WINDOW USED - LAST R BEFORE USE', F7.4)
30 TMAX = FLOAT(KMAX) * DT/(PI*EN0)
RETURN
END

```



```

*      Hinze's normalized Q11 is CONST * ARG3 * DIFF11.
      DIFF11 = (BETA * T / ARG)**2 * ABK23 + BK13 - ABK23
      SIN2T = SIN(2.0*T)
*      Hinze's normalized Q12 is CONST * ARG3 * DIFF12.
      DIFF12 = 0.5 * (ALFA * BETA * T / ARG * ARG) * SIN2T * ABK23
*      Hinze's normalized Q22 is CONST * ARG3 * DIFF22.
      DIFF22 = (ALFA * SIN2T / TWOARG)**2 * ABK23 + BK13 - ABK23
      IB = IB + 1
      IF(IB.GT.NANGLE) IB = 1
C      TORN = KAWT - 3
C      GO TO (235, 236) TORN
*      Multiplication by direction cosines - tangential wind component.
235 S11 = DIFF11 * COSA * BCOS(IB)
      S12 = DIFF12 * (SINA * BCOS(IB) + COSA * BSIN(IB))
      S22 = DIFF22 * SINA * BSIN(IB)
      GO TO 24
*      Multiplication by direction cosines - normal wind component.
C 236 S11 = DIFF11 * SINA * BSIN(IB)
C      S12 = - DIFF12 * (COSA * BSIN(IB) + SINA * BCOS(IB))
C      S22 = DIFF22 * COSA * BCOS(IB)

      24 ARG3 = ARG ** .3333333333
*      Hinze's normalized Qab.
      R ( K ) = CONST * ARG3 * (S11 + S12 + S22)
D      WRITE(7,2401) BK13, BK23, ARG, ARGB, SIN2T
2401 FORMAT(1H , 'BK13, BK23, ARG, ARGB, SIN2T', 6E12.4)
D      WRITE(7,2402) DIFF11, DIFF12, DIFF22
2402 FORMAT(1H , 'DIFF11, DIFF12, DIFF22', 3E12.4)
D      WRITE(7,2403) IB, BCOS(IB), BSIN(IB), COSA, SINA
2403 FORMAT(1H , 'IB, BCOS(IB), BSIN(IB), COSA, SINA',
*      *I4,4F10.4)
D      WRITE(7,2404) S11, S12, S22, CONST, ARG3, R(K)
2404 FORMAT(1H , 'S11, S12, S22, CONST, ARG3, R(K)', 6E12.4)
      IF(K.LT.3) GO TO 25

*      Terminate the autocorrelation function if it has converged.

      CHECK = ABS(R(K)) + ABS(R(K-1)) + ABS(R(K-2))
      IF(CHECK.LT.CHKSM) GO TO 26
25 continue
      GO TO 27
26 KMAX = K
27 IF(KWINDOW.EQ.0) GO TO 30
      RK = R(K-1)
      FMAX = KMAX
      DO 29 K = 1, KMAX
      FK = K
29 R(K) = R(K) * (0.50 + 0.50 * COS (PI * FK/FMAX))
      WRITE(7,2901) RK
2901 FORMAT (1H0, 'Hanning WINDOW USED - LAST R BEFORE USE', F7.4)
30 TMAX = FLOAT(KMAX) * DT/(PI*EN0)
      RETURN
      END

```

C#####

```

SUBROUTINE COOLEY(A,NN)
C   PCF CREATION DATE - 11 OCT 70, TIME 22.45.48
C   AUTHOR...JIM WINKELMAN, MODIFCATIONS FOR CDC 6600,MILT. SMITH
C   FAST FOURIER TRANSFORM FOR N=2**L
C   CALL THE SUBROUTINE FIRST WITH N=-MAX(N) TO BE USED
C       A IS THE COMPLEX ARRAY OF OBSERVATIONS AND IS REPLACED
C       WITH A SCRAMBLED COMPLEX ARRAY OF ANSWERS
C   CALL THE SUBROUTINE WITH N=0 TO UNSCRAMBLE THE ANSWER ARRAY
C       THE ARRAY TO BE UNSCRAMBLE MUST BE THE SAME SIZE AS THE
C       LAST ARRAY TRANSFORMED
C   REFERENCE..COOLEY-TUKEY, MATH OF COMP, APRIL 65,VOL 19 NO 90
C
  DIMENSION A(16384),W(8192)
  COMPLEX W,A,X
  COMPLEX CSQRT
  IF(NN)1,3,2
1  N=-NN
  W(1)=(1.0,0.0)
  X=(0.0,1.0)
  K=1
11 DO 12 J=1,K
  M=J+K
12 W(M)=X*W(J)
  K=K+K
  X=CSQRT(X)
  IF((K+K).LT.N) GO TO 11
  RETURN
2  MM=NN
  N=NN
  L=1
23 M=MM/2
  I=1
  DO 21 K=1,N,MM
  MK=M+K-1
  DO 22 J=K,MK
  JM=J+M
  X=W(I)*A(JM)
  A(JM)=A(J)-X
22 A(J)=A(J)+X
21 I=I+1
  IF(M.LE.1) RETURN
  MM=M
  L=L+1
  GO TO 23
3  DO 31 J=2,N-1
  MSK = 1
  I = J-1
  K=0
  DO 33 II=1,L
  IM = I.AND.MSK
  IF(IM.GT.0)K = K+1
  IF(II.EQ.L)GO TO 33
  K = ISHFT(K,1)
  MSK = ISHFT(MSK,1)
33  CONTINUE
  K=K+1
  IF(K.LE.J) GO TO 31
  X=A(J)
  A(J)=A(K)
  A(K)=X
31 CONTINUE
  RETURN
End

```

C*****

CCCC

C This subroutine computes the Fourier cosine and sine coefficients
C A(EN0) and B(EN0) for a given frequency EN0, prints out these coeffi-
C cients.

CCCC

```

SUBROUTINE FOURALTER (D1, DT, EN0, ANGLE)
  DIMENSION D1(8192)
  READ(12) MMT, (D1(I), I = 1, MMT)
  PI = 3.14159265
  CMMT = MMT
  FAC = 2.0 * PI * EN0 * DT
  SUMA = 0.
  SUMB = 0.
  DO 1 I = 1, MMT
    FI = I - 1
    SUMA = SUMA + D1(I) * COS(FI * FAC)
  1 SUMB = SUMB + D1(I) * SIN(FI * FAC)
  A = 2.0 * SUMA / CMMT
  B = 2.0 * SUMB / CMMT
  AMP = SQRT (A*A + B*B)
  ANGLE = 0.
  ANGLE = 180.0 * ATAN2(B, A) / PI
  WRITE(7,1001) A, B, AMP, ANGLE
1001 FORMAT(1H0,'A, B, AMP, ANGLE IN DEGREES', 4F10.4)
  RETURN
END

```

```

C****
*      This subroutine calculates the summation for the modified
*      Bessel function of the second kind with orders 1/3 and 2/3.
*      The standard designation of  $K(1/3)(x)$  or  $K(2/3)(x)$ , as may be
*      seen, for example, on page 358 of C.R. Wylie: "Advanced Engineering
*      Mathematics" - 3rd edition. When on the UNIVAC or VAX this summation
*      converges to an acceptable value only if the argument  $x$  is 8 or less.
*      This is presumably due to roundoff or truncation errors.
C****
      SUBROUTINE BESSEL (X, BK13, BK23, TZ)
      DOUBLE PRECISION F43, F53, G43, G53, G73, G83,
*TW043, TW053, TW073, TW083
      DOUBLE PRECISION X43, X53, XSQ, X73, X83, SUM13, SUM23,
* A13, A23
      DOUBLE PRECISION TP13, TM13, TP23, TM23, F13, F23, F73, F83
      TOL = 0.000001
      PI = 3.141592654
      C13 = 0.5 * PI/SIN(PI/3.)
      C23 = 0.5 * PI/SIN(2.0*PI/3.)
      F13 = 1./3.
      F23 = 2./3.
      F43 = 4./3.
      F53 = 5./3.
      F73 = 7./3.
      F83 = 8./3.
*      Gamma function or 4/3
      G43 = .8929797410964966
      GS43 = G43
*      Gamma function or 5/3
      G53 = .9027454853057861
      GS53 = G53
      G73 = F43 * G43
      G83 = F53 * G53
      TW043 = 2.0**F43
      TW053 = 2.0**F53
      TW073 = 2.0**F73
      TW083 = 2.0**F83
10  X43 = X**F43
      X53 = X**F53
      XSQ = X*X
      X73 = X**F73
      X83 = X**F83
      SUM13 = 0.
      SUM23 = 0.

C****
*      The following four summations are to be used only for testing
*      the program. As printed out at the end of the subroutine they
*      are the Bessel functions
*       $i^{(1/3)} J(-1/3)(ix)$ 
*       $i^{(-1/3)} J(1/3)(ix)$ 
*       $i^{(2/3)} J(-2/3)(ix)$ 
*       $i^{(-2/3)} J(2/3)(ix)$ , respectively,
*      that are given on page 235 of Jahnke and Emde: "Tables of Functions".
C****
D      SUM13N = 0.
D      SUM13P = 0.
D      SUM23N = 0.
D      SUM23P = 0.

```

```

*      Index of summation
      AK = 1.0
      FK = AK
*      i**(1/3) J(-1/3)(ix) - i**(-1/3) J(1/3)(ix)
200 A13 = X53/(TWO53*FK*G53) - X73/(TWO73*FK*G73)
*      i**(2/3) J(-2/3)(ix) - i**(-2/3) J(2/3)(ix)
      A23 = X43/(TWO43*FK*G43) - X83/(TWO83*FK*G83)
D      A13N = X53/(TWO53*FK*G53)
D      A23N = X43/(TWO43*FK*G43)
D      A13P = X73/(TWO73*FK*G73)
D      A23P = X83/(TWO83*FK*G83)
D      WRITE(7,2002)A13,X53,TWO53,FK,G53,X73,TWO73,G73
D      WRITE(7,2001)A23,X43,TWO43,FK,G43,X83,TWO83,G83
      SUM13 = SUM13 + A13
      SUM23 = SUM23 + A23
D      SUM13N = SUM13N + A13N
D      SUM13P = SUM13P + A13P
D      SUM23N = SUM23N + A23N
D      SUM23P = SUM23P + A23P
2001 FORMAT(1H , 'A23,X43,TWO43,FK,G43,X83,TWO83,G83',/10G12.4)
2002 FORMAT(1H , 'A13,X53,TWO53,FK,G53,X73,TWO73,G73',/10G12.4)
      IF(ABS(A13).LT.TOL.AND.ABS(A23).LT.TOL) GO TO 30
      X43 = X43 * XSQ
      X53 = X53 * XSQ
      X73 = X73 * XSQ
      X83 = X83 * XSQ
      TWO43 = 4.0 * TWO43
      TWO53 = 4.0 * TWO53
      TWO73 = 4.0 * TWO73
      TWO83 = 4.0 * TWO83
      G43 = G43 * (AK + F13)
      G53 = G53 * (AK + F23)
      G73 = G73 * (AK + F43)
      G83 = G83 * (AK + F53)
      AK = AK + 1.0
      FK = FK * AK

C****
*      NEXT STEP FOR TEST ONLY
C****
C      IF(AK.GT.20.0) GO TO 30
      GO TO 20
30 CONTINUE
      TP13 = (X**F13)/((2.0**F13)*GS43)
      TM13 = (X**(-F13))/((2.0**(-F13))*1.5*GS53)
      TP23 = (X**F23)/((2.0**F23)*GS53)
      TM23 = (X**(-F23))/((2.0**(-F23))*3.0*GS43)
      SUM13 = SUM13 + TM13 - TP13
      SUM23 = SUM23 + TM23 - TP23
D      SUM13N = SUM13N + TM13
D      SUM13P = SUM13P + TP13
D      SUM23N = SUM23N + TM23
D      SUM23P = SUM23P + TP23

*      K(1/3)(x)
      BK13 = SUM13 * C13
*      K(2/3)(x)
      BK23 = SUM23 * C23

D      WRITE(7,3001)AK, TZ, X, BK13, BK23
3001 FORMAT(1H , 'AK, T, X, K(1/3), K(2/3)',F5.0,4G12.4)
D      WRITE(7,3101)X, SUM13N, SUM13P, SUM23N, SUM23P
3101 FORMAT(1H , 'X, S13N, S13P, S23N, S23P',5F12.3)
40 RETURN
      END

```

C*****

```

SUBROUTINE RODAPRINT(LU, KP)
COMMON MMT, MMTA, DT, DTA, DTND, DTAND, EN1, EN1ND, EN2,
*EN2A, EN2ND, EN2AND, NANGLE, NANGLEA, RADIUS, EN0, Z, U,
*Z0, KSG, SIGU, SIGV, EL1, EL2, ILIAS, KNDOPT,
*KWINDOW, CHK, KMAX, NHAR, USTAR, ALFA, BETA, SIGU2,
* SIGV2, PVAR(7), PRMS(7), PVARVK(7)
IF(KP.NE.1) GO TO 40
WRITE(LU,1001) RADIUS
1001 FORMAT(1H0,'RADIUS OF ROTATION',F6.1,
*' M')
WRITE(LU,1051) EN0
1051 FORMAT(1H0,'RATE OF ROTATION', F11.4,' HZ')
WRITE(LU,1101) Z, Z0
1101 FORMAT(1H0,'HUB HEIGHT',F14.1,' M',/1H ,'SURFACE
*ROUGHNESS LENGTH',F10.4,' M')
WRITE(LU,1151) U
1151 FORMAT(1H ,'MEAN WIND SPEED',F10.2,' M/S')
WRITE(LU,1201) SIGU, SIGV
1201 FORMAT(1H0,'TURBULENCE RMS VALUES',/1H ,5X,'U-COMPONENT',
*F10.3,' M/S',/1H ,5X,'V-COMPONENT',F10.3,' M/S')
WRITE(LU,1301) SIGU2, SIGV2
1301 FORMAT(1H0,'TURBULENCE VARIANCES',/1H ,5X,'U-COMPONENT',
*F10.3,' (M/S)**2',/1H ,5X,'V-COMPONENT',F10.3,
*' (M/S)**2')
WRITE(LU,1401) USTAR
1401 FORMAT(1H0,'FRICTION VELOCITY',F9.3,' M/S')
WRITE(LU,1501) EL1, EL2
1501 FORMAT(1H0,'TURBULENCE INTEGRAL LENGTH SCALES',
*/1H ,5X,'LONGITUDINAL',F7.1,' M',
*/1H ,5X,'LATERAL ',F7.1,' M')
WRITE(LU,1601) MMT
1601 FORMAT(1H0,'NUMBER DATA TO BE SIMULATED',I5)
WRITE(LU,1701) DT
1701 FORMAT(1H ,'DISCRETIZATION INTERVAL ',F13.4,' SEC')
WRITE(LU,1801) ILIAS
1801 FORMAT(1H0,'ALIAS FACTOR ',I5)
DEG = 360./FLOAT(NANGLE)
WRITE(LU,1901) DEG
1901 FORMAT(1H0,'ANGULAR DISCRETIZATION INTERVAL', F7.1,
*' DEGR.EES')
IF(KNDOPT.EQ.0) WRITE(LU,2001)
2001 FORMAT(1H0,'NANGLE WAS READ IN - DT WAS CALCULATED')
IF(KNDOPT.NE.0) WRITE(LU,2101)
2101 FORMAT(1H0,'DT WAS READ IN - NANGLE WAS CALCULATED')
WRITE(LU,2201) ALFA, BETA
2201 FORMAT(1H0 ,'ALFA, BETA', 2F12.4)
WRITE(LU,2301) KMAX, NHAR
2301 FORMAT(1H0,'LIMIT ON MEMBERS OF AUTOCORRELATION FUNCTION',
*I5,/1H ,'NUMBER OF HARMONICS IN SPECTRA',I19,/1H ,'This is
* also a comparison between number of harmonics in original
* spectrum and reduced version.')

WRITE(LU,2401) EN1
2401 FORMAT(1H0,'FUNDAMENTAL FREQUENCY IS',F12.6,' HZ')
WRITE(LU,2501) CHK
2501 FORMAT(/1H ,'MAX FINAL VALUE OF CORRELATION ACCEPTABLE WITHOUT
* WINDOWING', F8.5)
IF(LU.NE.7) GO TO 50
WRITE(LU,3001)

```

```

3001 FORMAT(1H1,'DIFFERENT FORMS OF VARIABLES:',
  */1H ,5X,'_ - original',
  */1H ,5X,'_A - including extensions associated with alias
  * removal',/1H ,5X,'_ND - dimensionless variable',
  */1H ,5X,'_AND - both of the above')
WRITE(LU,3101) DT, DTA, DTND, DTAND
3101 FORMAT(1H0,'DISCRETIZATION INTERVAL - DT',
  */1H ,5X,'_',F9.3,' SEC',/1H ,5X,'_A', F8.3,' SEC',
  */1H ,5X,'_ND',F7.3,/1H ,5X,'_AND',F6.3)
WRITE(LU,3201) MMT, MMTA
3201 FORMAT(1H0,'NUMBER OF SIMULATED DATA - MMT',
  */1H ,5X,'_',I9,/1H ,5X,'_A',I8)
WRITE(LU,3301) EN1, EN1ND
3301 FORMAT(1H0,'FUNDAMENTAL FREQUENCY - EN1'/1H ,5X,
  */1H ,5X,'_',F13.5,' HZ',/1H ,5X,'_ND',F11.5)
WRITE(LU,3401) EN2, EN2A, EN2ND, EN2AND
3401 FORMAT(1H0,'NYQUIST FREQUENCY - EN2',
  */1H ,5X,'_',F13.5,' HZ',/1H ,5X,'_A',F12.5,' HZ',
  */1H ,5X,'_ND',F11.5,/1H ,5X,'_AND',F10.5)
WRITE(LU,3501) NANGLE, NANGLEA
3501 FORMAT(1H0,'NUMBER OF SAMPLING POSITIONS IN CIRCLE - NANGLE',
  */1H ,5X,'_',I6,/1H ,5X,'_A',I5)
IF(KP.EQ.1) GO TO 50
40 CONTINUE
IF(LU.EQ.7) WRITE(7,4101)
4101 FORMAT(1H1,'VARIANCES FOR FIRST HALF-P AND FOR 6P
  * FROM 80-MEMBER SPECTRUM'/1H ,5X,'S(n)c, - (M/S)**2')
IF(LU.EQ.10) WRITE(10,4111)
4111 FORMAT(1H0,'VARIANCES FOR FIRST HALF-P AND FOR 6P
  * FROM 80-MEMBER SPECTRUM'/1H ,5X,'S(n)c, - (M/S)**2')
WRITE(LU,4201) PVAR
4201 FORMAT(1H ,F10.4, F15.4, 5F10.4)
WRITE(LU,4301) PRMS
4301 FORMAT(1H0,'RMS'/1H ,5X,'F10.4, F15.4, 5F10.4)
WRITE(LU,4311)
4311 FORMAT(1H0,'SAME VARIANCES COMPUTED BY INTEGRATING THE
  * VON KARMAN SPECTRUM, Svk(n)ca')
WRITE(LU,4201) PVARVK
50 RETURN
END

```

C#####

```
      SUBROUTINE HAWTMEAN (DLM, NANGLE, Z, RADIUS, U, Z0, MMT,  
* IFFSET, DSIN)  
      DIMENSION DSIN(1), DLM(1)  
      DENOM = ALOG (Z/Z0)  
      DO 20 I = 1, NANGLE  
      J = I + IFFSET  
      IF(J.GT.NANGLE) J = J - NANGLE  
      Z1 = Z + RADIUS * DSIN(J)  
      DLM(I) = U * ALOG(Z1/Z0) / DENOM  
D      WRITE(7,1991) Z1, J, DSIN(J), DLM(I)  
1991  FORMAT(1H , 'Z1, J, DSIN(J), DLM(I)', F10.2, I6, 2F10.3)  
      20 CONTINUE  
      RETURN  
      END
```


C#####

```

      SUBROUTINE VAWTTNMEAN (DLM, NANGLE, RADIUS, U, MMT, IFFSET,
      *DCOS, DSIN, KAWT, EN0)
      DIMENSION DLM(1), DCOS(1), DSIN(1)
      PI = 3.141592654
      K3 = KAWT - 3
      GO TO (10, 30) K3
10  SPEED = 2.0 * PI * EN0 * RADIUS
D   WRITE(7,1001) SPEED
1001 FORMAT(1H , 'SPEED', F10.2)
      DO 20 I = 1, NANGLE
      J = I + IFFSET
      IF(J.GT.NANGLE) J = J - NANGLE
      DLM(I) = U * DSIN(J) + SPEED
D   WRITE(7,1501), I, J, DSIN(J), DLM(I)
1501 FORMAT(1H , 'I, J, DSIN(J), DLM(I)', 2I6, F10.3, F10.2)
      20 CONTINUE
      GO TO 50
30  DO 40 I = 1, NANGLE
      J = I + IFFSET
      IF(J.GT.NANGLE) J = J - NANGLE
      DLM(I) = U * DCOS(J)
D   WRITE(7,3501) I, J, DCOS(J), DLM(I)
3501 FORMAT(1H , 'I, J, DCOS(J), DLM(I)', 2I6, F10.3, F10.2)
      40 CONTINUE
      50 RETURN
      END

```


A.2 GLOSSARY

The following listing describes the commonly used variables in the program. Variables not listed are in one of three categories: 1) working or temporary variables defined and used within a small segment of the program, 2) generalized loop indices, or 3) modifications of basic variables, indicated by names ending with A, ND, or AND (see Section 3.3.1.1).

One helpful aspect of the glossary is that it gives the units of all variables. Of course, this depends on the units of such input variables as height and mean wind speed. The program assumes that lengths are in meters and times in seconds. Dimensionless variables are labeled 'dmls.'

SCALARS

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub-routine</u>
ALFA	Blade radius/turbulence length scale L_y .	dmls.	
ALIAS	Floating point ILIAS, alias reduction factor.	dmls.	
ANGLE	Phase angle of 1P harmonic in simulated data. Zero value indicates a cosine wave.	deg	
BETA	Blade rotation rate/(mean wind speed x turbulence length scale L_x).	dmls.	
BK13	Value of modified Bessel function of 2nd kind, $K(1/3)$.	dmls.	BESSEL
BK23	Same as above, but for $K(2/3)$.	dmls.	BESSEL
CHECK	Criterion for declaring acf convergent.	dmls.	
CHK	Read-in tolerance level defining convergence of acf.	dmls.	
CMMT	Floating point MMT.	dmls.	

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub-routine</u>
DSEED	Parameter used in IMSL routine for generating uncorrelated random values evenly spaced from zero to one.	dm/s.	
DT	Discretization interval for simulated data.	sec	
EL1	Longitudinal integral length scale for u-component turbulence, L_x .	m	
EL2	Lateral integral length scale for u-component turbulence, L_y .	m	
EN	Dimensional frequency argument for von Karman spectrum.	Hz	
ENO	Blade rotation rate.	Hz	
EN1	Fundamental frequency of data: reciprocal of total time span.	Hz	
EN2	Nyquist frequency of spectrum $S(n)_r$, and the spectrum of simulated data.	Hz	
ENVK	Dimensionless frequency for von Karman spectrum.	dm/s.	
FAC	Time factor converting Fourier squared amplitudes to the one-sided spectral density $S(n)$.	sec	
FF	Fundamental frequency of spectral densities $S(n)_f$, $S(n)_r$, $Svk(n)_r$.	Hz	
ILIAS	Alias reduction factor. [If ILIAS = 4, 1/4 of the power spectrum $S(n)_f$, calculated from FFT of acf, is retained as $S(n)_r$.]	dm/s.	
JTCPL	1. Index of the last member of acf as it is entered into the FFT process.		

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub- routine</u>
JTCPL (cont'd.)	<p>2. Index of last member of $S(n)_r$ as it is entered into FFT process to compute impulse response function. Smaller value than above if ILIAS is greater than 1.</p> <p>3. Index of last value of $S(n)$ for simulated data. (Same value as in 2.)</p> <p>4. Index of last value of random phase used to calculate simulated data. (Same value as in 2.)</p>	dm/s.	
K8	Option to write impulse response function to disk.		
K9	Option to write $S(n)_r$ and spectrum of simulated data to disk. These spectra have half as many degrees of freedom as the simulated data have.		
K11	Option to write 80-member spectrum $S(n)_c$, (0.1P, 0.2P...8P) and corresponding altered von Karman spectrum to disk.		
K12	Option to write simulated data to file.		
K13	Option to write von Karman spectra, original and altered, to file. These spectra have half as many degrees of freedom as the simulated data have.		
K14	Option to write complex Fourier coefficients of transform of simulated data to file.		
K15	Option to calculate banded $nS(n)$ spectra for simulated data; also does so for the von Karman spectra stored if K13 does not equal zero.		

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub-routine</u>
KAWT	Simulation choice option: 1) HAWT u-component 2) VAWT u-component 3) VAWT v-component 4) VAWT tangential component 5) VAWT radial component.		
KBR	Option for calculation method for simulated data: 0) Convolution integral of impulse response function with Gaussian white noise. 1) Fourier transform of amplitudes from spectral harmonics and random phase.		
KEL	Option for length scales EL1 and EL2: 0) Let program calculate them. 1) Read them in.		
KMAX	Maximum number of members allowed in acf.		
KNDOPT	Option governing specification of discretization interval: 0) Specify angular value in degrees. 1) Specify time value in seconds.		
KSERIAL	Alphanumeric serial number for run, five characters.		
KSG	Option for SIGU and SIGV. 0) Let program calculate them, isotropically. 1) Read them in.		
KWINDOW	Option to multiply acf by Hamming window values. 0) Do not use window. 1) Use window.		

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub- routine</u>
MMT	Number of simulated data. MMT must be 2^N , where N is an integer.		
NANGLE	Discretization interval in terms of number of angular divisions of rotational circle.	dmls.	
NDG	Number of degrees of freedom in Gaussian white noise.	dmls.	
NEF	Number of frequencies used in spectra $S(n)_c$ and corresponding von Karman spectra where frequency spacing interval is 0.1P.	dmls.	
NHAR	Number of harmonics (degrees of freedom) in spectrum $S(n)_r$ and corresponding von Karman spectra. (NHAR = MMT/2.)	dmls.	
NP	Arbitrary number of points to be used on one side of the two-sided impulse response function, not counting central value at zero argument.	dmls.	
OMEGA	Blade rotation rate.	radians/sec	
PI	3.141592654	dmls.	
RADIUS	Radius of rotation, blade radius.	m	
SIG2	SIGU2 or SIGV2, as is appropriate. If SIGU and SIGV are calculated internally, they are equal.	$(m/s)^2$	
SIGU	Rms of u-component turbulence.	m/s	
SIGU2	Variance of u-component turbulence.	$(m/s)^2$	
SIGV	Rms of v-component turbulence.	m/s	
SIGV2	Variance of v-component turbulence.	$(m/s)^2$	
T	Dimensionless running time used in calculation of acf and in the cosine integration of the acf to obtain $S(n)_c$.	dmls.	

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub-routine</u>
THETA	Angle argument in phase angle vector.	radians	
TMAX	Length of acf in seconds.	sec	
TWOARG	Argument of calculated Bessel functions.	dmls.	
U	Mean wind speed at height Z.	m/s	
USTAR	Friction velocity.	m/s	
USTAR2	Square of friction velocity.	(m/s) ²	
VAR	Variance from integrating $S(n)_c$.	(m/s) ²	
VSUM	1. Variance from integrating $S(n)_r$, 2. Variance from integrating $S(n)_r$ of simulated data.	(m/s) ² (m/s) ²	
Z	Simulated wind turbine hub height.	m	
Z0	Surface roughness length.	m	

ARRAYS

D1(I)	Final simulated wind data.	m/s	
D1M(I)	One cycle of simulated mean wind effect.	m/s	
ENL(N)	80 linearly spaced frequencies at interval of 0.1P for spectral density SPECL(N).	Hz	
ENL1(N)	20 linearly spaced frequencies at interval of 0.005P for spectral density SPECL1(N).	Hz	
ENP(N)	Same as ENL(N) but numbered in P units (harmonics), i.e., 0.1, 0.2, ..., 8.0.	P	
G1(I)	Gaussian white noise vector of unit variance.	dmls.	
HT1(I)	Two sided impulse response function. Mathematically, this is $h(t)\Delta t$ where $h(t)$ is a true impulse response function.	m/s	

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub- routine</u>
KAWTER(C)*30	Alphameric array indicating type of simulation.		
PRMS(M)	Square root of PVAR(M).	m/s	
PVAR(M)	Variance in each of the harmonic spikes of the rotational spectrum. PVAR(1) is variance of first 0.5P; PVAR(2) is variance of first spike, etc. This version is calculated by integrating SPECL(N).	(m/s) ²	
PVARVK(M)	Variances found by integrating over corresponding frequency ranges of von Karman spectrum.	(m/s) ²	
PVAR2(M)	Same as PVAR(M) but calculated by integrating XIF1(N).	(m/s) ²	
R(T)	Autocorrelation function incorporating rotational feature.	dm/s.	
RP(TS)	Evenly spaced subset of values from R(T) selected for printing convenience. RP is not used analytically.	dm/s.	
SMOM(4)	Mean, variance, skewness, kurtosis of simulated data.		
SPECL(N)	Spectral density at 80 frequencies, 0.1P, 0.2P...8.0, of simulated data. SPECL is calculated by direct cosine integration of R(T).	(m ² /s)	
SPECL1(N)	Same as SPECL(N) but for the 20 frequencies (0.005, 0.01.....0.1)P.	(m ² /s)	
VKSPEC(N)	Von Karman spectrum for same frequencies as SPECL(N).	(m ² /s)	
XIF1(N)	Spectral density S(n) calculated by FFT of R(T), where fundamental frequency is reciprocal of time length of data set.	(m ² /s)	

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>	<u>Sub- routine</u>
XTEND(K)	Input complex vector for FFT.		
XVK(N)	Von Karman spectrum corresponding to XIF1.	(m ² /s)	
XVKA(N)	Altered von Karman spectrum corresponding to XIF1.	(m ² /s)	

A.3 TEST CASE

VAWT TANGENTIAL SIMULATION

SERIAL NUMBER 07461

RADIUS OF ROTATION 8.3 M

RATE OF ROTATION 1.0000 HZ

HUB HEIGHT 16.7 M

SURFACE ROUGHNESS LENGTH 0.0500 M

MEAN WIND SPEED 10.00 M/S

TURBULENCE RMS VALUES

U-COMPONENT 1.652 M/S

V-COMPONENT 1.652 M/S

TURBULENCE VARIANCES

U-COMPONENT 2.729 (M/S)**2

V-COMPONENT 2.729 (M/S)**2

FRICTION VELOCITY 0.688 M/S

TURBULENCE INTEGRAL LENGTH SCALES

LONGITUDINAL 70.1 M

LATERAL 28.1 M

NUMBER DATA TO BE SIMULATED 1024

DISCRETIZATION INTERVAL 0.0417 SEC

ALIAS FACTOR 4

ANGULAR DISCRETIZATION INTERVAL 15.0 DEGREES

ANGLE WAS READ IN - DT WAS CALCULATED

ALFA, BETA 0.2958 0.0227

LIMIT ON MEMBERS OF AUTOCORRELATION FUNCTION 2048

NUMBER OF HARMONICS IN SPECTRA 512

This is also a comparison between number of harmonics in original spectrum and reduced version.

FUNDAMENTAL FREQUENCY IS 0.023438 HZ

MAX FINAL VALUE OF CORRELATION ACCEPTABLE WITHOUT WINDOWING 0.00100

DIFFERENT FORMS OF VARIABLES:

- original
 _A - including extensions associated with alias removal
 _ND - dimensionless variable
 _AND - both of the above

DISCRETIZATION INTERVAL - DT

- 0.042 SEC
 _A 0.010 SEC
 _ND 0.131
 _AND 0.033

NUMBER OF SIMULATED DATA - MMT

- 1024
 _A 4096

FUNDAMENTAL FREQUENCY - EN1

- 0.02344 HZ
 _ND 0.00746

NYQUIST FREQUENCY - EN2

- 12.00000 HZ
 _A 48.00000 HZ
 _ND 3.81972
 _AND 15.27887

NUMBER OF SAMPLING POSITIONS IN CIRCLE - NANGLE

- 24
 _A 96

ANGLEA 1.5708

COSA, SINA 0.000 1.000

DIRECTION COSINES FOR MOVING POINT

Hanning WINDOW USED - LAST R BEFORE USE-0.0004

AUTOCORRELATION FUNCTION										906 steps										9.44 seconds									
0.9307	0.8880	0.8483	0.8091	0.7695	0.7293	0.6883	0.6467	0.6044	0.5617	0.5188	0.4759	0.4331	0.3907	0.3489															
0.3079	0.2679	0.2290	0.1914	0.1553	0.1207	0.0878	0.0566	0.0272	-0.0004	-0.0261	-0.0499	-0.0719	-0.0921	-0.1104															
-0.1271	-0.1422	-0.1556	-0.1676	-0.1782	-0.1875	-0.1956	-0.2027	-0.2087	-0.2138	-0.2181	-0.2217	-0.2246	-0.2269	-0.2287															
-0.2300	-0.2309	-0.2313	-0.2313	-0.2309	-0.2301	-0.2289	-0.2272	-0.2250	-0.2223	-0.2190	-0.2149	-0.2102	-0.2047	-0.1982															
-0.1908	-0.1824	-0.1728	-0.1620	-0.1500	-0.1366	-0.1218	-0.1055	-0.0878	-0.0685	-0.0476	-0.0251	-0.0011	0.0245	0.0516															
0.0801	0.1101	0.1413	0.1738	0.2074	0.2418	0.2770	0.3127	0.3487	0.3848	0.4205	0.4555	0.4894	0.5216	0.5516															
0.5785	0.6017	0.6205	0.6343	0.6427	0.6457	0.6433	0.6356	0.6228	0.6054	0.5838	0.5587	0.5309	0.5008	0.4692															
0.4363	0.4028	0.3689	0.3350	0.3014	0.2682	0.2358	0.2042	0.1737	0.1444	0.1164	0.0897	0.0646	0.0409	0.0187															
-0.0019	-0.0209	-0.0384	-0.0545	-0.0690	-0.0822	-0.0940	-0.1046	-0.1139	-0.1222	-0.1294	-0.1356	-0.1410	-0.1456	-0.1494															
-0.1527	-0.1553	-0.1575	-0.1592	-0.1606	-0.1616	-0.1622	-0.1627	-0.1628	-0.1627	-0.1624	-0.1618	-0.1610	-0.1599	-0.1584															
-0.1567	-0.1545	-0.1519	-0.1488	-0.1451	-0.1408	-0.1359	-0.1302	-0.1237	-0.1163	-0.1080	-0.0988	-0.0884	-0.0770	-0.0645															
-0.0508	-0.0359	-0.0198	-0.0025	0.0160	0.0356	0.0563	0.0780	0.1007	0.1243	0.1486	0.1734	0.1987	0.2241	0.2495															
0.2746	0.2991	0.3228	0.3451	0.3659	0.3847	0.4013	0.4153	0.4264	0.4345	0.4395	0.4411	0.4396	0.4348	0.4270															
0.4162	0.4027	0.3868	0.3688	0.3490	0.3278	0.3055	0.2824	0.2588	0.2350	0.2113	0.1877	0.1647	0.1422	0.1205															
0.0997	0.0798	0.0610	0.0432	0.0266	0.0112	-0.0031	-0.0162	-0.0282	-0.0390	-0.0488	-0.0576	-0.0654	-0.0722	-0.0782															

-0.0834	-0.0879	-0.0917	-0.0949	-0.0976	-0.0998	-0.1016	-0.1030	-0.1042	-0.1050	-0.1056	-0.1060	-0.1063	-0.1064	-0.1064
-0.1063	-0.1060	-0.1056	-0.1051	-0.1045	-0.1037	-0.1026	-0.1014	-0.0999	-0.0980	-0.0959	-0.0933	-0.0903	-0.0868	-0.0828
-0.0781	-0.0729	-0.0669	-0.0603	-0.0528	-0.0446	-0.0356	-0.0257	-0.0150	-0.0035	0.0088	0.0220	0.0359	0.0505	0.0658
0.0816	0.0979	0.1146	0.1314	0.1483	0.1650	0.1815	0.1975	0.2127	0.2271	0.2403	0.2522	0.2625	0.2712	0.2781
0.2830	0.2860	0.2868	0.2857	0.2825	0.2774	0.2704	0.2617	0.2515	0.2399	0.2271	0.2133	0.1987	0.1836	0.1681
0.1524	0.1367	0.1212	0.1059	0.0911	0.0768	0.0630	0.0500	0.0376	0.0261	0.0153	0.0054	-0.0038	-0.0121	-0.0197
-0.0264	-0.0325	-0.0378	-0.0425	-0.0465	-0.0500	-0.0529	-0.0554	-0.0575	-0.0591	-0.0605	-0.0615	-0.0623	-0.0629	-0.0633
-0.0636	-0.0637	-0.0638	-0.0638	-0.0637	-0.0636	-0.0635	-0.0633	-0.0631	-0.0629	-0.0625	-0.0621	-0.0617	-0.0611	-0.0603
-0.0594	-0.0583	-0.0570	-0.0554	-0.0535	-0.0512	-0.0486	-0.0456	-0.0421	-0.0382	-0.0338	-0.0289	-0.0235	-0.0175	-0.0110
-0.0039	0.0037	0.0118	0.0205	0.0295	0.0390	0.0488	0.0590	0.0693	0.0797	0.0901	0.1004	0.1105	0.1203	0.1295
0.1382	0.1462	0.1533	0.1595	0.1647	0.1687	0.1715	0.1732	0.1736	0.1727	0.1707	0.1674	0.1631	0.1577	0.1514
0.1442	0.1364	0.1279	0.1189	0.1097	0.1002	0.0905	0.0809	0.0714	0.0621	0.0530	0.0443	0.0360	0.0281	0.0207
0.0138	0.0074	0.0015	-0.0038	-0.0086	-0.0129	-0.0167	-0.0201	-0.0230	-0.0255	-0.0276	-0.0293	-0.0307	-0.0319	-0.0328
-0.0335	-0.0339	-0.0343	-0.0345	-0.0346	-0.0346	-0.0345	-0.0344	-0.0343	-0.0342	-0.0341	-0.0340	-0.0339	-0.0338	-0.0337
-0.0336	-0.0335	-0.0333	-0.0332	-0.0330	-0.0328	-0.0324	-0.0320	-0.0314	-0.0307	-0.0299	-0.0288	-0.0275	-0.0260	-0.0243
-0.0223	-0.0199	-0.0173	-0.0144	-0.0111	-0.0075	-0.0036	0.0006	0.0052	0.0100	0.0151	0.0205	0.0260	0.0317	0.0375
0.0434	0.0493	0.0551	0.0608	0.0662	0.0714	0.0762	0.0806	0.0846	0.0880	0.0907	0.0929	0.0944	0.0952	0.0953
0.0948	0.0935	0.0916	0.0891	0.0860	0.0824	0.0783	0.0738	0.0691	0.0640	0.0588	0.0535	0.0481	0.0427	0.0374
0.0323	0.0273	0.0225	0.0179	0.0137	0.0097	0.0060	0.0026	-0.0005	-0.0032	-0.0057	-0.0078	-0.0097	-0.0113	-0.0127
-0.0138	-0.0147	-0.0154	-0.0159	-0.0163	-0.0165	-0.0167	-0.0167	-0.0167	-0.0166	-0.0165	-0.0164	-0.0162	-0.0160	-0.0159
-0.0157	-0.0156	-0.0155	-0.0154	-0.0154	-0.0154	-0.0153	-0.0154	-0.0154	-0.0154	-0.0154	-0.0154	-0.0153	-0.0153	-0.0151
-0.0149	-0.0146	-0.0143	-0.0138	-0.0132	-0.0124	-0.0116	-0.0105	-0.0093	-0.0080	-0.0064	-0.0047	-0.0028	-0.0008	0.0015
0.0038	0.0064	0.0090	0.0118	0.0146	0.0175	0.0204	0.0234	0.0262	0.0290	0.0317	0.0343	0.0367	0.0388	0.0407
0.0424	0.0437	0.0447	0.0454	0.0457	0.0457	0.0453	0.0447	0.0436	0.0423	0.0407	0.0389	0.0369	0.0346	0.0322
0.0297	0.0271	0.0245	0.0219	0.0192	0.0167	0.0142	0.0118	0.0095	0.0073	0.0053	0.0035	0.0018	0.0003	-0.0011
-0.0023	-0.0033	-0.0042	-0.0050	-0.0056	-0.0061	-0.0064	-0.0067	-0.0069	-0.0070	-0.0070	-0.0070	-0.0069	-0.0068	-0.0067
-0.0066	-0.0064	-0.0062	-0.0061	-0.0059	-0.0058	-0.0057	-0.0056	-0.0056	-0.0055	-0.0055	-0.0055	-0.0055	-0.0056	-0.0056
-0.0057	-0.0057	-0.0058	-0.0059	-0.0059	-0.0060	-0.0060	-0.0059	-0.0059	-0.0059	-0.0057	-0.0056	-0.0054	-0.0051	-0.0047
-0.0038	-0.0032	-0.0025	-0.0018	-0.0010	-0.0001	0.0009	0.0019	0.0030	0.0041	0.0053	0.0065	0.0077	0.0089	0.0101
0.0112	0.0123	0.0133	0.0143	0.0151	0.0159	0.0165	0.0170	0.0174	0.0176	0.0177	0.0177	0.0175	0.0172	0.0167
0.0161	0.0155	0.0147	0.0138	0.0129	0.0119	0.0109	0.0098	0.0088	0.0077	0.0067	0.0057	0.0047	0.0038	0.0030
0.0022	0.0014	0.0007	0.0001	-0.0004	-0.0008	-0.0012	-0.0016	-0.0018	-0.0020	-0.0022	-0.0023	-0.0024	-0.0024	-0.0024
-0.0024	-0.0023	-0.0022	-0.0021	-0.0020	-0.0019	-0.0018	-0.0017	-0.0016	-0.0015	-0.0015	-0.0014	-0.0013	-0.0013	-0.0013
-0.0012	-0.0012	-0.0012	-0.0013	-0.0013	-0.0013	-0.0014	-0.0014	-0.0014	-0.0015	-0.0015	-0.0016	-0.0016	-0.0017	-0.0017
-0.0017	-0.0017	-0.0017	-0.0016	-0.0016	-0.0015	-0.0013	-0.0012	-0.0010	-0.0008	-0.0006	-0.0003	0.0000	0.0003	0.0006
0.0009	0.0012	0.0016	0.0019	0.0023	0.0026	0.0029	0.0032	0.0035	0.0037	0.0040	0.0042	0.0043	0.0044	0.0045
0.0046	0.0046	0.0045	0.0045	0.0043	0.0042	0.0040	0.0038	0.0036	0.0033	0.0031	0.0028	0.0025	0.0022	0.0019
0.0017	0.0014	0.0012	0.0009	0.0007	0.0005	0.0003	0.0001	0.0000	-0.0001	-0.0002	-0.0003	-0.0004	-0.0005	-0.0005
-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0004	-0.0004	-0.0004	-0.0003	-0.0003	-0.0003	-0.0002	-0.0002
-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002
-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003
0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

VARIANCE FROM INTEGRATION OF ROTATIONAL S(M) COMPUTED BY FFT OF ACF 2.536335 (M/S)**2

S(n) analysis - 80 evenly spaced frequencies

FREQUENCY(HZ)	FREQUENCY(P)	S(N)	VKS(N)
0.10000	0.1	1.324181	5.983362
0.20000	0.2	0.377920	1.989780
0.30000	0.3	0.227861	1.022823
0.40000	0.4	0.192371	0.635545
0.50000	0.5	0.200628	0.438895
0.60000	0.6	0.247778	0.324183
0.70000	0.7	0.367296	0.250872
0.80000	0.8	0.717184	0.200888
0.90000	0.9	2.666211	0.165123
1.00000	1.0	7.158296	0.138555
1.10000	1.1	2.192568	0.118220
1.20000	1.2	0.447438	0.102271
1.30000	1.3	0.184516	0.089505
1.40000	1.4	0.107870	0.079111
1.50000	1.5	0.084275	0.070521
1.60000	1.6	0.087221	0.063332
1.70000	1.7	0.118553	0.057247
1.80000	1.8	0.218021	0.052047
1.90000	1.9	0.714943	0.047563
2.00000	2.0	2.119880	0.043667
2.10000	2.1	0.578218	0.040257
2.20000	2.2	0.142955	0.037254
2.30000	2.3	0.065643	0.034594
2.40000	2.4	0.041595	0.032226
2.50000	2.5	0.035115	0.030107
2.60000	2.6	0.038622	0.028202
2.70000	2.7	0.052791	0.026483
2.80000	2.8	0.087275	0.024925
2.90000	2.9	0.191929	0.023510
3.00000	3.0	0.384230	0.022218
3.10000	3.1	0.171948	0.021037
3.20000	3.2	0.075826	0.019953
3.30000	3.3	0.046341	0.018955
3.40000	3.4	0.034783	0.018035
3.50000	3.5	0.031528	0.017185
3.60000	3.6	0.033969	0.016397
3.70000	3.7	0.042327	0.015665
3.80000	3.8	0.059367	0.014984
3.90000	3.9	0.092792	0.014349
4.00000	4.0	0.126968	0.013756

FREQUENCY(HZ)	FREQUENCY(P)	S(N)	VKS(N)
4.10000	4.1	0.088171	0.013201
4.20000	4.2	0.055818	0.012682
4.30000	4.3	0.040119	0.012194
4.40000	4.4	0.032491	0.011736
4.50000	4.5	0.029698	0.011304
4.60000	4.6	0.030480	0.010898
4.70000	4.7	0.034574	0.010514
4.80000	4.8	0.042230	0.010152
4.90000	4.9	0.053272	0.009809
5.00000	5.0	0.060331	0.009484
5.10000	5.1	0.051687	0.009176
5.20000	5.2	0.040326	0.008884
5.30000	5.3	0.032609	0.008606
5.40000	5.4	0.028125	0.008342
5.50000	5.5	0.026151	0.008091
5.60000	5.6	0.026205	0.007852
5.70000	5.7	0.027985	0.007623
5.80000	5.8	0.031113	0.007406
5.90000	5.9	0.034560	0.007198
6.00000	6.0	0.035921	0.006999
6.10000	6.1	0.033784	0.006809
6.20000	6.2	0.029810	0.006627
6.30000	6.3	0.026215	0.006452
6.40000	6.4	0.023741	0.006285
6.50000	6.5	0.022452	0.006125
6.60000	6.6	0.022221	0.005971
6.70000	6.7	0.022824	0.005823
6.80000	6.8	0.023886	0.005681
6.90000	6.9	0.024732	0.005544
7.00000	7.0	0.024786	0.005413
7.10000	7.1	0.024216	0.005287
7.20000	7.2	0.022866	0.005165
7.30000	7.3	0.021265	0.005047
7.40000	7.4	0.019958	0.004934
7.50000	7.5	0.019143	0.004825
7.60000	7.6	0.018827	0.004720
7.70000	7.7	0.018882	0.004618
7.80000	7.8	0.019062	0.004520
7.90000	7.9	0.019043	0.004425
8.00000	8.0	0.018811	0.004333

SPECTRAL DENSITY FOR 20 DIVISIONS OF LOWEST FREQUENCY BAND
FREQUENCIES

0.005000	0.010000	0.015000	0.020000	0.025000	0.030000	0.035000	0.040000	0.045000	0.050000
0.055000	0.060000	0.065000	0.070000	0.075000	0.080000	0.085000	0.090000	0.095000	0.100000
S(N)									
3.88	3.85	3.79	3.71	3.62	3.50	3.37	3.22	3.07	2.90
2.73	2.56	2.39	2.22	2.05	1.89	1.73	1.59	1.45	1.32
SUMS OF S(N) FOR THE TWO SERIES					22.02	54.85			

0.33821	0.37947	0.30143	4	14	17	0.07044	0.07044	0.21048	0.25501
0.26865	0.30143	0.23943	4	11	14	0.06927	0.06927	0.24035	0.29079
0.21339	0.23943	0.19019	3	9	11	0.07571	0.07571	0.27531	0.33235
0.16950	0.19019	0.15107	3	7	9	0.09019	0.09019	0.31840	0.38295
0.13464	0.15107	0.12000	2	6	7	0.11050	0.11050	0.35177	0.42114
0.10695	0.12000	0.09532	2	5	6	0.13126	0.13126	0.36823	0.43827

VARIANCE OF S(N) ON THIS PAGE, S(N)c 2.4766 (M/S)**2

LENGTH SCALE FROM INTEGRATION OF ACF IS 3.6 M

VARIANCES FOR FIRST HALF-P AND FOR 6P FROM 80-MEMBER SPECTRUM

S(n)c, - (M/S)**2

0.3741	1.4173	0.4122	0.1115	0.0602	0.0400	0.0292
--------	--------	--------	--------	--------	--------	--------

RMS

0.6117	1.1905	0.6420	0.3340	0.2453	0.1999	0.1708
--------	--------	--------	--------	--------	--------	--------

SAME VARIANCES COMPUTED BY INTEGRATING THE VON KARMAN SPECTRUM, Svk(n)ca

1.0070	0.1539	0.0438	0.0221	0.0136	0.0094	0.0069
--------	--------	--------	--------	--------	--------	--------

VARIANCES FOR FIRST HALF-P AND FOR 6P FROM SPECTRUM OF SIMULATED DATA, S(n)r

0.3673	1.4263	0.4147	0.1120	0.0605	0.0398	0.0296
--------	--------	--------	--------	--------	--------	--------

SPECTRAL ESTIMATES FROM SIMULATED DATA

0.0000	3.6486	3.0074	2.2062	1.4836	0.9710	0.6704	0.5100	0.4159	0.3491
0.2995	0.2652	0.2421	0.2247	0.2111	0.2015	0.1958	0.1925	0.1909	0.1913
0.1940	0.1987	0.2049	0.2131	0.2241	0.2381	0.2547	0.2747	0.3003	0.3330
0.3730	0.4220	0.4866	0.5766	0.6983	0.8610	1.1042	1.5259	2.2617	3.3886
4.8013	6.1664	7.0342	7.0674	6.2379	4.8466	3.3504	2.1234	1.3130	0.8595
0.6181	0.4711	0.3653	0.2885	0.2360	0.1989	0.1697	0.1460	0.1283	0.1154
0.1054	0.0969	0.0906	0.0867	0.0843	0.0826	0.0821	0.0834	0.0863	0.0900
0.0947	0.1018	0.1121	0.1246	0.1391	0.1583	0.1871	0.2268	0.2763	0.3450
0.4673	0.6950	1.0561	1.5047	1.9105	2.1156	2.0272	1.6788	1.2093	0.7770

VARIANCE OF S(N)r FROM SIMULATED DATA 2.5363

SMOM(1), SMOM(2) 0.0000 2.5363

SKEWNESS AND KURTOSIS 0.1009 2.9448

HALF-RANDOMIZING SIMULATION - PHASE RANDOMIZED

21 LOGARITHMICALLY SPACED BANDS AT 10. PER SPECTRAL DECADE

BANDED NSN SPECTRA

BAND CENTER, HI, LOW (HZ), NS(N), HARMONIC COUNT	PER BAND [NS(N):ORIG	SIM	VK	VKA]
10.69501 12.00000 9.53194 105 408 512	0.12547	0.12547	0.02343	0.02846
8.49535 9.53194 7.57149 85 324 408	0.14169	0.14169	0.02725	0.03310
6.74810 7.57149 6.01425 67 258 324	0.16401	0.16401	0.03172	0.03852
5.36020 6.01425 4.77729 54 205 258	0.20215	0.20215	0.03689	0.04481
4.25776 4.77729 3.79473 43 163 205	0.24871	0.24871	0.04297	0.05220
3.38206 3.79473 3.01426 34 130 163	0.26092	0.26092	0.04990	0.06061
2.68647 3.01426 2.39431 28 103 130	0.31014	0.31014	0.05811	0.07058
2.13394 2.39431 1.90187 22 82 103	1.43917	1.43917	0.06778	0.08233
1.69504 1.90187 1.51071 18 65 82	0.32362	0.32362	0.07903	0.09598

1.34642	1.51071	1.20000	14	52	65	0.24843	0.24843	0.09177	0.11146
1.06950	1.20000	0.95319	11	42	52	3.89765	3.89765	0.10492	0.12742
0.84953	0.95319	0.75715	10	33	42	1.85797	1.85797	0.12177	0.14785
0.67481	0.75715	0.60142	7	27	33	0.23564	0.23564	0.13981	0.16971
0.53602	0.60142	0.47773	7	21	27	0.11699	0.11699	0.16191	0.19646
0.42578	0.47773	0.37947	5	17	21	0.08213	0.08213	0.18908	0.22928

UNBANDIED NSN SPECTRA

0.023438	0.085513	0.085513	0.367659	0.394380
0.046875	0.140972	0.140972	0.411544	0.470174
0.070313	0.155125	0.155125	0.395881	0.463950

ANALYSIS OF SIMULATED DATA INCLUDING MEAN WIND EFFECT

A, B, AMP, ANGLE IN DEGREES -0.4952 -0.0209 0.4957 -177.5802

PHASE ANGLE FOR 1P IN SIMULATED DATA -177.6 DEGREES

OFFSET ANGLE BETWEEN MEAN WIND AND TURBULENCE AT 1P (DELAY) 0.0 DEGREES

OFFSET, IFFSET, -11.8 17

ONE CYCLE OF MEAN WIND EFFECT - M/S

42.49 42.15 42.49 43.49 45.08 47.15 49.56 52.15 54.74 57.15 59.22 60.81 61.81 62.15 61.81 60.81 59.22 57.15 54.74 52.15
49.56 47.15 45.08 43.49

NUMBER OF COMPLETE MEAN WIND CYCLES IN SIMULATION 42

VARIANCES FOR FIRST HALF-P AND FOR 6P FROM SPECTRUM OF SIMULATED DATA, S(n)r

0.4467 55.9733 0.7604 0.1565 0.0792 0.0477 0.0384

SPECTRAL ESTIMATES FROM SIMULATED DATA

4.3466	3.5060	2.8048	1.9575	1.3102	0.7740	0.5326	0.4728	0.4466	0.2192
0.2127	0.3647	0.2804	0.1323	0.4593	0.3747	0.0345	0.4905	0.0319	0.0129
0.2966	0.2778	0.0012	0.2135	0.9288	1.0551	1.1599	0.1764	0.4858	0.3847
1.5659	0.3952	2.7477	2.4338	4.3573	0.5928	4.0769	10.7664	3.6592	26.3678
21.3448	29.1704	452.5435	1678.2128	52.2266	12.4226	20.8991	18.6026	11.6762	9.3697
2.8875	1.6797	0.8501	3.5953	0.6085	2.5141	0.5190	1.3119	0.8335	1.2896
0.9222	0.9675	1.1110	0.9894	0.8554	0.6363	0.8971	0.8580	0.8123	0.7592
0.6222	0.1448	0.1499	0.3218	0.5300	0.7072	0.2993	0.6705	0.3239	1.0874
0.1899	1.3990	1.9194	2.1765	2.2794	3.4165	1.8661	2.8276	0.6552	1.2249

VARIANCE OF S(N)r FROM SIMULATED DATA 57.5320

SMOM(1), SMOM(2) 52.1589 57.5319

SKEWNESS AND KURTOSIS 0.0593 1.6718

HALF-RANDOMIZING SIMULATION - PHASE RANDOMIZED
 21 LOGARITHMICALLY SPACED BANDS AT 10. PER SPECTRAL DECADE
 BANDED NSN SPECTRA

BAND CENTER, HI, LOW (HZ), NS(N), HARMONIC COUNT PER BAND [NS(N):ORIG	SIM	VK	VKA]
10.69501 12.00000 9.53194 105 408 512	0.12547	0.20253	0.02343
8.49535 9.53194 7.57149 85 324 408	0.14169	0.22827	0.02725
6.74810 7.57149 6.01425 67 258 324	0.16401	0.21740	0.03172
5.36020 6.01425 4.77729 54 205 258	0.20215	0.23036	0.03689
4.25776 4.77729 3.79473 43 163 205	0.24871	0.32947	0.04297
3.38206 3.79473 3.01426 34 130 163	0.26092	0.29481	0.04990
2.68647 3.01426 2.39431 28 103 130	0.31014	0.50631	0.05811
2.13394 2.39431 1.90187 22 82 103	1.43917	2.15444	0.06778
1.69504 1.90187 1.51071 18 65 82	0.32362	1.06075	0.07903
1.34642 1.51071 1.20000 14 52 65	0.24843	1.73564	0.09177
1.06950 1.20000 0.95319 11 42 52	3.89765	222.62056	0.10492
0.84953 0.95319 0.75715 10 33 42	1.85797	8.96405	0.12177
0.67481 0.75715 0.60142 7 27 33	0.23564	0.66668	0.13981
0.53602 0.60142 0.47773 7 21 27	0.11699	0.30116	0.16191
0.42578 0.47773 0.37947 5 17 21	0.08213	0.07377	0.18908
0.33821 0.37947 0.30143 4 14 17	0.07044	0.08463	0.21048
0.26865 0.30143 0.23943 4 11 14	0.06927	0.06650	0.24035
0.21339 0.23943 0.19019 3 9 11	0.07571	0.06249	0.27531
0.16950 0.19019 0.15107 3 7 9	0.09019	0.08204	0.31840
0.13464 0.15107 0.12000 2 6 7	0.11050	0.08796	0.35177
0.10695 0.12000 0.09532 2 5 6	0.13126	0.11145	0.36823

UNBANDED NSN SPECTRA

0.023438	0.085513	0.082172	0.367659	0.394380
0.046875	0.140972	0.131477	0.411544	0.470174
0.070313	0.155125	0.137637	0.395881	0.463950

APPENDIX B

COMPARISON OF VON KARMAN SPECTRA WITH
CORRESPONDING ROTATIONAL SPECTRA WHEN ROTATIONAL
RATE AND ROTATION RADIUS OF THE LATTER APPROACH ZERO

APPENDIX B

COMPARISON OF VON KARMAN SPECTRA WITH CORRESPONDING ROTATIONAL SPECTRA WHEN ROTATIONAL RATE AND ROTATION RADIUS OF THE LATTER APPROACH ZERO

Because the autocorrelation functions of the rotational data reduce to von Karman autocorrelation functions when the rotational rate approaches zero, the rotational spectra that are the transforms of these acf's should approach the corresponding von Karman spectra. Specifically, this should hold for the u- and v-components. Powell et al. (1985) showed that this was not exactly the case for the HAWT u-component model. There, the acf transformed into a different spectrum that could be "derived" from the von Karman u-spectrum by transposing the number 1.339 in the denominator.

For this report, a more thorough investigation of the program was conducted. In particular, since the program calculates the acf's as functions of dimensionless parameters, a new reduced version of the program was written that calculated the HAWT u-component acf using von Karman's original dimensional parameters. The results of this analysis were the same as the previous results. In other words, no mistake was made in the transformation between dimensional and dimensionless parameterizations.

The spectral transforms of the acf's in dimensionless parameters for VAWT u modeling and VAWT v modeling for rotation rates and radii that approach zero were compared with the von Karman u- and v-spectra. In all cases, it was found that the rotational spectra with rotational features approaching zero also approached the von Karman spectra that can be derived from the original simply by replacing the frequency variable F where it equals nL/U with $F/1.339$. This is the same as replacing L by $L/1.339$. Note that 1.339 is a conspicuous number in the original von Karman spectra. These spectra are as follows:

von Karman u-spectrum:

$$\left[n S_u(n) / \sigma^2 \right] = 4F / \left[1 + 1.339(2\pi)^2 F^2 \right]^{0.83333}$$

von Karman variant u-spectrum:

$$\left[nS_u(n)/\sigma^2 \right] = 4F / \left\{ 1.339 \left[1 + (2\pi F)^2 \right]^{0.83333} \right\}$$

von Karman v-spectrum:

$$\left[nS_v(n)/\sigma^2 \right] = 2F \left[1 + (8/3) (1.339(2\pi F)^2) \right] / \left[1 + (1.339(2\pi F)^2) \right]^{1.83333}$$

von Karman variant v spectrum:

$$\left[nS_v(n)/\sigma^2 \right] = 2F \left[1 + (8/3)(2\pi F)^2 \right] / \left\{ 1.339 \left[1 + (2\pi F)^2 \right]^{1.83333} \right\} .$$

These comparisons are shown in Figure B.1. From Figure B.2, we see that the starting tangential component is like the v-component while the starting radial component is like the u-component. When the rotation rate is reduced to approach zero for the tangential and radial component simulations, they approach v- and u-components, respectively, as shown in Figure B.2. We were unable to envisage any kind of programming mistake that could have consistently produced this kind of error. Therefore, we believe the program is correct.

FIGURES B.1. Rotational Spectra with Rotational Rate and Radii Approaching Zero, Compared to von Karman Spectra and von Karman Variant Spectra.
a. VAWT u-spectrum; b. VAWT v-spectrum.

FIGURE B.2. Rotational Spectra with Rotational Rate and Radii Approaching Zero, Compared to von Karman Spectra and von Karman Variant Spectra.
a. VAWT tangential spectrum; b. VAWT radial spectrum.

APPENDIX C

SOME BASIC TURBULENCE DEFINITIONS AND LENGTH SCALE CONSIDERATIONS

APPENDIX C

SOME BASIC TURBULENCE DEFINITIONS AND LENGTH SCALE CONSIDERATIONS

C.1 BASIC TURBULENCE DEFINITIONS

Consider a time series $U(t)$. Subtracting out the mean value yields a new time series, $u(t)$, with a mean of zero. The autocorrelation function is defined by

$$\rho_u(\tau) = \langle u(t)u(t + \tau) \rangle / (\text{Variance of } u) , \quad (C.1)$$

where $\langle \rangle$ indicates a time average. (The τ is not the dimensionless variable of Equation (7).) In particular,

$$\rho_u(0) = 1 \quad (C.2)$$

and for a stationary process

$$\rho_u(\tau) \rightarrow 0, \text{ as } \tau \rightarrow \infty. \quad (C.3)$$

By assuming Equation (C.3), we can define the integral time scale

$$L_u t = \lim_{T \rightarrow \infty} \int_0^T \rho_u(\tau) d(\tau) . \quad (C.4)$$

We may conceive of correlation in space as well as in time. Thus, letting x and y be the alongwind and crosswind directions, respectively,

$$\rho_u(x) = \left[u(x_0 + x) u(x_0) \right] / \text{Variance } (u), \quad (C.5)$$

where the brackets indicate spatial averaging over x_0 , is the spatial correlation of u in the alongwind direction. Assuming that

$$\rho_u(x) \rightarrow 0, \text{ as } x \rightarrow \infty,$$

we can define an integral length scale in the x direction. This is

$$L_u x = \lim_{x \rightarrow \infty} \int_0^x \rho_u(x) dx . \quad (C.6)$$

Similarly, the spatial correlation of u in the crosswind direction is given by

$$\rho_u(y) = [u(y_0 + y) u(y_0)] / \text{Variance } (u) , \quad (C.7)$$

and an integral scale for u may be defined in the crosswind direction:

$$L_u y = \lim_{y \rightarrow \infty} \int_0^y \rho_u(y) dy . \quad (C.8)$$

Turbulence loses its correlation in a shorter length in the crosswind direction than in the alongwind direction. Therefore, $L_u y$ is less than $L_u x$.

One would assume that evaluation of $\rho_u(x)$ or $\rho_u(y)$ would require simultaneous recording of wind from a line of many anemometers in x or y directions, respectively. This is true for $\rho_u(y)$ but not for $\rho_u(x)$. By assuming Taylor's hypothesis, we can write

$$\rho_u(x) = \rho_u(t) \quad \text{when} \quad x = U\tau . \quad (C.9)$$

From that

$$L_u x = U L_u t . \quad (C.10)$$

Therefore, $L_u x$ may be evaluated from analyzing time series data from one anemometer, which is not true of $L_u y$.

In a similar manner, length scales for the lateral component of turbulence, the v-component, can be defined. These would be $L_v x$ and $L_v y$.

APPENDIX D

SAMPLES OF OUTPUT

APPENDIX D

SAMPLES OF OUTPUT

The types of output we illustrate here are rotational spectra and simulated time series data. These results were generated using the following set of input parameters. The machine parameters are known to be appropriate for the VAWT but not for the HAWT. However the same input data were used for both, for the purpose of comparing model output. The parameters are:

Radius of Rotation	8.3 m
Rate of Rotation	1.0000 Hz
Hub Height	16.7 m
Mean Wind Speed	10.00 m/s
Turbulence RMS Values	
u-Component	1.652 m/s
v-Component	1.652 m/s
Turbulence Variances	
u-Component	2.729 (m/s)^2
v-Component	2.729 (m/s)^2
Friction Velocity	0.688 m/s
Turbulence Integral Length Scales	
Longitudinal	70.1 m
Lateral	28.1 m
Number of Data to be Simulated	1024
Discretization Interval	0.0417 sec
Alias Factor	4
Angular Discretization Interval	15.0 degrees

Figure D.1 compares the turbulence spectra of the simulated HAWT u-component and the simulated VAWT u-component. Both spectral density $S(n)$ and the logarithmic spectrum $nS(n)$ are shown. It should be emphasized that the mean wind effect has been omitted in each case. If it had been included, the 1P spike would have been higher in both spectra, considerably higher for the

FIGURE D.1. Rotational HAWT u- and VAWT u-Spectra.
a. $S(n)$; b. $nS(n)$

VAWT u-spectrum. Clearly, however, the effect of turbulence alone in the u-component on the rotationally sampled spectrum of wind is more severe for the VAWT than for the HAWT, i.e., more severe on the horizontal circle than on the vertical circle.

Similar plots for the four VAWT simulations (u, v, tangential and radial) are shown in Figure D.2. Interesting features of this figure are:

1. At low P, the VAWT radial simulation has the strongest peaks.
2. At higher P, only the two u simulations maintain a distinct harmonic spike structure (see Figure D.1).

FIGURE D.2. Rotational Spectra $S(n)$ and $nS(n)$
for the Four VAWT Simulations
a. $S(n)$; b. $nS(n)$

In both Figure D.1 and Figure D.2, the $S(n)$ spectra are the 80-frequency spectra $S(n)_c$. The $nS(n)$ spectra are made by banding the $S(n)_r$ spectral estimates in eight evenly spaced bands.

The turbulence variances for the five runs are given in Table D.1. The spectra $S(n)_r$ and $S(n)_c$ are defined in Section 3.3.1.2.

The theoretical Eulerian turbulence variance for all cases is $2.73 (m/s)^2$. The variances above are less because the total length of the simulated time series is only 43 seconds, rather than the 10 or 15 minutes that is required to attain the theoretical variance from field data.

TABLE D.1. Variances of the Five Simulations, in $(\text{m/s})^2$

	<u>$S(n)_r$</u>	<u>Integration of $S(n)_c + S(n)_{c1}$</u>
HAWT u	2.17	2.41
VAWT u	2.26	2.54
VAWT v	2.41	2.35
VAWT t	2.53	2.48
VAWT r	2.45	2.72

Simulated data for VAWT u-component and VAWT radial component turbulence are shown in Figure D.3. The simulated wind speed time series are derived from these spectra. The graphs illustrate turbulence only. The changing mean wind effect is not included because it would mask the turbulence. The difference in the character of these stationary data over a short period is evident.

The variances in the first five harmonics for each type of simulation are shown in Figure D.4. One graph, D.4.a, compares the spike variances for the HAWT u and VAWT u simulations; the other, D.4.b, compares the spike variances for all four VAWT simulations. The energy in the first spike of the VAWT u simulation is greater than that in the first spike of the HAWT u simulation. However, the greatest differences are between the VAWT tangential and radial simulations on one hand, and the three other simulations on the other.

FIGURE D.3. Simulated Turbulence Data. a. VAWT u-Components; b. VAWT radial component

FIGURE D.4. Turbulence Variances for the First Five Harmonics
a. HAWT and VAWT turbulence, u-components; b. VAWT
turbulence, u-, v-, tangential and radial
components

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