Data Analysis Method for Wind Turbine Dynamic Response Testing

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NOTICE .

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ABSTRACT

The Wind Research Branch at the Solar Energy Research Institute (SERI) has developed an efficient data analysis package for personal computer use in response to growing needs of the wind turbine industry and SERI'S Cooperative Field Test Program. This new software is used by field test engineers to examine wind turbine performance and loads during testing, as well as by data analysts for detailed post-processing.

The Wind Data Analysis Tool Set, WINDATS, has been written as a collection of tools that fall into two general groups. First, the preparatory tools perform subsection, filtering, decimation, preaveraging, scaling, and derivation of new channels. Second, analysis tools are used for mean removal, linear detrending, azimuth averaging and removal, per-rev averaging, binning, and spectral analysis. The input data file can be a standard ASCII file as is generated by most data acquisition software.

INTRODUCTION

SERI's cooperative field test activities have resulted in large quantities of data, and we have found that the analysis of this data base is very time consuming. An assortment of data processing tools is available, including commercial software, but the time and effort required to apply them to large quantities of data are often restrictive. We have determined that our data analysis requirements would be better met by a software tool tailored specifically to our needs. The goal of this work, therefore, is to streamline and simplify our data processing capability with emphases on consolidation, speed, efficiency, accuracy, and flexibility. This paper begins with a brief review of the U.S. Department of Energy's (DOE) Cooperative Field Test Program and then presents the resulting data analysis method.

COOPERATIVE FIELD TEST PROGRAM

Over the past several years, DOE has sponsored a series of cooperative tests with the wind energy industry to provide a better understanding of both the operating environment and operating characteristics of wind energy conversion systems. SERI has been intimately involved with most of these tests by coordinating test planning, providing test equipment, and providing test engineering support to help run the field tests. Typically, the wind turbines are heavily instrumented with sensors to measure the dynamic responses of the machines to wind inflow. The wind itself is also measured in detail, often with a vertical plane array of anemometers located upwind of the turbine to provide wind data over the plane of rotation.

Figure 1 shows one test turbine, the Northern Power Systems (NPS) 100-kW wind turbine, on which field tests were performed during the summers of 1987 and 1988. The NPS 100-kW "North Wind 100" wind turbine has a two-bladed, upwind, teetered rotor employing a passive pitch rotor control system. The 17.8-m diameter rotor has two fiberglass blades and is located at a hub height of 25.6 m, atop a tapered steel tubular tower.

The machine was located in Altamont Pass, Calif. The test program objectives were to acquire and document the operating loads and performance parameters of the turbine, and provide a detailed view of the wind characteristics for correlation with
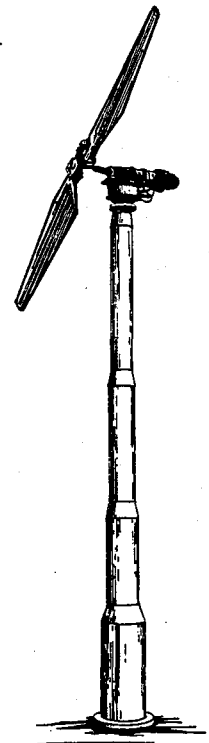

FIGURE 1

the loads and performance data. Eighty-two chan-
nels of data were recorded in multiplexed form on a
16-track magnetic tape for analysis. The following
discussion uses a small portion of these data to
demonstrate the capabilities of the data analysis
method.

COMPUTATIONAL NEEDS

Most of the tools mentioned earlier are used at
SERI. However, they are scattered throughout sepa-
rate programs that are quite useful by themselves
but are not designed with a standardized beginning-
to-end data analysis path in mind. Thus, it is
awkward and time-consuming to analyze the large
amounts of wind turbine field test data and present
them in a meaningful form to other researchers. A
typical 10-min data set would take perhaps 6 hr to
process. In addition, the tools are not readily
available for use at the field test sites to pro-
duce timely feedback, which is necessary to ensure
quality data and successful testing. Therefore,
computational requirements include flexibility,
transportability, processing time reduction (less
than 1 hr total for a 10-min data set), batch
processing (a single program in which all opera-
tions can be run without intermittent human atten-
tion), and the use of a commonly available comput-
ing environment (such as a personal computer).

Speed, batch processing, and flexibility are
achieved by using an interactive front-end proces-
sor to set up a control file for the data reduc-
tion. Transportability is limited only by the
minimum computer requirements of 640K RAM with a
math coprocessor, a PC-DOS version 2.0 or higher,
and a FORTRAN 77 compiler if the source code re-
quires modification. The analysis package accepts
data files of any length, ASCII or binary, volts
(counts), or engineering units, and a maximum of 90
channels in any order. Intermediate files are
saved for future access. Two program units are
used. The spectral processor (WINSPEC) is separate
from the time-series analysis package (WINDATS).
This separation alleviates program memory size
problems and allows for planned expansion of the
spectral analysis module. Additional flexibility
is achieved, and user selectivity is possible at a
critical point in the analysis. Basic flow charts
for the two programs are shown in Figures 2a and
2b, and a sample process control file is presented
in Figure 3.

ANALYSIS TOOLS

The following discussion includes sample graphs
showing representative results for a segment of
time-series data from the recent field tests of the
NPS 100-kW wind turbine previously described. The
original data set contains 20 channels of data,
each sampled at 25 samples per second. An example
of one channel of the original time series data
sampled at 25 Hz for the entire 11 min is shown in
Figure 4. This plot represents the blade root flap-
wise bending moment. It is apparent from Figure 4
that the signal contains information over a wide
range of frequencies, but it is difficult to quan-
tify characteristics such as long-term trends and

FIGURE 2a
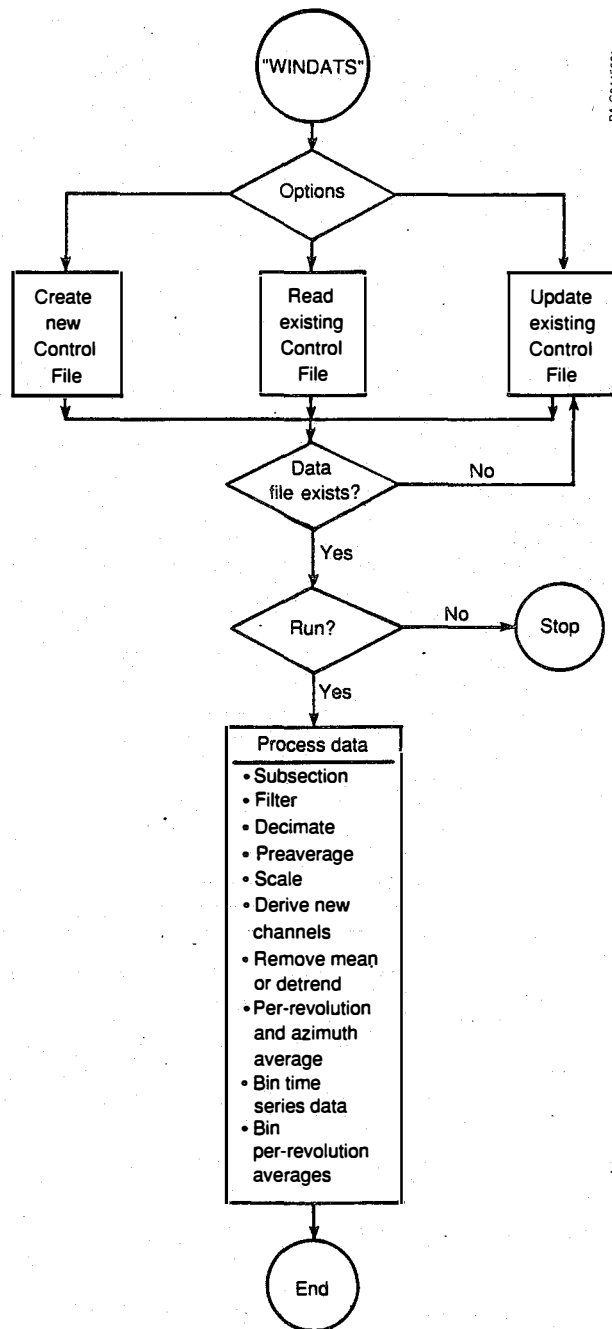
periodicity of the signal. Figure 5 shows the same
signal over a much shorter time interval
(10 sec). Here the periodicity of the signal can
be seen with much more detail. The data analysis
program will help correlate the behavior of this
bending moment with other measurements such as the
wind inflow and the blade position by applying the
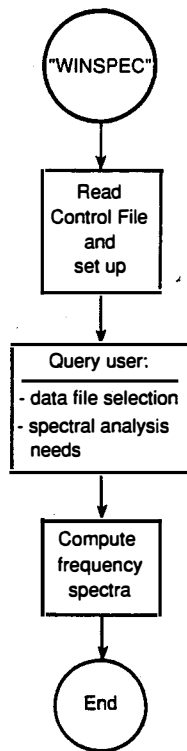data reduction and analysis techniques described
below.

FIGURE 2b

```
DATA DESCRIPTION:

fret54.dat                          data file
ibmpc                               source machine
ascii                               data file format
real*4                              data type
    25.000        sample rate (Hz)
   660.000        total time (seconds)
 16525            scans
    20            channels total
     3            channels needed
 channel position   name                        units
     1      1       AZIMUTH                      DEG
     2      2       B1RFBM                       FT-KIP
    18     18       BV6WS                        MPH

DATA PREPARATION NEEDS:

     y            prepare data
     y            use subsection
     y            filter
     y            decimate
     n            pre-average
     n            scale

DATA PREPARATION SPECIFICATIONS:

  26   16525      data subsection - start and stop scans
   6       1      number of poles, cyclic chans for filtering
   1
 channel  cutoff frequency (Hz)
    1          0.500
    2          0.500
   18          0.500
   25          decimation interval - keep every nth scan

DERIVED CHANNEL NEEDS:

     y            add derived channels
     y            derive a time channel
     n            derive yaw rate
     n            derive yaw error
     n            derive disc avgd wind speed
     n            derive disc avgd wind direction
     n            derive vertical wind shear
     n            derive horizontal wind shear
     n            derive temperature difference
     n            derive Richardson's number

DATA ANALYSIS NEEDS:

     y            analyze data
     n            remove mean
     y            detrend
     y            per-rev average and azimuth average
     y            get azimuth average residuals
     y            bin in time domain
     y            bin per-rev averages

DATA ANALYSIS SPECIFICATIONS:

   660    24      number of scans, azimuth bins for per-rev & az avg
   660            number of scans               for az-avg residuals
   660     1      number of scans, indep chans  for time domain bins
  indep   min        max        bins   # of dep chans
    19    0.000      40.0         20         1
    2             dependant channel number
```

FIGURE 3

Data Preparation

Analog data collected in the field are passed through analog filters before being sampled at a rate consistent with the bandwidth of interest. An input data file often contains channels that have been filtered at different cut-off frequencies, depending on analysis requirements and sensor limitations. Sometimes, the recorded sample rate is several times higher than that needed for initial data analysis. In order to reduce these large volumes of data to a more manageable size without introducing aliasing from lower sample rates, the program includes modules to filter raw data and reduce bandwidth requirements, and then to decimate the data at user-specified intervals. A low-pass Butterworth filter (recursive – Infinite Impulse Response, single-zero, multipole, cascaded) is used in WINDATS, with the convention

$$y(i) = B0*x(i) - A1*y(i-1) - A2*y(i-2) . \quad (1)$$

It is faster than a comparable nonrecursive (Finite Impulse Response) filter in most cases, although it is sometimes unstable with more than two poles. Two poles are usually sufficient, but six are often preferred for a very sharp rolloff. (This is a user option.) The discontinuous blade azimuth (sawtooth) signal is converted to a half-angle cosine function for full 360° coverage when filtering, so that it receives the same phase shift as the rest of the data. In decimation, every nth scan is retained, and the rest are discarded. Figure 6 shows the original time-series data shown in Figure 4 after being filtered at 0.5 Hz and

FIGURE 4

ROOT FLAP BENDING MOMENT:
10 SECONDS OF RAW DATA.
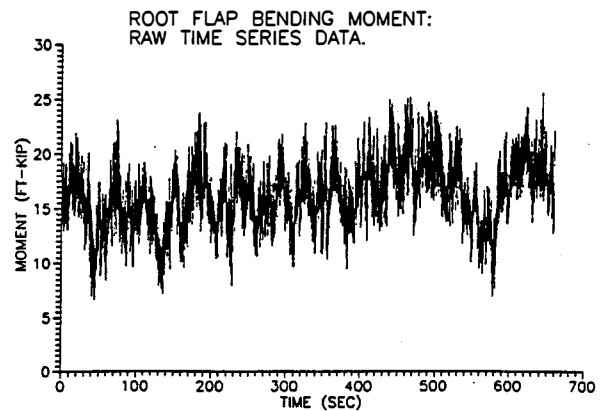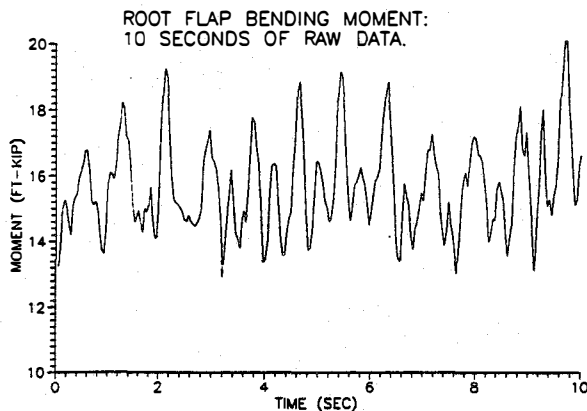
FIGURE 5

decimated by a factor of 25 to a sample rate of
1 Hz. Visual comparison of the two plots clearly
shows the reduction of high-frequency information.

Preaveraging is a crude form of filtering and deci-
mation: Every n consecutive scans are replaced by
one scan of averages for the group. It is not
recommended because it may introduce some errors
through aliasing, yet it is preferred occasionally.
Consequently, it is an option in WINDATS as well.

The scaling operation converts measurement units
(counts or volts) to engineering units. Slopes and
intercepts must be specified in the control file
for each channel in order to be applied to the
original time-series data. A maximum value can be
specified for cyclic data (such as blade azimuth or
yaw angle) to cause a modulus reduction to the
first cycle range (0° to 360°). This is necessary
for angular position sensors with redundant ranges
such as 360° to 720° and 0° to -360°.

Once this preprocessing is complete, the derived-
channels option can create new channels that are
functions of the original channels. The derived
channels currently available are:

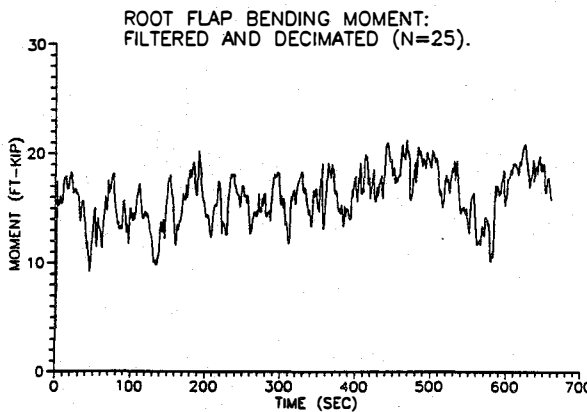● time (scan #/sample rate),
● yaw rate (delta yaw angle/delta time),

ROOT FLAP BENDING MOMENT:
FILTERED AND DECIMATED (N=25).

FIGURE 6

● yaw error (yaw angle - wind direction),
● disc-averaged wind speed and direction,
● vertical and horizontal wind shears,
● vertical temperature difference, and
● Richardson's number.

New derived channels can be added to this option as
the need arises.

After each full pass through the data, statistics
are computed for each channel in the resulting data
file. These statistics include mean, standard
deviation, and minimum and maximum values over the
time segment.

Data Analysis

The analyst is often interested in examining only
the harmonic content of a signal, so WINDATS allows
the user two basic methods for removing the DC and
very low frequency signal components. The first
method, mean removal, is accomplished by
subtracting a channel's mean over the total time
segment from each of its data points:

$$x'(i) = x(i) - \bar{x} ,$$

$$\text{where } \bar{x} = \sum_{i=1}^{N} x(i)/N , \qquad (2)$$

where $x'(i)$ are new data points, $x(i)$ are
individual data points, $\bar{x}$ is the mean, N is the
number of data points, and i is the scan number.
The second method, detrending, involves fitting a
linear trend line to the data using a least squares
fit, and then subtracting the line from the data:

$$x'(i) = x(i) - y(i) , \qquad (3)$$

$$\text{where: } y(i) = Ax(i) + B,$$

where A and B are the trend coefficients, and y
represents the linear fit to the data.

It is assumed that for stationary operating condi-
tions of the test turbine, deterministic and sto-
chastic portions of the signals can be separated by
the process of azimuth averaging. Azimuth
averaging is accomplished by binning: dividing the
rotor azimuth range into several equal groups and
assigning data points from numerous rotor cycles to
their respective groups. WINDATS accepts a user-
specified number of groups (bins). Mean values and
standard deviations for each channel are determined
for corresponding data sets that fall in each bin:

$$\bar{y}(k) = \sum_{i=1}^{N} y\bigl[x(i)\bigr]/N(k) \qquad (4)$$

$$\text{for } xmin(k) \le x(i) < xmax(k) ,$$

where i is the scan number, k is the bin number,
$x(i)$ are azimuth points, xmin and xmax define the
range of bin k, N is the number of data points in
that bin, $y[x(i)]$ are data points corresponding to

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azimuth x(i), and y is the mean for bin k. The azimuth averaged root flap bending moment is shown in Figure 7. Notice the characteristic smooth signal shape. This signal represents the deterministic bending moment that occurs with every rotor revolution and is independent of wind turbulence.

The random loads, which are superimposed on this deterministic part of the time-series data, also contain useful information for examining the rotor loads and their contribution to fatigue damage. Residuals, which represent this stochastic portion of the signal, are produced when the azimuth average is subtracted from the original data, cycle by cycle:

$$y'(i) = y[x(i)] - \bar{y}(k) \qquad (5)$$

for x(i) in bin k, where y'(i) are the residual data points. The random nature of these residuals is apparent in Figure 8.

Per-rev averaging, which is defined as the sum of all samples for a signal over one blade revolution divided by the number of samples contained in that revolution, reduces a column of data so that a single average represents each rotor revolution. This method is useful as another way to remove higher frequency variations in a signal that occur over each cycle, to show long-term trends in the
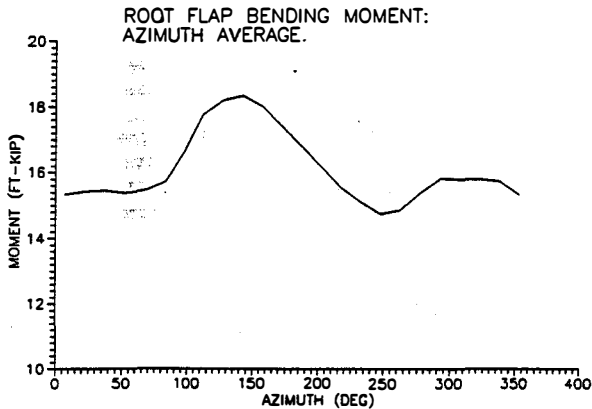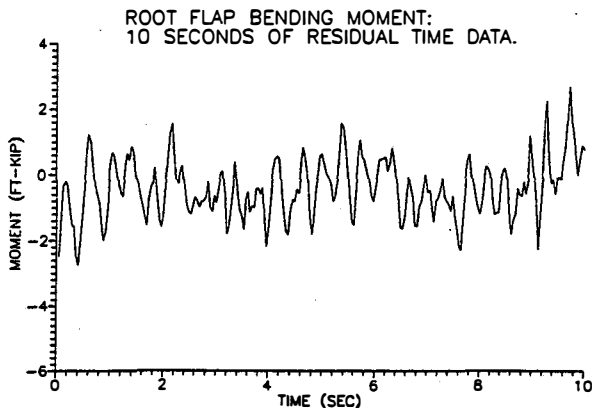
data, and sometimes to facilitate binning. It is essentially the same as preaveraging with a one-revolution block size triggered by the rotor azimuth signal.

Binning is a simple technique used in place of regression analysis to characterize the interdependency between any two channels. The data models needed for regression are often discontinuous or too complex for adequate representation of wind turbine data. In binning, the independent channel is divided into a user-specified number of equal segments, or bins. Each dependent value is placed in its respective bin, then means are calculated for each bin. The formulas are the same as for azimuth averaging, but now x(i) and y[x(i)] are corresponding independent and dependent data points. Figure 9 shows the characteristic relationship between bending moment and wind speed that results from the method-of-bins.

Spectral analysis is useful for looking at the frequency content of time-series data. The power spectral density routine applies a square or cosine-tapered data window to segments of the time-series data and then performs a discrete Fourier transform to multiple data segments:

$$X(k) = (1/N) \sum_{r=0}^{N-1} x(r)\exp(-2\pi i k r/N) \qquad (6)$$

for k = 0,1,2,...,(N-1), where N is the number of values in the segment, i is $\sqrt{-1}$, r is the scan number, x(r) are time-series data points, k is the frequency index [freq(k) = (k*sample rate)/N], and X(k) are Fourier coefficients (see [1,2]). The program then converts the Fourier coefficients to spectral estimates {X(k)*conj[X(k)]} and averages the resulting frequency-transformed segments together. If desired, linear or logarithmic smoothing can be applied to the final frequency spectrum. Frequency units can be specified as hertz or radians per second. The first point (at zero frequency), which represents the steady component, or the mean, normally should be dropped before plotting on a logarithmic scale since the log of zero does not exist. The power spectral density plot of the root flap bending moment is

ROOT FLAP BENDING MOMENT:
AZIMUTH AVERAGE.

FIGURE 7

ROOT FLAP BENDING MOMENT:
10 SECONDS OF RESIDUAL TIME DATA.

FIGURE 8

ROOT FLAP BENDING MOMENT:
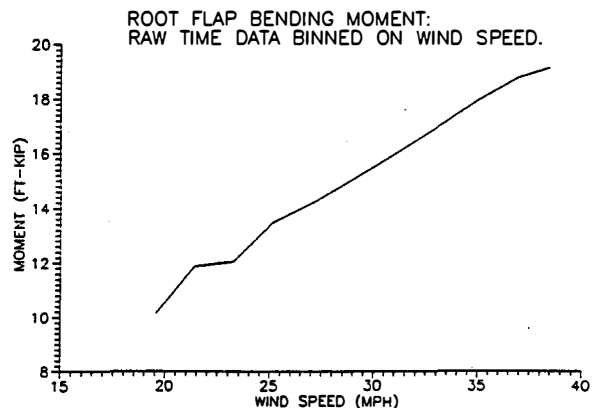RAW TIME DATA BINNED ON WIND SPEED.

FIGURE 9

shown in Figure 10. The large peaks in this graph at 1.2 and 2.4 Hz are typical harmonics of the rotor speed (1.2 revolutions per second) and are probably deterministic rotor responses such as those induced by tower passage and gravity loading along the blade. The first and second flapwise natural frequency modes are indicated by broad peaks around 3.25 Hz and 9.0 Hz, respectively.

For a more detailed discussion of the analysis of the Northern Power 100-kW wind turbine, see References 3 and 4. Data analysis methods and specific techniques used in WINDATS were taken from References 5-9.

CONCLUSIONS

This analysis package has proven to be a useful tool to efficiently process large amounts of test data in a timely manner. Although researchers have started using this analysis package in the office and in the field, it is still in the development stage. We plan to add a few more operations, such as the choice of a least squares data fit in place of azimuth-averaging, using a Fourier series with several low-frequency terms to produce a model of the deterministic part of the data. Subtracting the curve fit from the original time-series data leaves residuals as before (the stochastic part), representing the contributions from wind turbulence. Several operations related to spectral analysis will also be added, such as computing the integrated area under the power spectral density curve to yield the variance of the signal over the bandwidth of the frequency range of interest. Frequency weighting, normalization, and transfer and correlation functions would also be useful for complete frequency domain analysis capabilities.

ROOT FLAP BENDING MOMENT: POWER SPECTRUM OF RAW DATA.

FIGURE 10

REFERENCES

[1] R. Sharif-Razi, R. Thresher, and W.E. Holley, *Digital Stimulation of Turbulence Excitation for Dynamic Analysis of Wind Turbines*, Mechanical Engineering Department, Oregon State University, Corvallis, NASA Grant NAG-3-87, March, 1985.
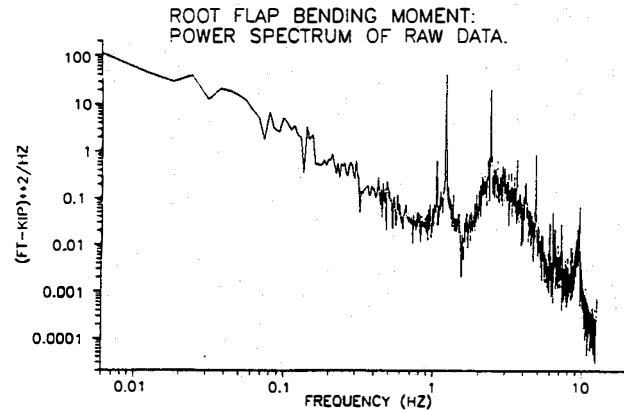
[2] D.E. Newland, *Random Vibrations and Spectral Analysis*, Longman Inc., New York, 1975.

[3] R.M. Osgood and S.M. Hock, *Preliminary Results from the Dynamic Response Testing of the Northern Power Systems 100-kW Wind Turbine*, SERI/TP-217-3342, Solar Energy Research Institute, Golden, Colorado, June 1988.

[4] S.M. Hock, R.W. Thresher, and A.D. Wright, *A Comparison of Results from Dynamic Response Field Tests*, SERI/TP-217-3423, Solar Energy Research Institute, Golden, Colorado, November 1988.

[5] A.C. Hansen, *Wind Turbine Dynamic Data Analysis Solftware User's Guide* (and software), Mechanical Engineering Department, University of Utah, Salt Lake City, SERI Subcontract No. XL-6-05078-2, October 1987.

[6] P.H. Madsen, *DAP-1, A Data Analysis Package for Spectral Analysis, Version 1.2*, Wind Energy Research Center, Solar Energy Research Institute, Golden, Colorado, No. 217/Draft/ WRB1075/-11-6-87.

[7] R.K. Otnes and L. Enochson, *Applied Time Series Analysis*, Vol. 1, J. Wiley and Sons, New York, 1978.

[8] S.D. Stearns and R.A. David, *Signal Processing - Algorithms*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1988.

[9] W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling, *Numerical Recipes, The Art of Scientific Computing*, Cambridge University Press, New York, 1986.