ANALYSIS OF DATA FOR THE RESPONSE OF FULL-SCALE TRANSMISSION TOWER SYSTEMS TO REAL WINDS

by

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CHAPTER I

INTRODUCTION

1.1 Importance

Due to the increasing construction of tall buildings, monuments and towers, the accurate analysis of wind data is becoming more and more important. There are relatively few reports which explain the analysis of wind data, although much wind research has been completed during recent decades. This area of wind data analysis should be understood more completely to predict response of buildings and structures in wind environment.

In the future, many large transmission towers will be constructed to handle the increasing need for energy. With new and larger cables coming into use (with 500 to 1200 Kilovolts capacity), these transmission lines cannot be designed by previcus experience alone. A full understanding of the wind response of transmission line systems is needed so that new types of towers and lines can be designed properly. If the design code can come closer to reflecting the real response behavior, the towers and lines can be designed in a more efficient manner. Because of the number of units

of this type of system that will have to be constructed in the coming years, a 5 to 10% reduction in cost due to more complete knowledge of the structural response to wind can save millions of dollars.

Because of the importance of this area of wind loads on transmission line structures, several full-scale experiments have been set up in recent years. Measurements and analysis of recorded data need further development before they can provide the design information needed.

1.2 Previous Works

A review of summaries of previous works(6) shows that a fair amount of full scale experimental wind research has been done on tall buildings and tall towers. In 1968, H. Arakawa of Tokai University, Japan conducted a project on characteristics of strong wind over the city of Tokyo. Data were taken from Tokyo Tower at five levels (26, 67, 107, 173 and 253m). These data were used to study the physical processes in the atmospheric boundary layer. Arakawa published a paper(1) on strong gusts in the lowest 250m layer over the city of Tokyo. In 1973, M. Shears (19) reported on wind and vibration studies of a 330m high TV tower in Yorkshire, England. In 1975, P. C. Birkemoe(4) presented a paper which used field data of the CN Communications Tower. These research efforts gave engineers added knowledge of the design of tall structures in an urban environment.

Since 1976 several full scale studies(13,14,15) have been conducted by the Bonneville Power Administration (BPA) cn various aspects of the mechanical behavior of non-energized transmission systems with lattice-type towers. These studies include static and dynamic responses, icing effects, effects of brcken cables, etc. on the transmission structures. The most comprehensive test site in terms cf number of recording channels of wind and response data has been built by the Electrical Power Research Institute (EPRI) near Oklahoma City, Oklahoma. GAI Consultants has written a report cn this project(10).

1.3 Objectives

The previous works mentioned above did not give detailed introduction to the statistical aspects of the problem of wind and structural response data analysis. Engineers who do not have a statistics backgound cannot easily understand statistical aspects of data, such as the mean, standard deviation, time history, histogram and power spectrum cf a recorded channel of data. For this reason, procedures for calculating the statistical properties of wind and structural respcnse data are discussed in this report.

The objective of this research is to indicate statistical procedures for analyses of data of full-scale wind load experiment and their implications. These analysis

procedures can be used for any structural system, including electrical transmission line system.

1.4 Wind Data Considered

The methods of analysis described in this thesis are applied to an actual set of recorded data at a full-scale experiment site to illustrate and clarify the concepts involved. These data were recorded at the Oklahoma City (OKC) site set up by EPRI in cooperation with the Oklahoma Gas & Electric (OG&E) Company.

The experimental site has a network of meteorological and structural response instruments to measure some of the characteristics of wind and structures. The site plan (17) is shown in Figure 1.1. The wind instrumentation, shown in Figure 1.2, consists of nine UVW anemometers (3 channels each) on four different meteorological towers 100 meters apart located parallel to the transmission line and three wind speed-and-direction instruments (2 channels each) on three different transmission towers. Additional meteorological instrumentation is three temperature sensors on meteorological tower number 4 and one dew point sensor at the instrument trailer. The strutural response instrumentation, shown in Figure 1.3, is installed on transmission tower number 287 and consists of seven swing angle indicators, four load cells, twelve strain gages, and

four foundation displacement transducers. The signals frcm these 64 sensors described above are amplified and transmitted to the instrumentation trailer. These signals are sampled at a rate of 16 samples per second per channel, and then are stored on two high-capacity magnetic disks. The recorded digital data can be accessed via a telephone modem and remote moniter system. Useful data are retained on magnetic tapes while other data on magnetic disks are discarded.

1.5 Scope

Two basic levels of anlysis are described in this thesis. In the validation level of analysis, field data are examined carefully and channels with problems are identified. This level of analysis includes plotting of the time history cf each channel, ccmparisons between channels, histogram plots, and data run and trend tests for stationarity checks. The validation methcds are treated in Chapter II.

The second level of analysis involves calculation and plotting of statistical quantities of major significance in wind engineering, including relationships between the measured wind data and the response of the transmissicn tower structures to the winds. Chapter III discusses those calculations related strictly to the wind, including the wind profile, the turbulence intensity, and the wind

spectrum. Chapter IV utilizes the power spectral density functions and cross spectral density functions to detect linear relationships between forces and responses and to predict peak response values of transmission tower structures. It may be noted that both time domain and frequency domain analyses are included in these calculations.

Examples of all calculations are included in each chapter and listings of computer programs used are given in Appendix A. All examples are taken from the Jan. 22, 1982 readings at the OKC site described above.

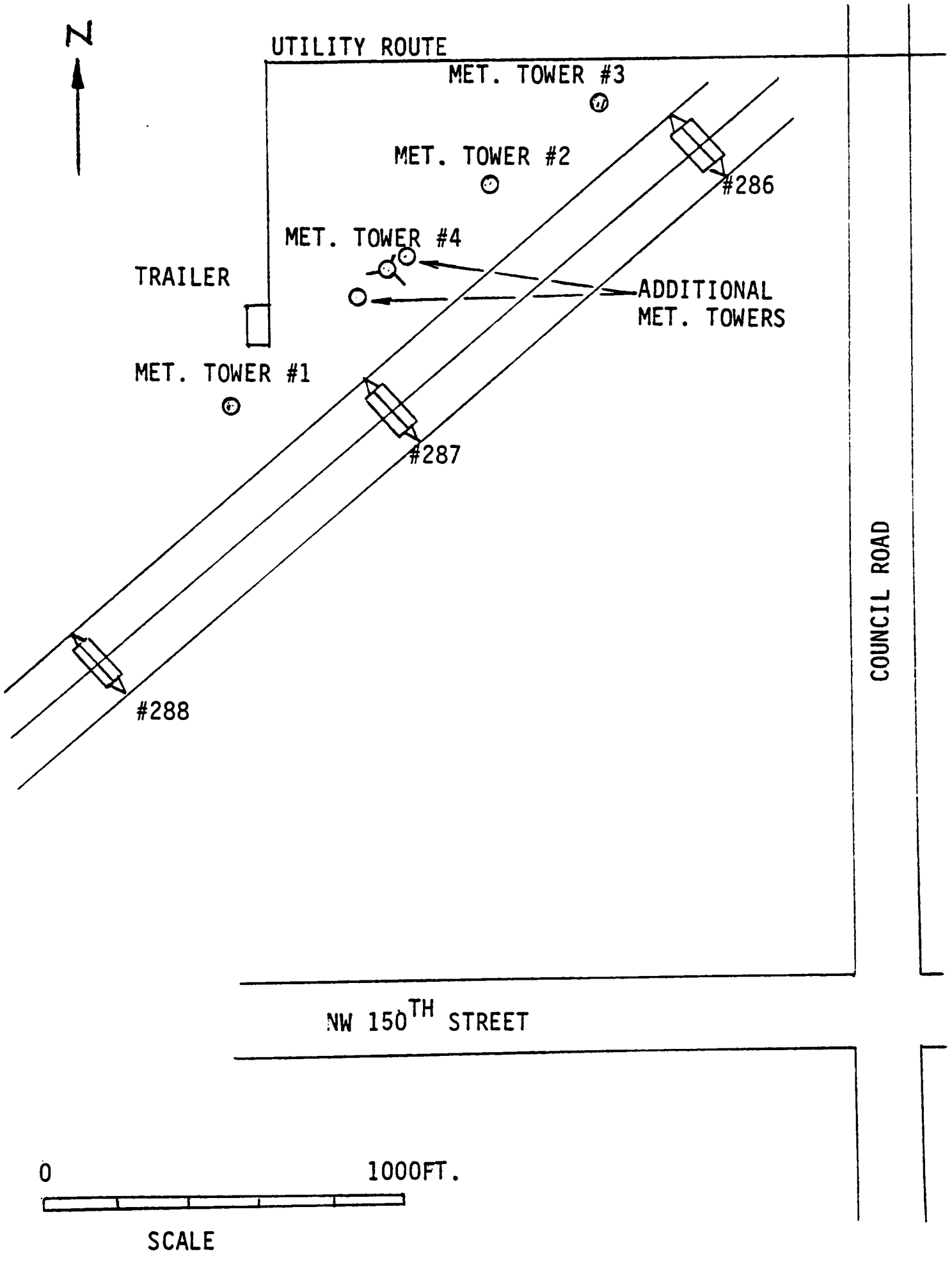


Figure 1. 1 OKC Site Plan

WS
WD: Windspeed and direction anemometers.

UVW: Wind component anemometers (components are normal and parallel to line and vertical).

T: Temperature sensor.

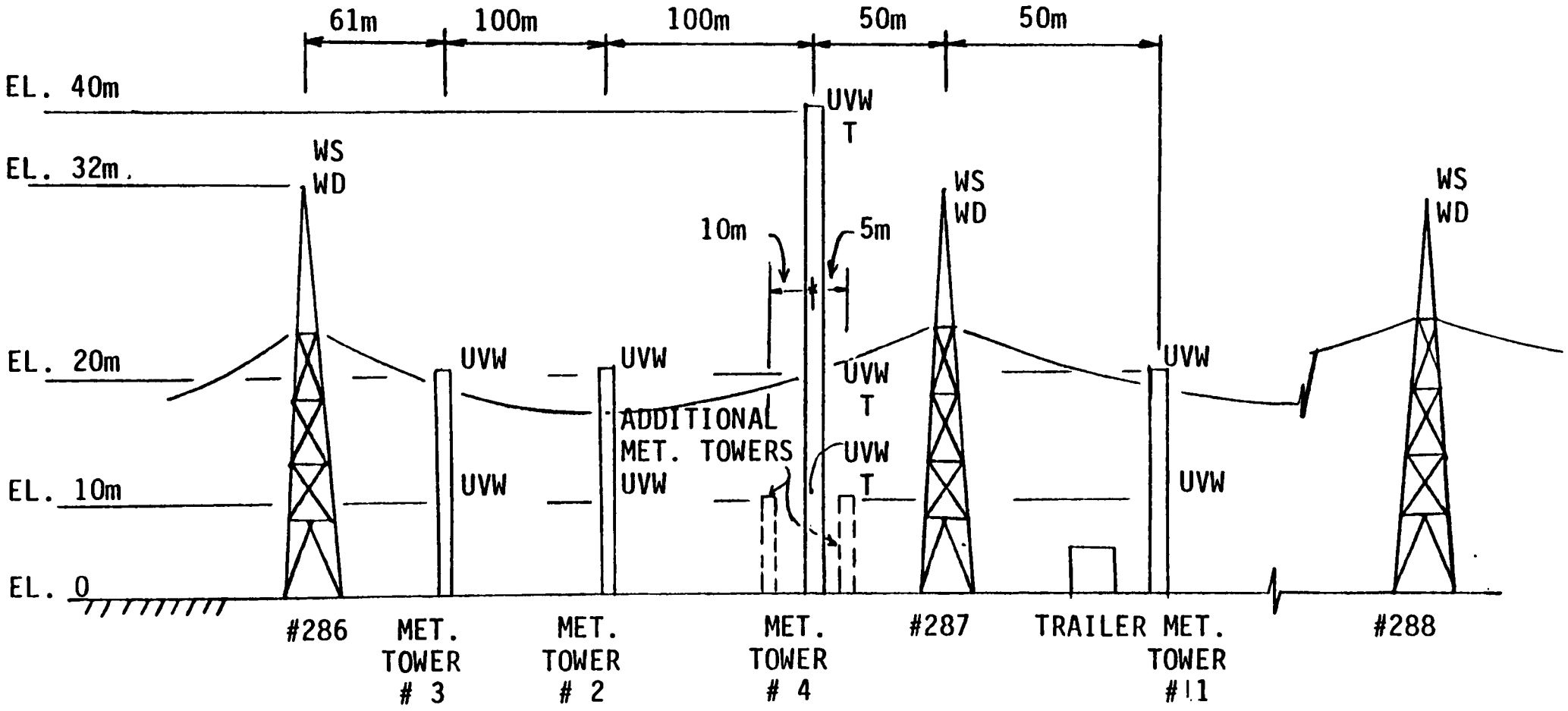
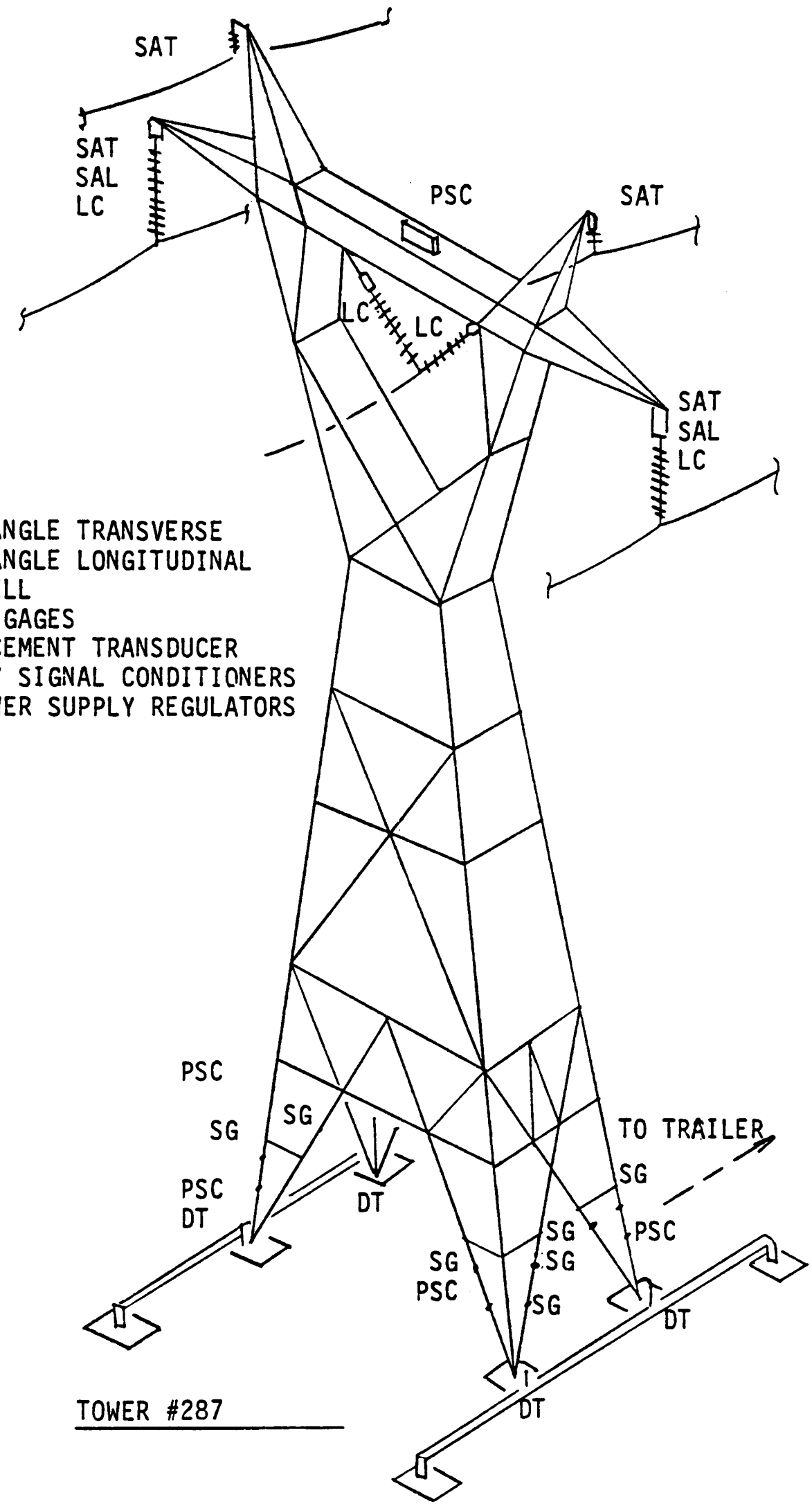


Figure 1.2 Meteorological Instrumentation



SAT: SWING ANGLE TRANSVERSE
SAL: SWING ANGLE LONGITUDINAL
LC : LOAD CELL
SG : STRAIN GAGES
DT : DISPLACEMENT TRANSDUCER
PSC: PRIMARY SIGNAL CONDITIONERS
AND POWER SUPPLY REGULATORS

Figure 1. 3 Structure Response Instrumentation

CHAPTER II

VALIDATION

The first step of data analysis is to check the validity of the recorded data. If the data are good, the analyst can proceed to the other methods in subsequent chapters. Some wind data may have noise and/or other problems in the recording system. Noise is a random component frequently found in time series data. The term comes from the fields of electrical and acoustical instrumentation where low pass filters are used to eliminate noise so that the true patterns can be identified. Recording problems can also be checked by comparison with other measurements at neighboring towers. The task of validation in this research is restricted to direct inspection of the data, calculation of a few basic characteristics of the data, and plots to show features of the data.

The various types of calculation described in this chapter are illustrated with results from real wind data obtained from the Oklahoma City experiment described in Chapter 1. In particular, results are given for 15 to 17 minute records of windspeeds measured on meteorological tower number 4 at different elevations.

2.1 Time Histcry

A time history plot illustrates a measured quantity versus time. It can show a possible trend, seasonality or noise in the data. For example, Fig.2.1 is a time-history plot of the windspeed at the 60-foot level cf meteorological tower 4 in the OKC experiment. The program TIMEHIST given in Appendix A was used to obtain this plot. No problems seem to appear in this record. The plot also shows the peak value, the mean and the standard deviation (sigma) in a graphical way to aid the analyst in understanding the statistics of the time series being displayed.

Two-second averages (not moving averages) are used to plot the time history in Fig.2.1. The main reason for averaging over two seconds is that the instruments cannot actually respond tc the winds as fast as 1/16 second. Secondarily, the resulting figure can show up and down trends and the high-frequency appearance rather than just a solid mass of lines due to a cumbersome number of data points. Consequently, the 2-second averages are good enough to express the time history and to show the properties of wind data.

2.2 Comparison To Expected Values And Between Channels

The expected values for the first and second moments of a time series can be written as:

$$\text{Mean value, } \bar{x} = \sum_{i=1}^{n} \frac{x_i}{n} \qquad (2.1)$$

$$\text{Variance, } s^2 = \sum_{i=1}^{n} \frac{(x_i-\bar{x})^2}{(n-1)} = \frac{\left(\sum_{i=1}^{n} x_i^2\right) - n\bar{x}^2}{(n-1)} \qquad (2.2)$$

Standard deviation, s = square root of the variance.

Calculation of these values in the present project is done by standard summation techniques in both the time history plotting and spectrum plotting routines.

The expected values of some channels of data in the sample obtained from the OKC site are listed on Table 2.1. Comparing the windspeeds at equal elevations, one can check the homogeneity of the wind field. If any channel has an expected value far away from the values of the other channels, one can say that this channel is not valid. From Table 2.1, the expected values of wind speed at the tops of transmission towers 286, 287 and 288 are not consistent when compared with the windspeeds measured on meteorological towers 2, 3, and 4. Thus the transmission tower values should not be used for further analysis. On the other hand, the expected values measured on the three meteorological towers show very consistent results, and can be used for further analysis. Similar comparisons can be made for wind directions, load cell values, strain measurements, etc.

2.3 Histogram

A histogram is a plot of the number of occurrences of some measured quantity within each of several intervals of the value of the quantity. The plot approximates a sample probability density function with respect to the interval values. If one divides the range of a time series x(i) having a minimum value a and a maximum value b:

$$a < x(i) < b,$$

into K equal-length intervals, each measurement in the series can be checked to see which interval it falls into and counted as one of the number of occurrences for that interval. Then the histogram can be plotted. The algorithm used to plot the histogram of a time series in this report is shown below, where N(j), the number of occurrences within interval j, is to be calculated. For i=1 to N, where N is the total number of measurements,

(1) If x(i)<a, add 1 to N(1) and go to step 5;

(2) If x(i)>b, add 1 to N(K+2) and go to step 5;

(3) If neither of the two preceding requirements is met, then a<x(i)<b; therefore compute

$$j = IFIX((x(i)-a)/c)+2 \qquad (2.3)$$

in which c = (b-a)/K, is the length of each interval, and

j is an integer indicating the number of the interval into which x(i) falls; then

(4) Add 1 tc N(j); and

(5) Repeat steps 1 through 4 for the next measurement.

The number of intervals is usually between 10 and 30. With a number of intervals larger than 40, the results are usually not good. N(j) can be expressed in another form as a sample probability density function.

$$P(j) = N(j)K/(N(b-a)) \qquad (2.4)$$

This can be interpreted as the derivative of the distribution function at the midpoint of each interval.

For comparison of the sample probability density function to the Gaussian probability density function over the same range and at the same intervals, a Gaussian frequency value equation may be written as

$$n(j) = p(j)N(b-a)/K \qquad (2.5)$$

in which

$n(j)$ is the Gaussian theoretical frequency value;

$p(j) = 1/\sqrt{2\pi\sigma^2}\ \exp(-(x(j)-\mu)^2/2\sigma^2)$ is the probability density function for a Gaussian distribution;

μ is the mean value; and

σ^2 is the variance value.

An overlay plot of N(j) and n(j) can help the analyst detect if the measured data follow a Gaussian distribution. When the histogram fits the theoretical curve, the data have a

normal distribution. For a time series with outliers or an unreasonable spike in the time history plot, the histogram may have a very high frequency at the mean value and be empty at most of the other ranges(18). Thus we can firmly conclude that the time series does not follow a normal distribution. Some histograms which cannot fit the Gaussian curve are not normally distributed.

Figure 2.2 shows the histogram of the horizontal windspeed at meteorological tower 4 at the 60 foot level. The program HISTGRAM given in Appendix A was used to obtain this plot. The plot uses 16,384 data points and the following general values

$a = 13.788$ mph $\qquad b = 39.909$ mph

$\mu = 26.82$ mph $\qquad \sigma = 3.996$ mph

These values were all calculated separately and used in the algorithm of the Gaussian curve calculations.

The principal application for assuming a Gaussian probability function of wind data is to establish a probablistic description for the instantaneous values of the data.

2.4 Stationarity Check

In simple wind experiments, the data are decomposed into

mean and fluctuating components. The mean and fluctuating components of the wind can be visualized via time history plots like the one in Fig.2.1.

A stationary time series is one that oscillates around a constant mean. It contains no trend. All of its statistical properties (ensemble averages, mean value, mean square value and variance, as discussed above) are independent of time. Another important property of a time series is its ergodicity. A time series is said to be ergodic if its time averages over any given interval are equal to the averages of all ensembles that might be selected from the total sample space (7,8). Ergodicity is always assumed for physical data, so that the analyst can choose one section of the time series to express the whole process. That is the importance of stationarity. An ergodic time series is always stationary, but the assumption of stationarity should be checked. A stationary time series is not necessarily ergodic.

There are certain statistical procedures which do not assume a normal distribution or other specific distribution function for the original random variable of interest. These procedures are called distribution-free procedures, and they are useful in performing statistical checks. The

most often used of the distribution-free procedures are the Run Test and the Trend Test(2).

Stationarity can also be checked by other methods. An autocorrelation plot will reveal if there is a trend in the data by not converging to zero as time interval increases. Also, a trend can be detected by fitting a straight line to the time series data and seeing if the difference between the slope of the line and zero is statistically significant.

2.4.1 Run Test

For a discrete time series x(i), i=1,2,3,...,N, the run test is based on a series of comparisons of the individual values of the series with the mean value, $\bar{x}$. If a particular value is greater than or equal to the mean, the procedure assigns a plus; if it is less than the mean, the procedure assigns a minus: $x(i) \geq \bar{x}$ (+) or $x(i) < \bar{x}$ (-). For example, consider a time series of N=10 observations with the following values:

1.3, 0.9, 1.6, 1.1, 0.9, 0.8, 0.7, 1.2, 1.3 and 1.3.

The mean is 1.1. The run test procedure lets all observations with a value greater than 1.1 be identified by (+) and all with a value less than 1.1 be identified by (-). The resulting comparisons, in order, are:

+ - + + - - - + + +

This series has 5 different changes in consecutive signs.

A run is defined as a sequence of identical observations (all plusses or all minuses) that are followed or preceded by a different observation or no observation at all. The number of runs is equal to the number of consecutive sign changes. In the sequence shown, there are five runs, three with plus signs and two with minus signs.

The run test is a statistical check concerning the probability that a time series is stationary according to whether or not the number of observed runs lies in a particular range of values. A limited tabulation is given in Table 2.2(2) to establish the limits on the range of observed runs, R, in a single time series, x(i), for stationarity by the run test method. For any desired level of significance α in the test, the limits on the observed runs are given by $r(n;1-\alpha/2)$ and $r(n;\alpha/2)$ where $n=N/2$. (The α represents the rejection level for the test, $1-\alpha$ represents the acceptance level for the test.) One therefore can check if the time series is stationary or not by $r(n;1-\alpha/2)<R<r(n;\alpha/2)$. The observed time series is stationary if the number of observed runs falls inside the interval at the chosen level of significance; if it falls outside the interval, then the series is not stationary.

For the example considered, $n=N/2=10/2=5$. From Table 2.2, for $\alpha=0.05$, $r(n;1-\alpha/2)=r(5;0.975)=2$, $r(n;\alpha/2)=r(5;0.025)=9$. The hypothesis that the time series is stationary is accepted since R=5 falls within the range between 2 and 9. In other words, the time series has no evidence of an underlying trend, and statistical techniques assuming stationarity should not be in error.

2.4.2 Trend Test

For a time series $x(i), i=1,2,3,\ldots,N$, each inequality that $x(i)>x(j)$ for $i<j$ is called a reverse arrangement. The symbol A is used to represent the total number of reverse arrangements in the series. The summation is performed with the following quantities:

$$h_{ij} = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{otherwise,} \end{cases} \tag{2.6}$$

$$A_i = \sum_{j=i+1}^{N} h_{ij}, \tag{2.7}$$

and

$$A = \sum_{i=1}^{N} A_i \tag{2.8}$$

Using the example time series of section 2.2, the number of reverse arrangements is as follows:

$A1=6$, $A2=2$, $A3=7$, $A4=3$, $A5=2$,

$A6=1$, $A7=0$, $A8=0$, $A9=0$.

The total number of reverse arrangements is A=21. A limited tabulation in Table 2.3 is used to test a single time series for stationarity by the trend test method. For any desired level of significance by comparing the observed value of A to the interval limits $A(N;1-\alpha/2)$ and $A(N;\alpha/2)$, one can check if the time series is stationary or not: $A(N;1-\alpha/2)<A<A(N;\alpha/2)$. The observation is stationary if the observed number of reverses falls inside the interval at the chosen level of significance; if A falls outside the interval, the series is not stationary.

For the example above, N=10, and from Table 2.3, for $\alpha=0.05$, $A(N;1-\alpha/2)=A(10;0.975)=11$, and $A(N;\alpha/2)=A(10;0.025)=33$. The hypothesis that the time series is stationary is accepted since A=21 falls within the range between 11 and 33. In other words the time series has no evidence of an underlying trend.

The trend test is basically similar to the run test. However, the trend test is more powerful in detecting monotonic trends in a time series, and weaker in detecting fluctuating trends, than the run test.

Turning to the full-scale results from the OKC site, alongwind windspeeds of 15 minutes duration at 3 levels of meteorological tower number 4 have been broken into 15

one-minute segments and analyzed for stationarity. The data set is broken into 15 segments since the data set has too many points for use of published limits as in Tables 2.2 and 2.3. The results of the run test and the trend test are listed on Table 2.4. The program STATCHEK given in Appendix A was used to obtain this table. All the results shown above fall within the required range. Thus the assumption of stationarity is good.

2.5 Lowpass Filter

For a single-degree-of-freedom system subjected to a forcing function x(t), the equation of motion is given by

$$\ddot{y} + 2\xi\omega_n^2\dot{y}(t) + \omega_n^2 y(t) = x(t) \tag{2.9}$$

This equation represents a continuous domain filter in the sense that the x(t) function can be regarded as the input to the filter, and the y(t) function can be regarded as the output. The equation expresses a bandpass filter centered at approximately, ω_n, the circular natural frequency of the filter. Assuming zero initial conditions, taking the Fourier transform of the above equation yields

$$-\omega^2 Y(f) + 2\xi\omega_n i\omega Y(f) + \omega_n^2 Y(f) = X(f) \tag{2.10}$$

where $\omega = 2\pi f$; and

H(f) is the transfer function;

$$\frac{Y(f)}{X(f)} = H(f) = \frac{1}{-\omega^2 + 2\xi\omega_n i\omega + \omega_n^2} \tag{2.11}$$

The quantity $|H(f)|$ is referred to interchangeably as gain, absolute value, or magnitude. A plot of $|H(f)|$ vs f is shown in Fig.2.3. From this figure, the transfer function or the frequency response function of this system is a bandpass filter which tends to pass information in a band centered at frequency f. That is, a single-degree-of-freedom mechanical system is a bandpass filter with a band centered nearly at the natural frequency.

For a digital data acquisition system, the output from the transducer first goes to an anti-aliasing filter. To prevent aliasing of higher-frequency information, the filter should eliminate everything above the Nyquist frequency, F, which is one half of the effective sampling rate, S. Thus the ideal anti-aliasing filter (shown in Fig.2.4) should have a transfer function of the form

$$H(f) = \begin{cases} 1 & -F<f<F \\ 0 & \text{otherwise} \end{cases} \qquad (2.12)$$

It is not possible to build a filter like this, however, since the edges or corners of the function must be rounded. A typical form for the lowpass filter employed for anti-aliasing is the Butterworth filter, whose absolute value squared is given by

$$|H(f)|^2 = \frac{1}{1+\left(\frac{2\pi f}{2\pi B}\right)^{2M}} \qquad (2.13)$$

in which B is the signal bandwidth, and M is decided from different precision requirements. Between 0<f<B, the absolute value squared tends to be flat until B is approached. For f>B, the absolute value rapidly becomes small with increasing f. The phase characteristic of a Butterworth filter is approximately linear across the pass band. This means that the phase corresponds to a simple delay. Thus the phase information is not changed very much by this filter.

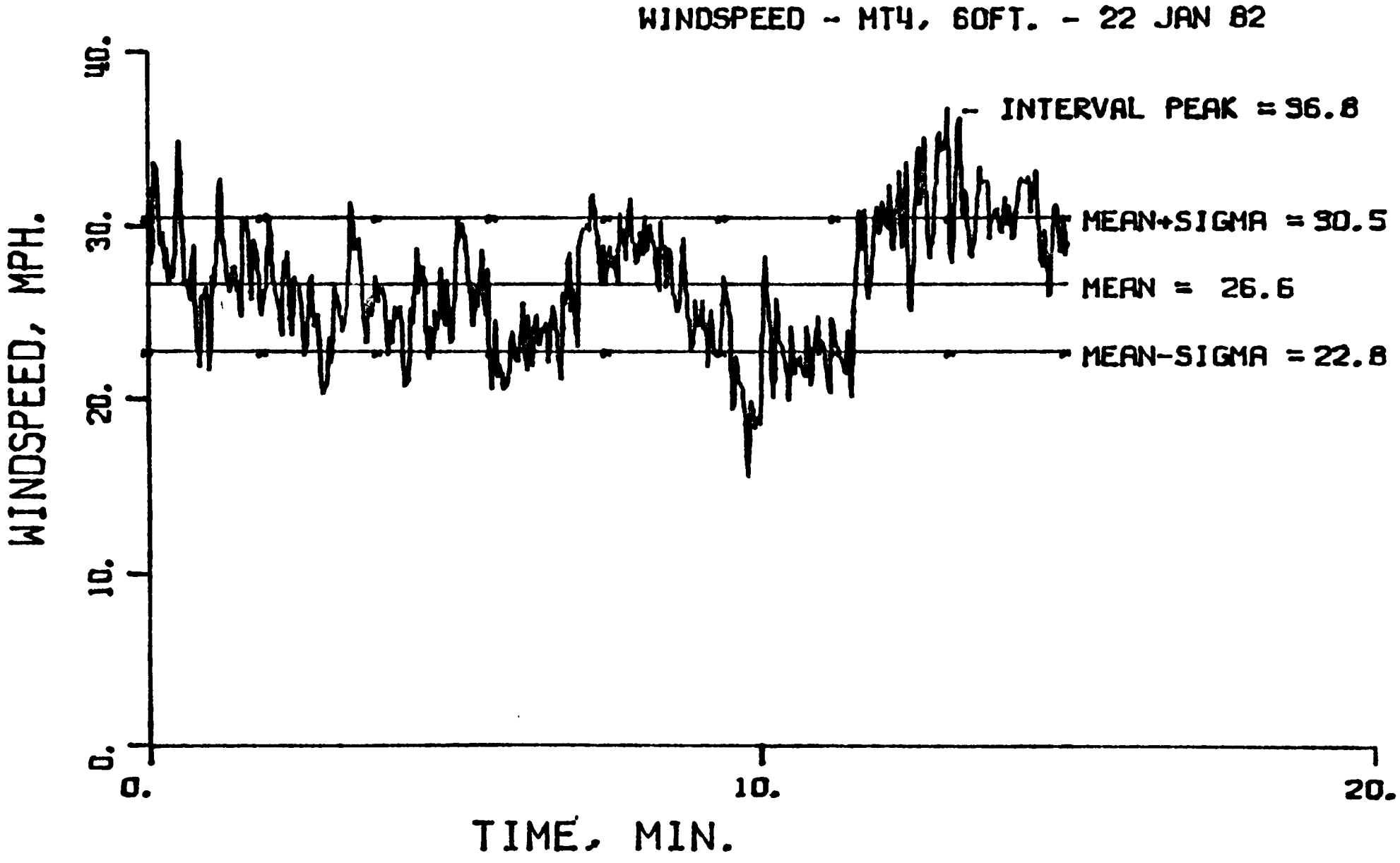


Figure 2.1 Time History Plot of Windspeed at 60 Foot Level of Meteorological Tower 4

Table 2.1 Statistics of the Data

	Mean	Standard Deviation
I. Windspeeds		
MT4, 30FT.	20.3	3.5
MT4, 60FT.	26.7	3.9
MT4, 120FT.	27.7	4.2
MT2, 60FT.	25.7	4.0
MT3, 30FT.	23.5	3.7
TT # 286	4.7	0.7
TT # 287	12.7	4.2
TT # 288	11.1	4.1
II. Directions		
MT4, 30FT.	97.2	8.3
MT4, 60FT.	113.8	6.6
MT4, 120FT.	118.9	6.5
MT2, 60FT.	116.6	6.5
MT3, 30FT.	115.0	6.4
TT # 286	98.9	13.8
TT # 287	120.6	9.5
TT # 288	111.8	7.9
III. Swing Angles		
NW I-STRING	-4.8	1.4
SE I-STRING	-5.7	1.6
IV. Loads		
NW I-STRING	-252.7	73.5
SE I-STRING	-246.0	66.1
V. Strains		
N LEG	-34.1	41.5
W LEG	-142.2	39.9
E LEG	68.6	36.0
S LEG	39.3	31.9

HISTOGRAM OF WINDSPEED AT MT4,60FT.

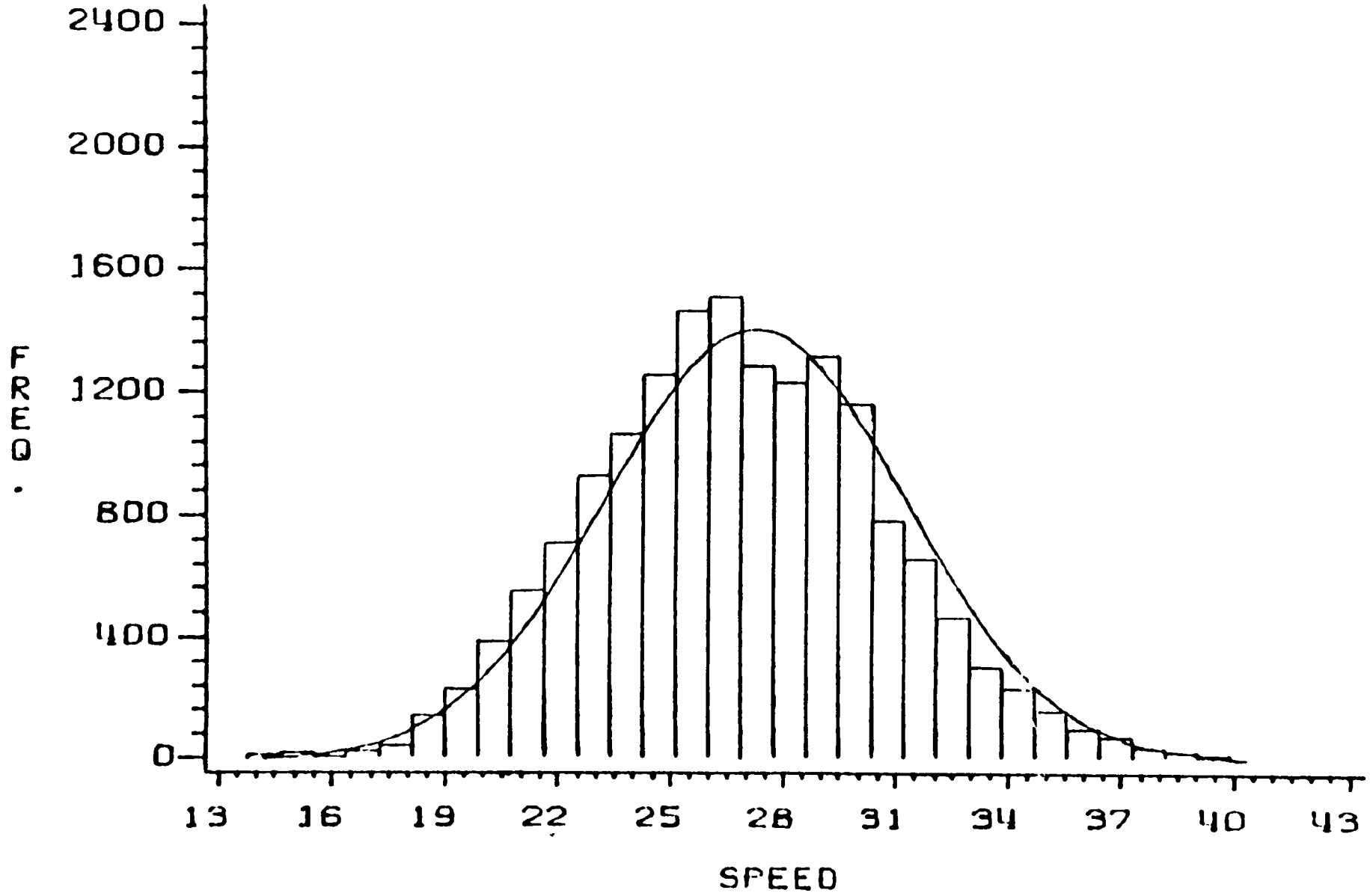


Figure 2.2 Histogram of Windspeed at 60 Foot Level of Meteorological Tower 4

Table 2.2 Percentage Points of Run Distribution

	α					
n=N/2	0.99	0.975	0.95	0.05	0.025	0.01
5	2	2	3	8	9	9
6	2	3	3	10	10	11
7	3	3	4	11	12	12
8	4	4	5	12	13	13
9	4	5	6	13	14	15
10	5	6	6	15	15	16
11	6	7	7	16	16	17
12	7	7	8	17	18	18
13	7	8	9	18	19	20
14	8	9	10	19	20	21
15	9	10	11	20	21	22
16	10	11	11	22	22	23
18	11	12	13	24	25	26
20	13	14	15	26	27	28
25	17	18	19	32	33	34
30	21	22	24	37	39	40
35	25	27	28	43	44	46
40	30	31	33	48	50	51
45	34	36	37	54	55	57
50	38	40	42	59	61	63
55	43	45	46	65	66	68
60	47	49	51	70	72	74
65	52	54	56	75	77	79
70	56	58	60	81	83	85
75	61	63	65	86	88	90
80	65	68	70	91	93	96
85	70	72	74	97	99	101
90	74	77	79	102	104	107
95	79	82	84	107	109	112
100	84	86	88	113	115	117

This table is taken from p.170, Ref.(2).

Table 2.3 Percentage Points of Reverse Distribution

	α					
N	0.99	0.975	0.95	0.05	0.025	0.01
10	9	11	13	31	33	35
12	16	18	21	44	47	49
14	24	27	30	60	63	66
16	34	38	41	78	81	85
18	45	50	54	98	102	107
20	59	64	69	120	125	130
30	152	162	171	263	272	282
40	290	305	319	460	474	489
50	473	495	514	710	729	751
60	702	731	756	1013	1038	1067
70	977	1014	1045	1369	1400	1437
80	1299	1344	1382	1777	1815	1860
90	1668	1721	1766	2238	2283	2336
100	2083	2145	2198	2751	2804	2866

This table is taken from p.171, Ref.(2).

Table 2.4 Stationarity Checks of Windspeeds of 15 Minutes Duration at 3 Levels of Meteorological Tower Number 4

Level (ft.)	Run Test (4<R<13)	Trend Test (32<A<72)
30	5	45
60	5	45
120	7	48

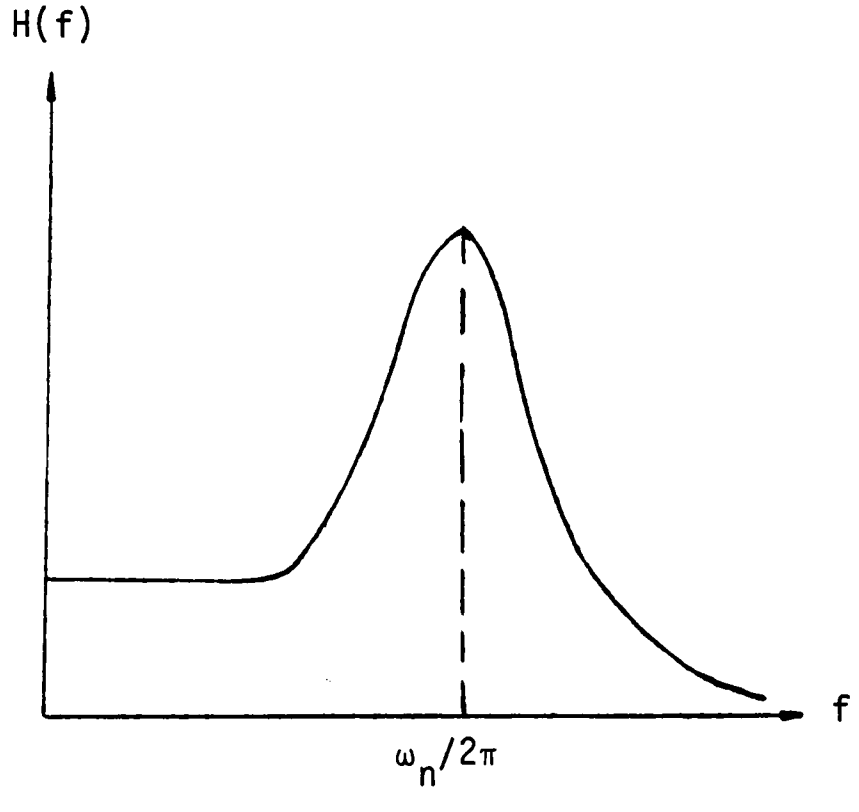


Figure 2.3 Frequency Response Function

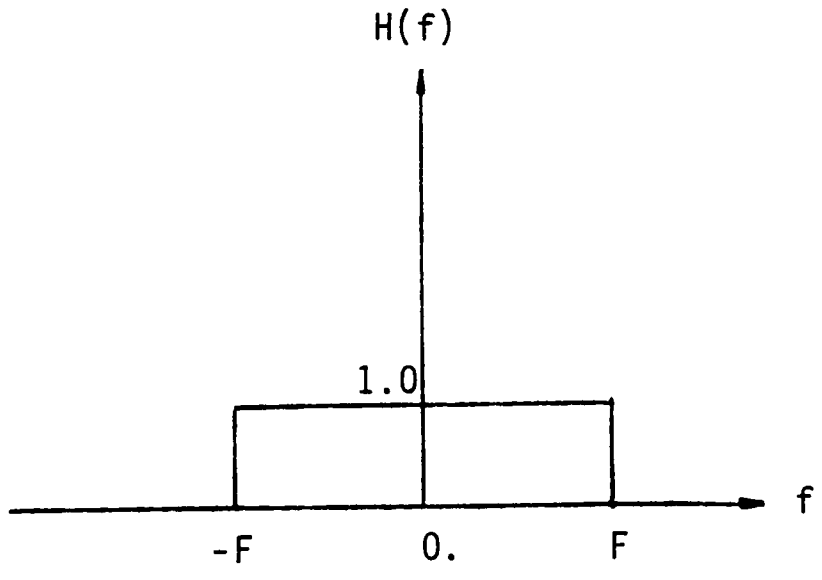


Figure 2.4 Ideal Anti-aliasing Filter

CHAPTER III

ANALYSIS OF WIND DATA

The three main topics discussed in this chapter are the mean wind profile, the turbulence intensity and the wind spectrum. The mean wind profile is important in wind engineering since it establishes the variation of the mean windspeed with height above the ground. This variation depends upon the resistance of the ground surface and its protrusions to the wind flow, a resistance that produces what is known as the atmospheric boundary layer. The surface resistance is described by a so-called "roughness" of the terrain, one of several key parameters used to characterize any terrain.

The turbulence intensity is the ratio of the root mean square windspeed variation to the mean alongwind speed at a particular point in space. It thus is a measure of the relative amplitude of the fluctuations compared to the mean or constant component. A more complete representation of these fluctuating components is the wind spectrum, which gives the distribution of the variance in the windspeed over the frequency domain. This spectrum is very useful in

determining the response that a structure will have when subjected to the wind, since a structure will be more sensitive to excitations in particular frequency ranges near its natural frequencies of vibration.

In the discussion of each wind property, results are presented for data from the Oklahoma City (OKC) site. The methods of determining these results, whether by computer programs or by hand calculation, are given in detail in order to illustrate the procedures necessary to utilize real wind data.

A fairly extensive discussion is given to the theory related to spectral density since this is the most obscure and confusing area for most engineers. It is important that the wind engineer have a grasp of both the underlying theory and the computational details, since small differences in computation can produce important differences in the results.

3.1 Mean Velocity Profiles

Wind velocity profiles are usually expressed by the mean values of, or the static components of, wind velocities. In large-scale storms, it may be assumed that within an area of uniform roughness over a sufficiently large fetch a region exists over which the flow is horizontally homogeneous.

Then there is a boundary layer as shown in Fig.3.1 in which the wind speed can be expressed by the logarithmic law or the power law. The height of the boundary is denoted by z_g and the windspeed at this height is the gradient windspeed, Ug.

3.1.1 The Logarithmic Law

If it is further postulated that a gradual change occurs from conditions near the ground to conditions in the outer part of the boundary layer and that the surface shear must depend upon the flow velocity at some small distance from the ground, the roughness of the terrain and the density of the air, then the logarithmic law for strong wind may be written as(20)

$$U(z) = \frac{1}{k} u_* \ln\frac{z}{z_0} \qquad (3.1)$$

where U(z) is the mean windspeed at height z;

k ≃ 0.4, is the von Karman constant;

u is the shear velocity of the flow;

z is the height above ground; and

z_0 is the surface roughness length.

To obtain the parameters u_* and z_0 in the logarithmic law, Eq.3.1 is first changed to the form

$$U = \frac{u_*}{k} (\ln z - \ln z_0) \qquad (3.2)$$

or

$$\ln z = \ln z_o + \left(\frac{k}{u_*}\right) U \tag{3.3}$$

This represents a straight line relationship between the natural logarithm of the height, z, and the mean windspeed, U. Windspeed measurements at least at two heights are required to define this line. If measurements are available at more than two heights, then a least squares method may be used to fit a straight line of this form to the data.

For adaptaticn of the general least squares method to Eq.3.3, it may be written in the form

$$y = a + bx \tag{3.4}$$

where y is lnz, a is a constant equal to $\ln z_o$, b is a constant equal to k/u*, and x is the measured mean windspeed, U. Then with n measured values of z and U, the coefficients a and b are determined as(5)

$$b = \frac{n\Sigma xy - (\Sigma x)(\Sigma y)}{n\,\Sigma x^2 - (\Sigma x)^2} \tag{3.5}$$

$$a = \frac{\Sigma y - b\Sigma x}{n} \tag{3.6}$$

Figure 3.2 illustrates the application of this method to the 15-minute mean windspeeds measured on meteorological tower number 4 at the OKC site. The three measured values, taken from Table 2.1, are shown in the inset table of the figure. The points plotted, when use is made of the least squares method, give the following values of the equation coefficients:

$$a = -0.217, \qquad b = 0.172$$

Thus Eq.3.3 takes the form

$$\ln z = -0.217 + (0.172)U$$

from which the following values of z_0 and u_* may be calculated

$$a = \ln z_0 = -0.217; \quad z_0 = e^{-0.217} = 0.80 \text{ ft.}$$

$$b = k/u_* = 0.172; \quad u_* = 0.4/0.172 = 2.33 \text{ mph.}$$

The parameters z_0 and u_* are often given in SI units, which come out for the data considered as

$$z_0 = 0.80 \text{ ft.} = 244 \text{ mm}$$

$$u_* = 2.33 \text{ mph} = 1.04 \text{ m/s}$$

3.1.2 The Power Law

In horizontally homogenous terrain, it may be assumed that the power law holds with a constant exponent α up to the gradient height, z_g, which defines the thickness of the boundary layer (see Fig.3.1). Both the gradient height and

the exponent α are functions of the roughness of the terrain. The power law for a strong wind can be expressed as (16)

$$\frac{U(z)}{U_g} = \left(\frac{z}{z_g}\right)^{\alpha} \tag{3.7}$$

where Ug is the windspeed at the gradient height, or the gradient windspeed.

In working with measured windspeeds, it is impossible to determine all three of the parameters α, Ug and z_g in Eq.3.7. However, the important parameter in terms of the variation of windspeed with height is the exponent α. It allows the comparison of winds at different heights in the form

$$\frac{U(z)}{U_1} = \left(\frac{z}{z_1}\right)^{\alpha} \tag{3.8}$$

where U_1 is the windspeed at height z_1, which will be taken as 30 feet in this section.

To obtain the exponent α from experimental data, the natural logarithm of each side of Eq.3.8 may be taken to give

$$\ln\left(\frac{U}{U_1}\right) = \ln\left(\frac{z}{z_1}\right) \tag{3.9}$$

Values of $\ln(z/z_1)$ and $\ln(U/U_1)$ are plotted in Fig.3.3, and a line has been fitted by least squares as in the case of the logarithmic law. The resulting value of α is

$$\alpha = 0.21$$

This value corresponds to a terrain roughness between ANSI categories B (suburban) and C (open), but is closer to category B.

3.1.3 Comparison Of Profiles

Figure 3.4 shows mean velocity profile plots as determined by the power law and by the logarithmic law. The two curves show that there is little difference between the two profiles, especially above the 30 foot level. Below 30 feet, the logarithmic law gives somewhat lower windspeeds. Currently, the logarithmic law is regarded by meteorologists as a superior representation of strong wind profiles in the lower atmosphere(20).

The plot in Fig.3.4 also shows, as have Figures 3.2 and 3.3, that the data considered did not conform well to the expected profile shape, in that the windspeeds at the three levels are off the curve. However, the difference in windspeed between the measured values and the curve is only about ten percent. Such a difference could be due to calibration or other problems in the experimental setup, but

field test facilities can always be expected to have some degree of experimental error.

3.2 Turbulence Intensity

In wind engineering there are two statistical schemes most commonly used to describe the turbulence characteristics of the wind: turbulence intensity and windspeed power spectrum. The windspeed power spectrum is discussed in section 3.4. The turbulence intensity, I_u , is defined as

$$I_u = \frac{\sigma_u}{\overline{U}} \tag{3.10}$$

where σ_u is the root mean square windspeed, and

$\overline{U}$ is the mean windspeed.

In statistics terminology this number is often called the coefficient of variation.

Values of turbulence intensity for the sample data from the OKC site are shown in Fig.3.5. The values range between 0.147 and 0.168, with slightly lower magnitudes at the higher elevations. These results were obtained using an averaging time cf 15 minutes.

The turbulence intensity is strongly related to the terrain roughness: a greater turbulence is caused by a

rougher terrain. The decrease in turbulence intensity with height is also expected-- at greater heights the RMS windspeed and the mean windspeed both increase but the RMS value increases less because the shearing action of the ground surface is less.

3.3 Power Spectral Density Function

A power spectral density function (PSD) is the distribution of variance, or the mean square value per cycle, of a time history function over frequency. The name "power spectrum" originated in the field of electrical engineering, where the average power dissipated in a circuit is the same as the mean square value of the current(18). A cross spectral density function (CSD) is defined between a pair of time histories. One may be the input to a system and the other the output.

A stationary time series having a zero mean value can be separated into frequency components using a standard Fourier analysis. The frequency decompositions of time histories are very important in time series analysis. In the dynamics of structures this information is crucial in estimating such important parameters as resonant frequencies and damping ratios. Thecretically, statistical characteristics are determined from ensemble averages at every instant of time. Because of costs, convenience and other reasons, however, in

most cases only a single time history is recorded. This record cannot represent an ensemble of time histories constituting the random process. Thus true ensemble averages can not be found. Ergodicity, which means time averages equal to ensemble averages, has to be assumed to carry out the statistical analysis. For most ergodic processes encountered in engineering, the power spectral density function approaches its limit rapidly with increasing duration of measurement(8), so that sufficient accuracy can usually be obtained with a relatively short sample of the time series.

The power spectrum plays a very important roll in a probabilistic analysis. It is used to understand the distribution of energy in the frequency domain and to analyze the dynamic behavior between the randomly varying input and output. The following procedures introduced in this section are used to build up the power spectral density function. The Fourier transform transfers a time domain function into a frequency domain function. The concept of the mean square value of a time function in terms of its component frequencies is used to set up the idea of a power spectral density function, which can be calculated by an autocorrelation function, by a discrete Fourier transform or by a fast Fourier transform. The aliasing in a discrete time series can be eliminated by a low-pass filter.

3.3.1 Fourier Transform

A fourier transform is often used in time series data analysis because of its efficient computation. It is an intermediate step in determining power spectral density functions, cross spectral density functions, filter functions, correlations and frequency response functions. Any periodic function x(t) can be expressed by a Fourier series, which is composed of sine and cosine functions(12).

$$x(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n \cos(n\omega t) + \sum_{n=1}^{\infty} B_n \sin(n\omega t) \qquad (3.11)$$

in which $\omega = 2\pi/T$ is the circular frequency of x(t);

T is the period of x(t);

$$A_n = \frac{2}{T} \int_{-T/2}^{T/2} x(t)\cos(n\omega t)dt; \quad n=0,1,2,3,\ldots,\infty; \qquad (3.12)$$

and

$$B_n = \frac{2}{T} \int_{-T/2}^{T/2} x(t)\sin(n\omega t)dt; \quad n=1,2,3,\ldots,\infty. \qquad (3.13)$$

$A_0/2$ is a static or time invariant component, which is equal to the mean value. Each sine and cosine term represents a dynamic or fluctuating component which may be described by a variance that is simply the mean square value about the mean.

The Fourier series equation can be written in exponential form by replacing the trigonometric functions with corresponding exponential terms, as given by the Euler equations. With this modification

$$x(t) = \sum_{-\infty}^{\infty} F(n\omega)e^{in\omega t} \tag{3.14}$$

where

$$F(n\omega) = \frac{1}{T}\int_{-T/2}^{T/2} x(t)e^{(-in\omega t)}dt \tag{3.15}$$

is the Fourier transform of $x(t)$. Letting $\Delta\omega = 2\pi/T$, the above equations can be written as

$$x(t) = \frac{1}{2\pi}\sum_{n=-\infty}^{\infty} F(n\omega)e^{(in\omega t)}\Delta\omega \tag{3.16}$$

and

$$F(n\omega) = \int_{-T/2}^{T/2} x(t)e^{(-in\omega t)}dt \tag{3.17}$$

Now consider a random function as a periodic function with its period, T, tending to infinity. When the period tends to infinity, the angular frequency increment $\Delta\omega$ tends to zero; hence the frequency n becomes a continuous variable, and the summation approaches an integral. In this case the nonperiodic function can be written as the exponential Fourier integral.

$$x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}d\omega \tag{3.18}$$

$$F(\omega) = \int_{-\infty}^{\infty} x(t)e^{(-i\omega t)}dt \tag{3.19}$$

$F(\omega)$ is the Fourier transform of $x(t)$. $F(\omega)$ and $x(t)$ constitute what is known as a Fourier transform pair.

3.3.2 Mean Square Value Of A Time Function

Using equations (3.18) and (3.19) for two time series $x_1(t)$ and $x_2(t)$, the following Parseval's formula for integrals can be found.

$$\int_{-\infty}^{\infty} x_1(t)x_2(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} F_2(\omega)\overline{F}_1(\omega)d\omega \tag{3.20}$$

in which

$$\overline{F}_1(\omega) = F_1(-\omega) \tag{3.21}$$

When $x_1(t) = x_2(t) = x(t)$, Eq.3.20 reduces to

$$\int_{-\infty}^{\infty} x^2(t)dt = \frac{1}{\pi}\int_{0}^{\infty} |F(\omega)|^2 d\omega \tag{3.22}$$

Using these equations, the mean square value of the function $x(t)$ may be expressed as

$$\overline{x}^2(t) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} x^2(t)dt \tag{3.23}$$

to relate it to the time domain, and as

$$\overline{x}^2(t) = \lim_{T\to\infty} \frac{1}{\pi} \int_0^{T/2} \frac{|F(\omega)|^2}{T} d\omega$$

$$= \lim_{T\to\infty} \frac{1}{2\pi} \int_0^{T} \frac{|F(\omega)|^2}{T} d\omega \qquad (3.24)$$

to relate it to the frequency domain. Then using Eq.3.22, the transformation between the time and frequency domains is obtained:

$$\lim_{T\to\infty} = \frac{1}{T} \int_{-T/2}^{T/2} x^2(t)dt = \lim_{T\to\infty} \frac{1}{2\pi} \int_0^{T} \frac{|F(\omega)|^2}{T} d\omega \qquad (3.25)$$

3.3.3 Power Spectral Density Function

If the integrand on the right side of equation(3.25) is defined as a new function, the power spectral density function,

$$S(\omega) = \frac{|F(\omega)|^2}{T} \qquad (3.26)$$

then the time history x(t) can be written as

$$\overline{x}^2(t) = \frac{1}{2\pi} \int_0^{\infty} S(\omega)d\omega \qquad (3.27)$$

In general, x(t) has frequency components which vary between 0 and infinity. Equation (3.27) indicates that $S(\omega)$ is the contribution to the mean square value (or total power) by the component of x(t) having a frequcncy ω. A plot of $S(\omega)$ vs ω is the power spectrum of x(t).

3.3.3.1 Autocorrelation Function

An autocorrelation function is used to describe the association or mutual dependence between values of the same time series at different times separated by the time interval τ. It is defined as

$$R_{xx}(\tau) = \lim_{T\to\infty} \int_{-T/2}^{T/2} x(t)x(t+\tau)dt \qquad (3.28)$$

Taking the Fourier transform of each side of Eq.3.28 and multiplying the right hand side by $e^{-i\omega t}e^{i\omega t}$, which is equal to 1,

$$\int_{-\infty}^{\infty} R_{xx}(\tau)e^{-i\omega\tau}d\tau = \frac{1}{T}\int_{-\infty}^{\infty} x(t)e^{i\omega t}dt \int_{-\infty}^{\infty} x(t+\tau)e^{-i\omega(t+\tau)}d\tau \qquad (3.29)$$

The first integral on the right-hand side is

$$\int_{-\infty}^{\infty} x(t)e^{i\omega t}dt = \overline{F}(\omega) \qquad (3.30)$$

and the second integral $\int_{-\infty}^{\infty} x(t+\tau)e^{i\omega(t+\tau)}d\tau$ is the Fourier transform of $x(t+\tau)$. Since $x(t+\tau)$ is only x(t) with a

time shift τ in the time origin, and for an infinite time period this difference vanishes, the Fourier transform of $x(t+\tau)$ is equal to the Fourier transform of $x(t)$, or $F(\omega)$. Thus the Fourier transform of the autocorrelation function is

$$\text{Fourier transform of } R_{XX}(\tau) = \frac{1}{T}\overline{F}(\omega)\,F(\omega) = \frac{|F(\omega)|^2}{T} \tag{3.31}$$

and, using Eq. 3.26,

$$S(\omega) = \frac{|F(\omega)|^2}{T} = \int_{-\infty}^{\infty} R_{XX}(\tau)e^{-i\omega\tau}d\tau \tag{3.32}$$

This means that the PSD is equal to, or can be calculated from, the Fourier transform of the autocorrelation function. Autocorrelation functions are symmetric about $\tau=0$; thus Eq. 3.32 can be written as

$$S(\omega) = 2\int_{0}^{\infty} R_{XX}(\tau)\,e^{-i\omega\tau}d\tau \tag{3.33}$$

For a real valued random process, the PSD is real. After imaginary parts are neglected,

$$S(\omega) = 2\int_{0}^{\infty} R_{XX}(\tau)\cos\omega\tau d\tau \tag{3.34}$$

3.3.3.2 Discrete Fourier Transform

The time history plot in Fig. 3.6 shows a continuous time

function x(t) sampled at N regular intervals of time Δt, to produce a discrete time series x(r), r=0,1,2,3,...,(N-1). A finite range Fourier transform X(n) may be defined for the continuous time function x(t) as

$$X(n) = \int_0^T x(t)e^{-i2\pi nt}dt \tag{3.35}$$

where the cyclic frequency $n= \omega/2^{\pi}$ has been used to replace the circular frequency ω. The integral on the right-hand side can be approximated for the discrete time series x(r) by a summation. Since the rth discrete value of time is $t=r(\Delta t)$, the total time is $T=N(\Delta t)$, and the cyclic frequency n can be represented by a discrete nondimensional frequency, k=nT, this summation becomes

$$X(n) = \sum_{r=0}^{N-1} x(r)\, e^{-i2\pi nt}\Delta t$$

$$= \frac{T}{N} \sum_{r=0}^{N-1} x(r)\, e^{-i2\pi rk/N} \tag{3.36}$$

This equation may also be written as

$$X(n) = \frac{T}{N} X(k) \qquad k=0,1,2,\ldots,N-1 \tag{3.37}$$

where

$$X(k) = \sum_{r=0}^{N-1} x(r)\, e^{-i(2\pi rk/N)} \tag{3.38}$$

is known as the Discrete Fourier Transform (DFT) of the time series x(r). The original series x(r) can be recovered by means of a discrete inverse Fourier transform:

$$x(r) = \frac{1}{N} \sum_{k=0}^{N-1} X(k)\, e^{i(2\pi kr/N)} \qquad (3.39)$$

Equations (3.38) and (3.39) have no concern with time. They just represent operations on sets of numbers. The X(k) values are complex numbers, but the x(r) values are real.

The frequency of each interval is calculated as $n=k/T=k/(N\,\Delta t)$. The lowest frequency is $n=1/(N\,\Delta t)$, when $k=1$. Thus the lowest frequency for which a Fourier Transform value can be obtained is dependent on the number of points in the time series.

3.3.3.3 Fast Fourier Transform Concept

In a three dimensional coordinate transformation, such as shown in Fig. 3.7, any general rotation can be written in terms of three two-dimensional components, roll, pitch and yaw. The total rotation is the product of three two-dimensional matrices:

$$T(\theta_1,\theta_2,\theta_3) = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 \\ \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 \\ 0 & 1 & 0 \\ \sin\theta_2 & 0 & \cos\theta_2 \end{bmatrix}$$

Yaw Pitch

$$\times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 \\ 0 & \sin\theta_1 & \cos\theta_1 \end{bmatrix} \qquad (3.40)$$

Roll

The actual computations necessary for performing a transformation of coordinates can thus be broken down into three two-dimensional matrix multiplications, rather than one three-dimensional matrix multiplication.

For the 3-dimensional case, the number of operations in one 3-dimensional transformation is equal to $3^2 = 9$, whereas the number of operations in the three 2-dimensional transformations is $3 \times 2^2 = 12$. Thus the latter approach is less efficient. However, for higher-dimensional cases the comparison shifts. In the 5-dimensional case, for example, the number of operations in one 5-dimensional transformation is $5^2 = 25$, whereas the number of operations in 5 2-dimensional transformations is $5 \times 2^2 = 20$. When the order is greater than 4, the above method of decomposing the transformation is better than one normal transformation.

A discrete, finite Fourier transform of N data points, as given by Eq. 3.38, may be viewed as a rotation in N-dimensional space (18). In mathematical terms, it is an orthogonal linear transform. The exponential term is a

transformation function which transforms the time series x(r) into X(k). If the number of points, N, equals some even power of 2, say $N=2^p$, then the transformation in Eq.3.38 needs only $N\log_2 N=Np$ operations. This is the concept of the Cooley-Tukey version of a Fast Fourier Transform (FFT). In comparison, a normal DFT needs N^2 operations, and the saving in computer time for long records is enormous. For example, for $N=2^{15}$, the computer time of a DFT is about 2000 times that of a FFT.

3.3.3.4 Power Spectral Density Estimates

The power spectral density estimates for a discrete random process are defined as

$$S(n) = \lim_{T\to\infty} \frac{2|X(n)|^2}{T} \simeq \left|\frac{T}{N} X(k)\right|^2 \frac{2}{T}$$

$$\simeq \frac{2T}{N^2}|X(k)|^2 \qquad (3.41)$$

Where $n=k/T$ is a frequency parameter and X(k) can be calculated with an FFT procedure.

The standard error of the unsmoothed spectral estimates is 100% (18). Thus the raw PSD estimates need to be smoothed or averaged somehow to produce more reliable estimates at each frequency. The smoothing of spectral functions of random time series data is usually accomplished in one of

these ways: frequency averaging, ensemble averaging, or a combination of the two.

The averaging together of neighboring raw spectral estimates in a single computed spectrum is called frequency averaging. Ensemble averaging is the averaging together of complete power spectral density functions at each frequency which are computed from different time segments of the same time history record.

3.3.3.5 Periodicity

If discrete frequency values, k, greater than N-1 are tried in the DFT of the time series, Eq. 3.38, a phenomenon called periodicity occurs. For example, letting k=N+m, then

$$X(N+m) = \sum_{r=0}^{N-1} x(r)\, e^{-i(2\pi rm/N)}\, e^{-i2\pi r} \qquad (3.42)$$

Now, since $e^{-i2\pi r} = 1$,

$$X(N+m) = \sum_{r=0}^{N-1} x(r)\, e^{-i(2\pi rm/N)}$$

$$= X(m) \qquad (3.43)$$

Thus the coefficients X(k) repeat themselves for k>(N-1).

Also it can be proved that in the frequency range $0<k/T<N/T$ the PSD is symmetric at the center of the range, $N/2T$, as shown in Fig.3.8. Thus only unique spectral estimates in the frequency range for n between 0 and $N/2T$ can be obtained. Estimates at higher frequencies are just repetitions of those in this range. The quantity $N/2T=1/(2\Delta t)$ is called, variously, the Nyquist, Shonnon or folding frequency, and it is one half the sampling frequency, $1/(\Delta t)$. This means only frequencies smaller than $1/(2\Delta t)$ can be determined for a time series with a sampling interval Δt.

3.3.3.6 Aliasing

Aliasing occurs when a sinusoid whose frequency is greater than one half the sampling rate appears as a lower frequency. That is, rather than appearing at its true frequency, the sinusoid appears at its aliased (lower) frequency. If this occurs at many frequencies it can distort the true spectrum as shown in Fig.3.9. A low-pass filter is necessary to remove the unwanted higher frequencies so that there are no contributions at frequencies above the Nyquist frequency.

3.4 Wind Spectrum

Wind can be decomposed into mean (constant) and fluctuating (gust) components. The most complete way to

describe the characteristics of the fluctuating wind components is in terms of the power spectrum of the wind. The power spectrum for wind analysis is a plot of the energy, or variance, in the wind fluctuations at each frequency versus the frequency. It represents a distribution of the energy of the wind fluctuations over the frequency domain. The PSD at any particular frequency, n, may be considered as the average fluctuating wind power passing a fixed point when the wind as a random process is filtered by a narrow band pass filter centered at n.

Many analytical functions have been suggested to represent power spectra of wind turbulence in the alongwind, crosswind and vertical directions. Wind turbulence is generated by the surface shear stress for neutral atmospheric conditions. It follows that the magnitude of the PSD should be proportional to the square of the friction velocity. Davenport(20) suggested an empirical spectrum to represent alongwind fluctuations for strong winds at heights somewhat greater than 10 meters. This spectrum is in reasonable agreement with measured data and has been shown to be valid over the frequencies of importance in structural engineering applications. It is written as

$$\frac{f\,Su(f)}{u_*^2} = 4.0\,\frac{x^2}{(1+x^2)^{4/3}} \qquad (3.44)$$

where f is the frequency, in cycles per second (Hz);

$S_u(f)$ is the alongwind gust PSD at frequency f, in $(m/sec)^2$;

$x = 1200f/V_{10}$ is an inverse measure of wavelength, in m^{-1};

V_{10} is the mean wind speed at 10 m, in m/sec.; and

u_* is the friction velocity, in m/sec.

The variance of the turbulence can be calculated from the area under the wind spectrum.

Since the natural frequencies of most structural systems are within the micrometeorological range which represent the gust fluctuations of the wind, the wind spectrum is plotted in this range. One needs to understand the winds which have frequencies near the natural frequencies, and may produce large amplifications due to dynamic effects.

Figure 3.1C shows a power spectrum of horizontal alongwind windspeed at the 60 foot level of meteorological tower number 4. This spectrum utilizes the International Mathematics and Statistical Libraries (IMSL) program FTFPS which uses a Fast Fourier Transform to calculate the spectral density estimates. Before calling FTFPS, the mean of a time series is calculated and removed. A zero mean time series is thus obtained. This routine estimates the

spectral values by the ensemble averaging method. If the time series is divided into more than 15 segments, which is one of the required parameters of the routine, the resulting estimates will be more accurate, but more lower frequencies will be lost. The number of time segments used in this spectrum is 16; thus the total set of 16384 data points is divided into 16 segments of 1024 points each. The highest frequency obtained is the Nyquist frequency, 8 Hz, which is one half of the sampling rate, 16 Hz. The lowest frequency is 0.015625 Hz which is restricted by the length of the segment. This routine applies a symmetric data window which is approximately the Parzen spectral window to each segment. This plot uses fS(f)/sigsq on the ordinate to give a normalized scale, and frequency in Hertz on the abscissa in a log scale. The sigsq on the ordinate is the variance of the time series. The spikes at frequencies higher than 0.5 Hertz indicate a significant level of random noise in these data. These spikes are also seen on power spectra shown in Chapter 4. The noise can be filtered by a 2-second moving average procedure(10).

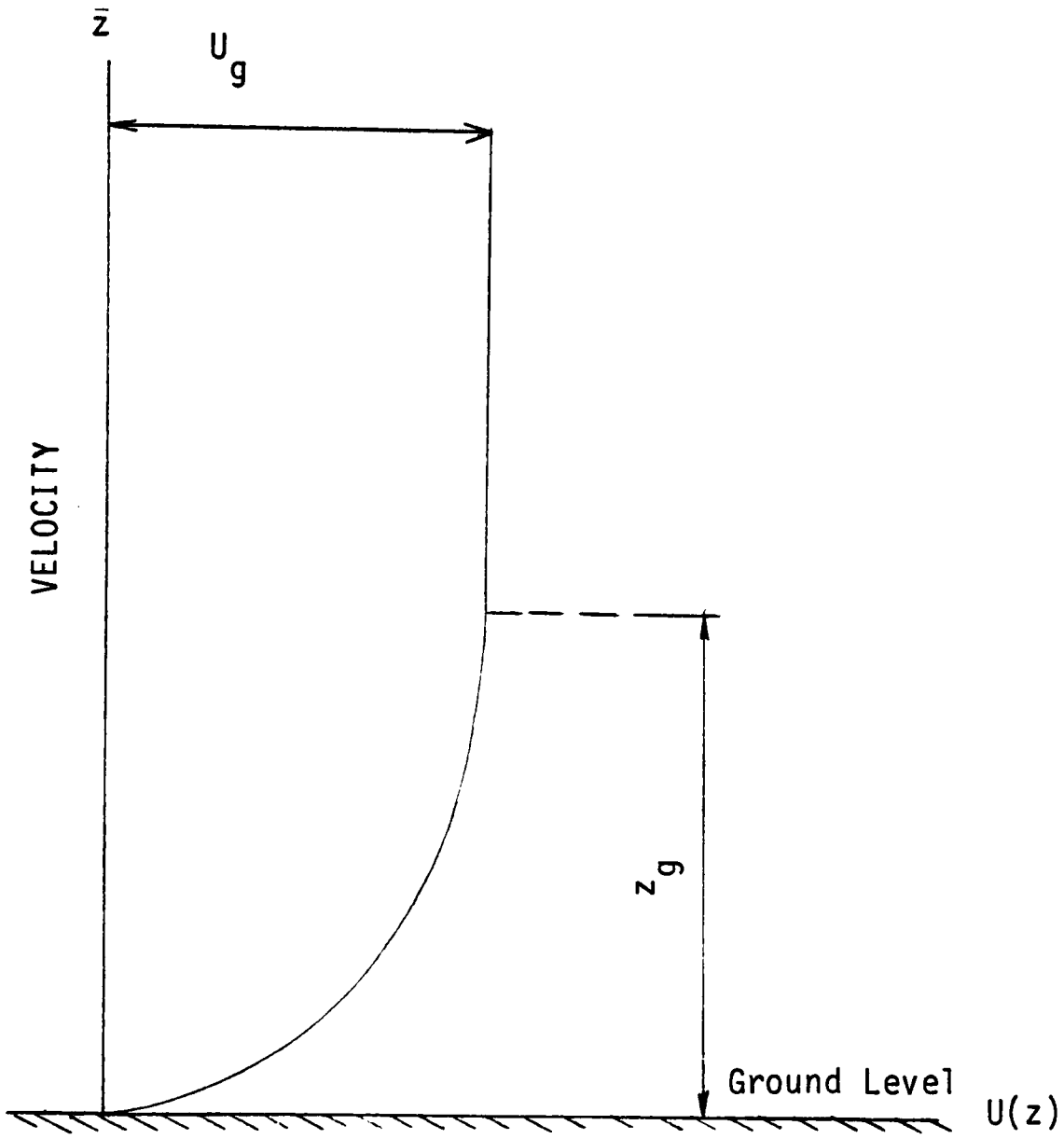


Figure 3.1 Wind Velocity Profile

Height, z (ft.)	lnz	Measured Mean Windspeed, U (mph)
30	3.40	20.8
60	4.09	26.7
120	4.79	27.7

Logarithmic Law:

$$U(z) = \frac{1}{k} u_* \ln \frac{z}{z_0}$$

where $k=0.4$

$u_*=2.33$ mph

$z_0=0.80$ ft.

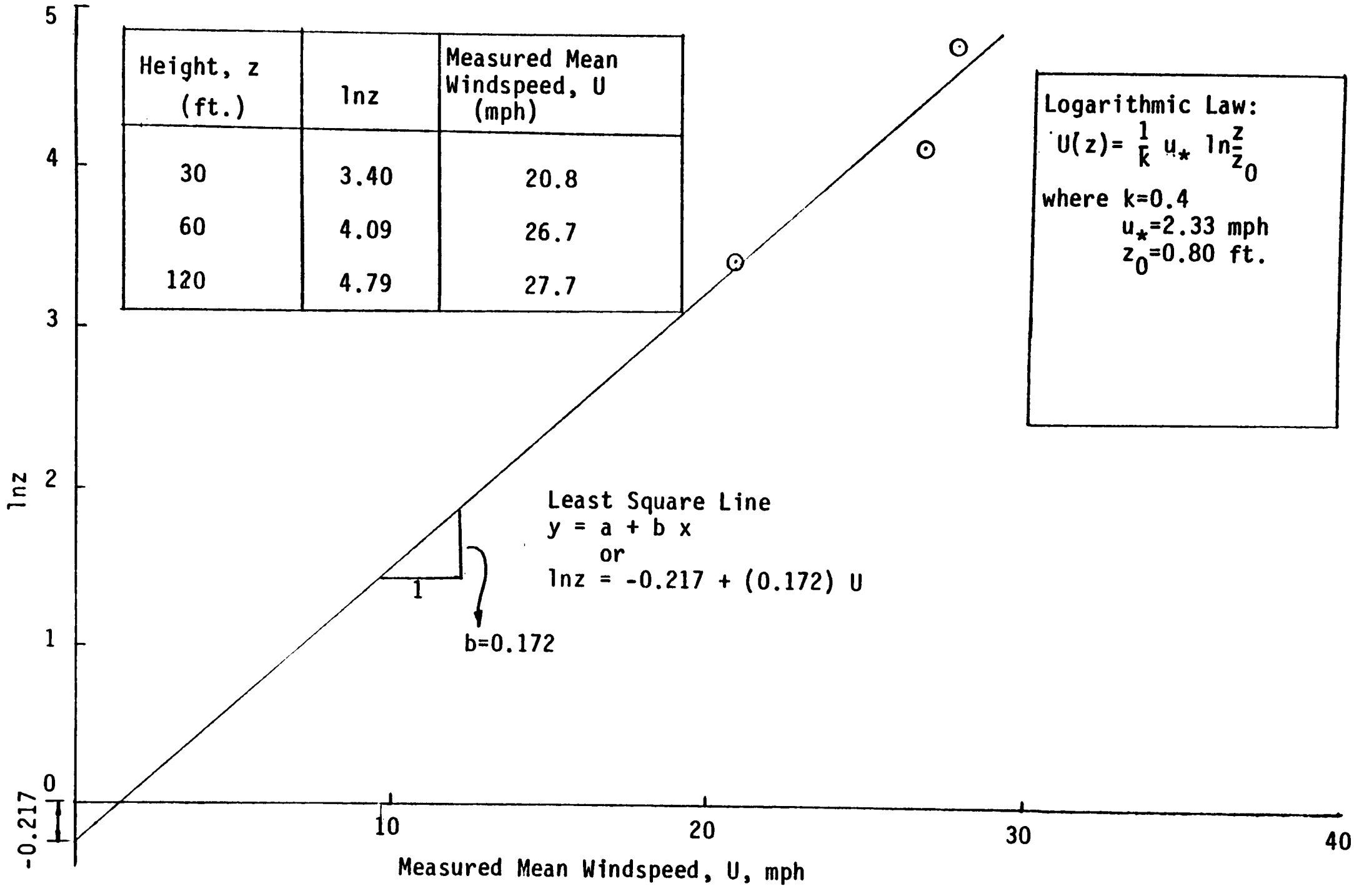


Figure 3.2 Determination of Mean Windspeed Profile by the Logarithmic Law for Meteorological Tower 4 at the OKC Site

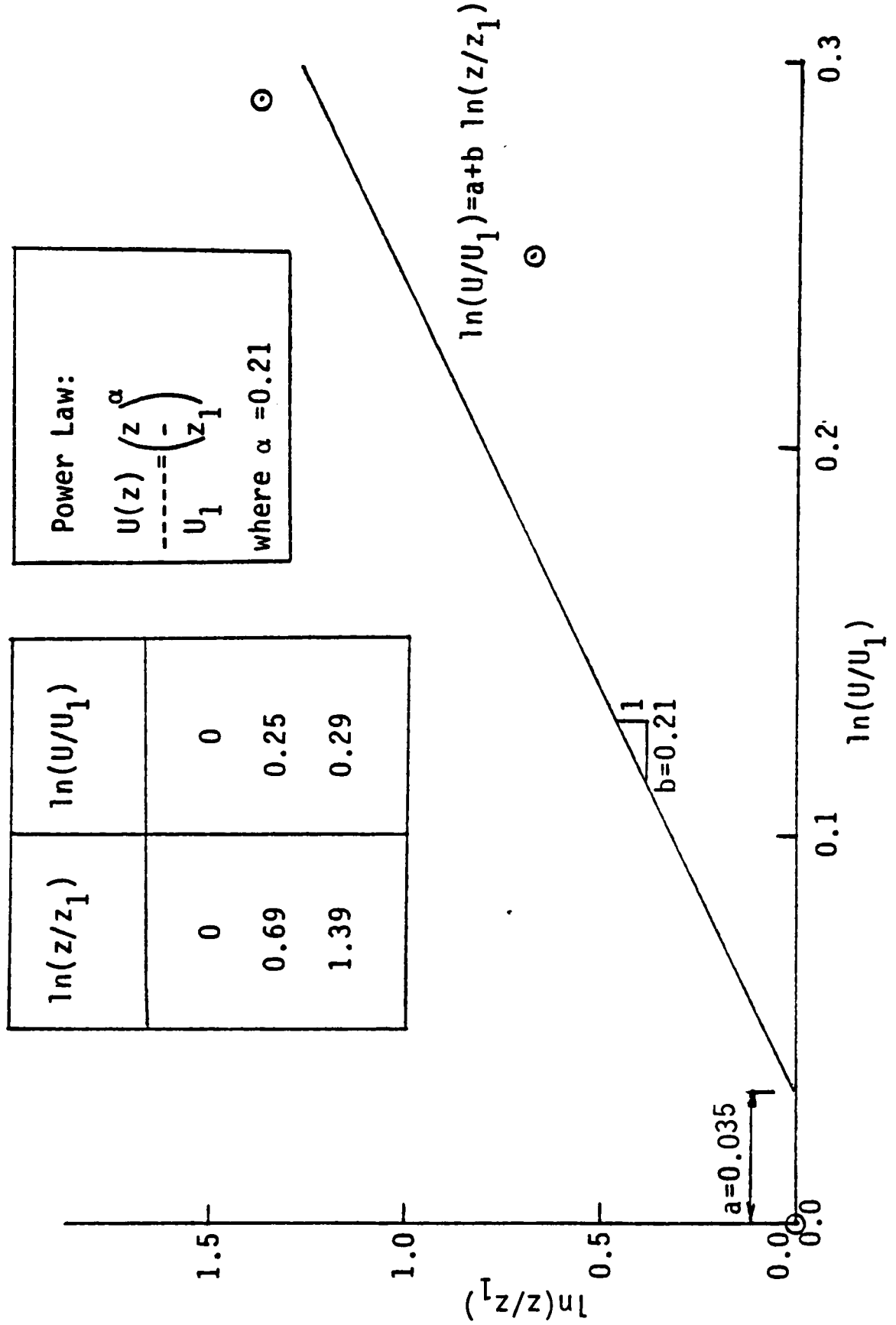


Figure 3.3 Determination of Mean Windspeed Profile by the Power Law

MEAN VELOCITY PROFILE

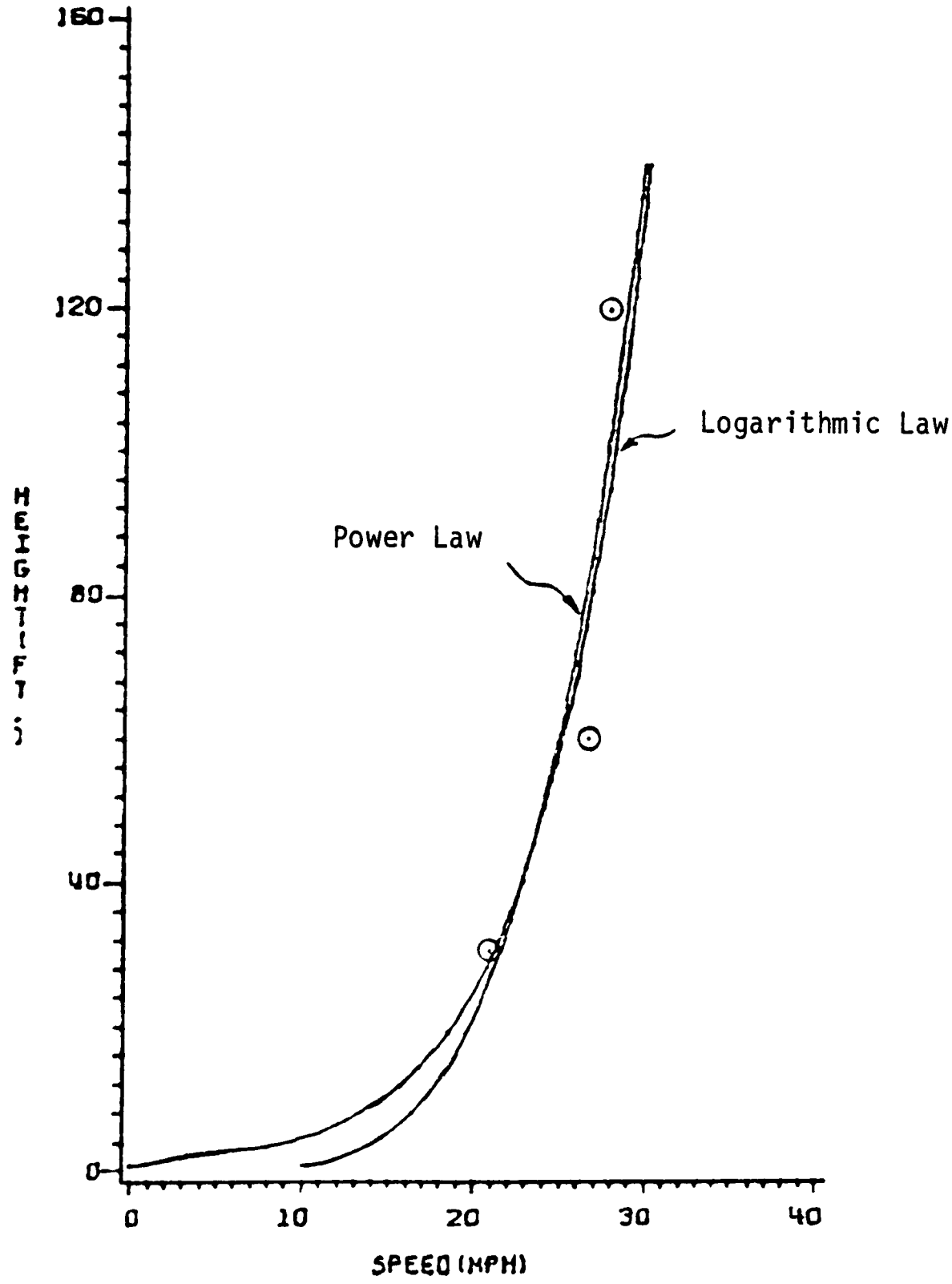


Figure 3.4 Mean Velocity Profile at Meteorological Tower 4

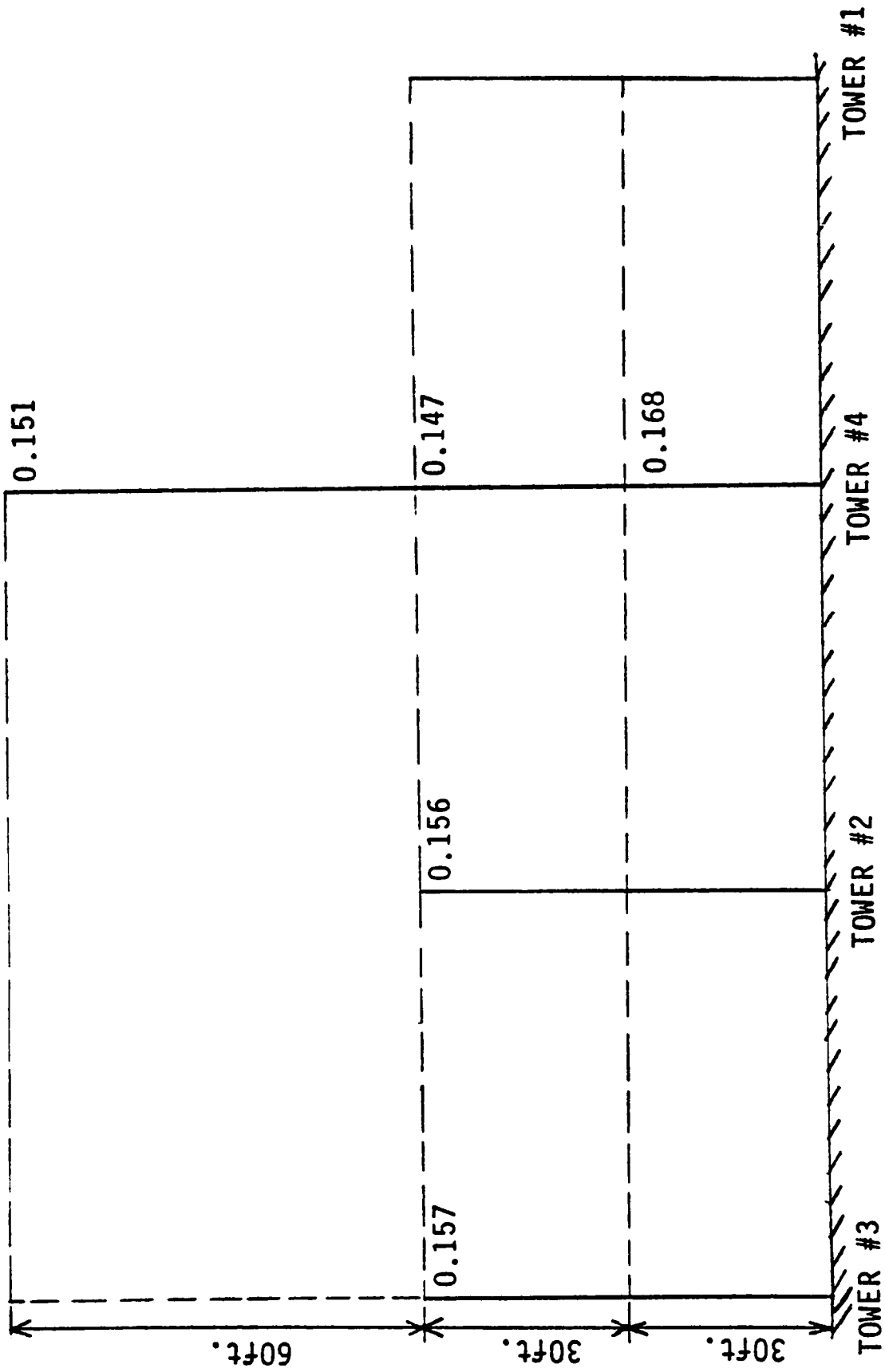


Figure 3.5 Values of Turbulence Intensity

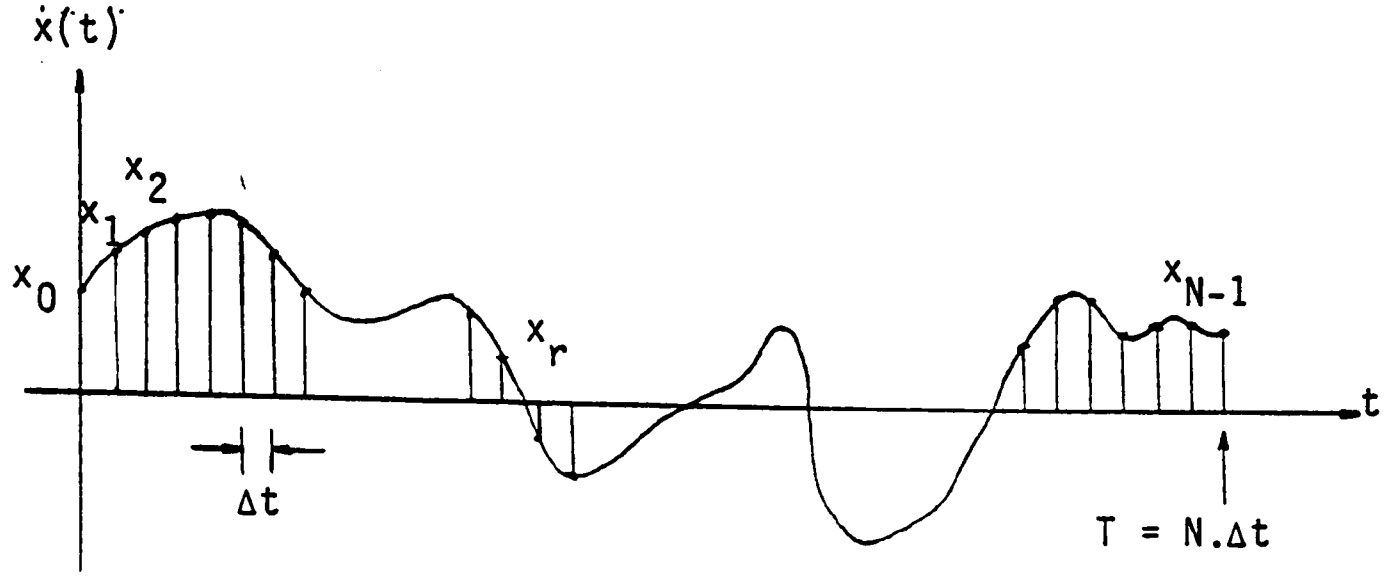


Figure 3.6 Discretized Time Series

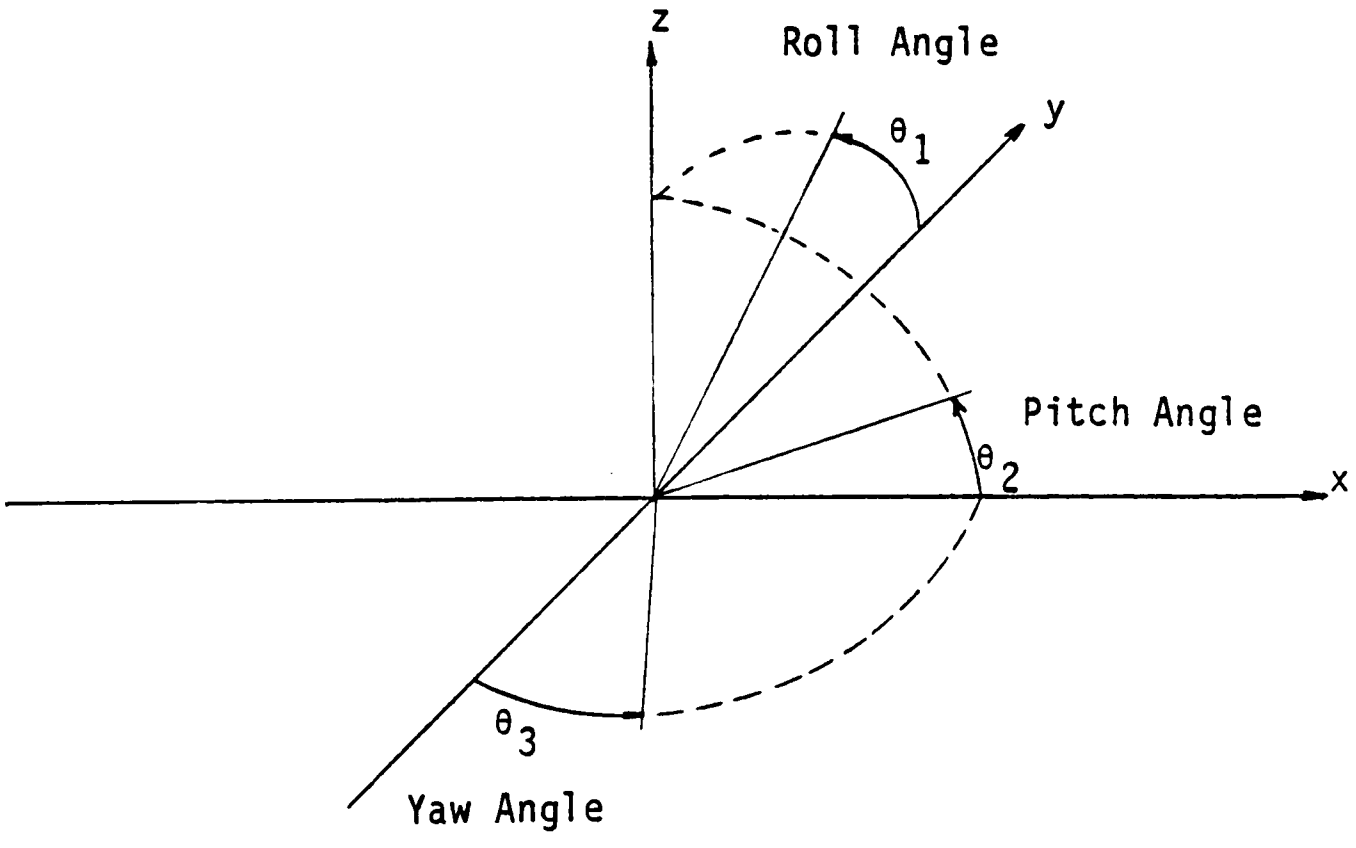


Figure 3.7 Illustration of Roll, Pitch and Yaw Angle

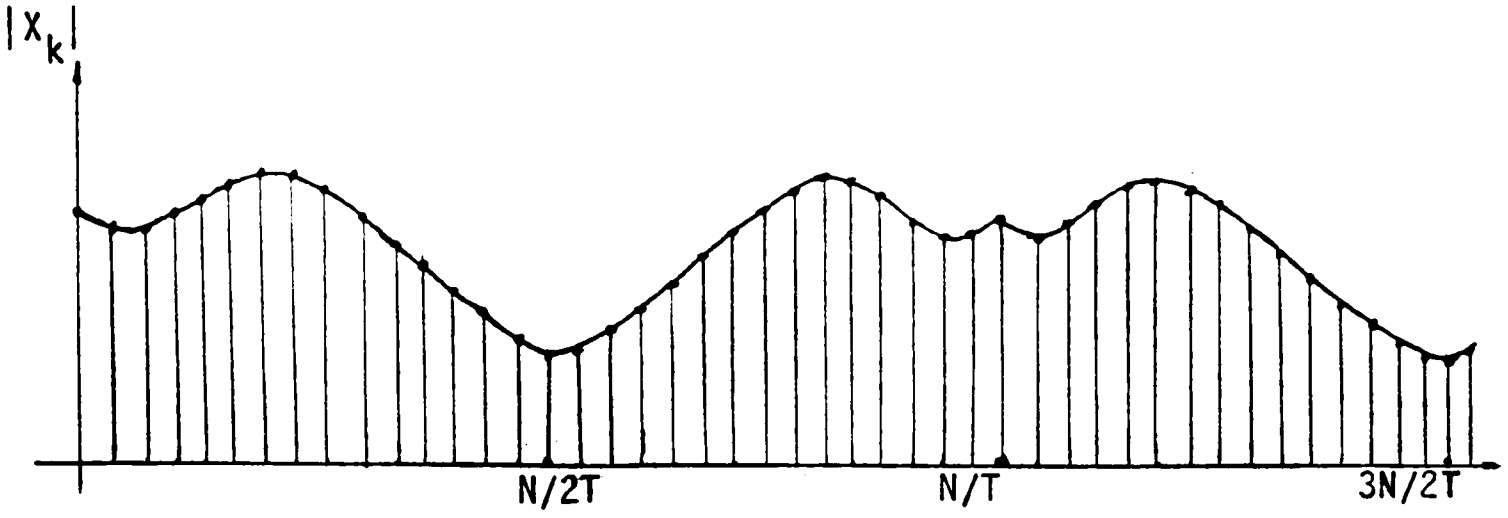


Figure 3.8 Discrete Fourier Transform Values

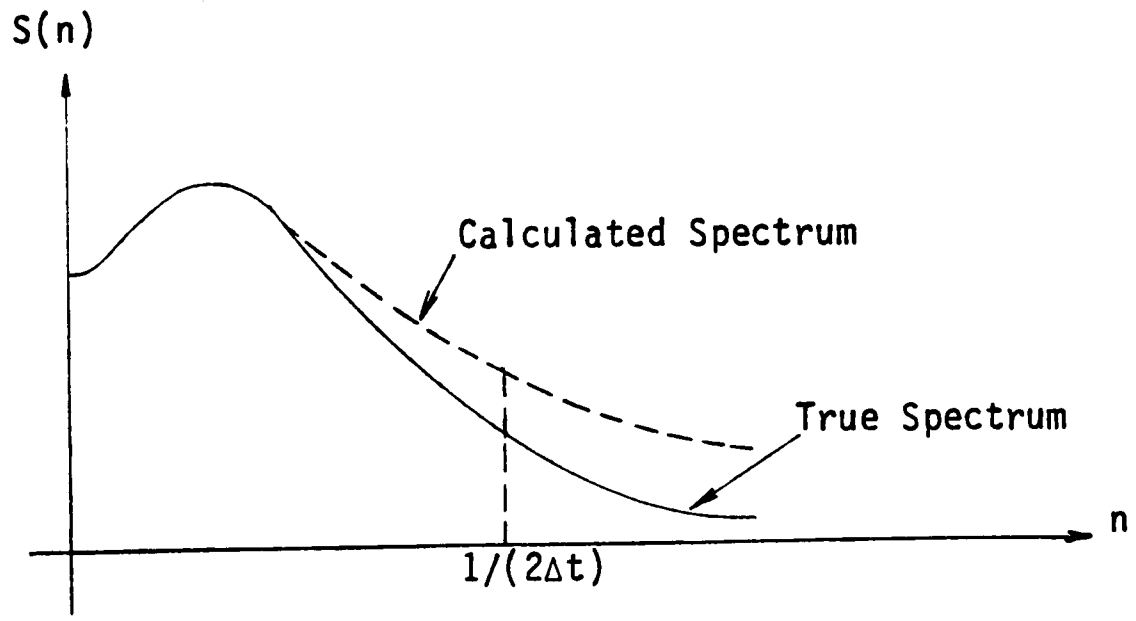


Figure 3.9 Aliasing Effect

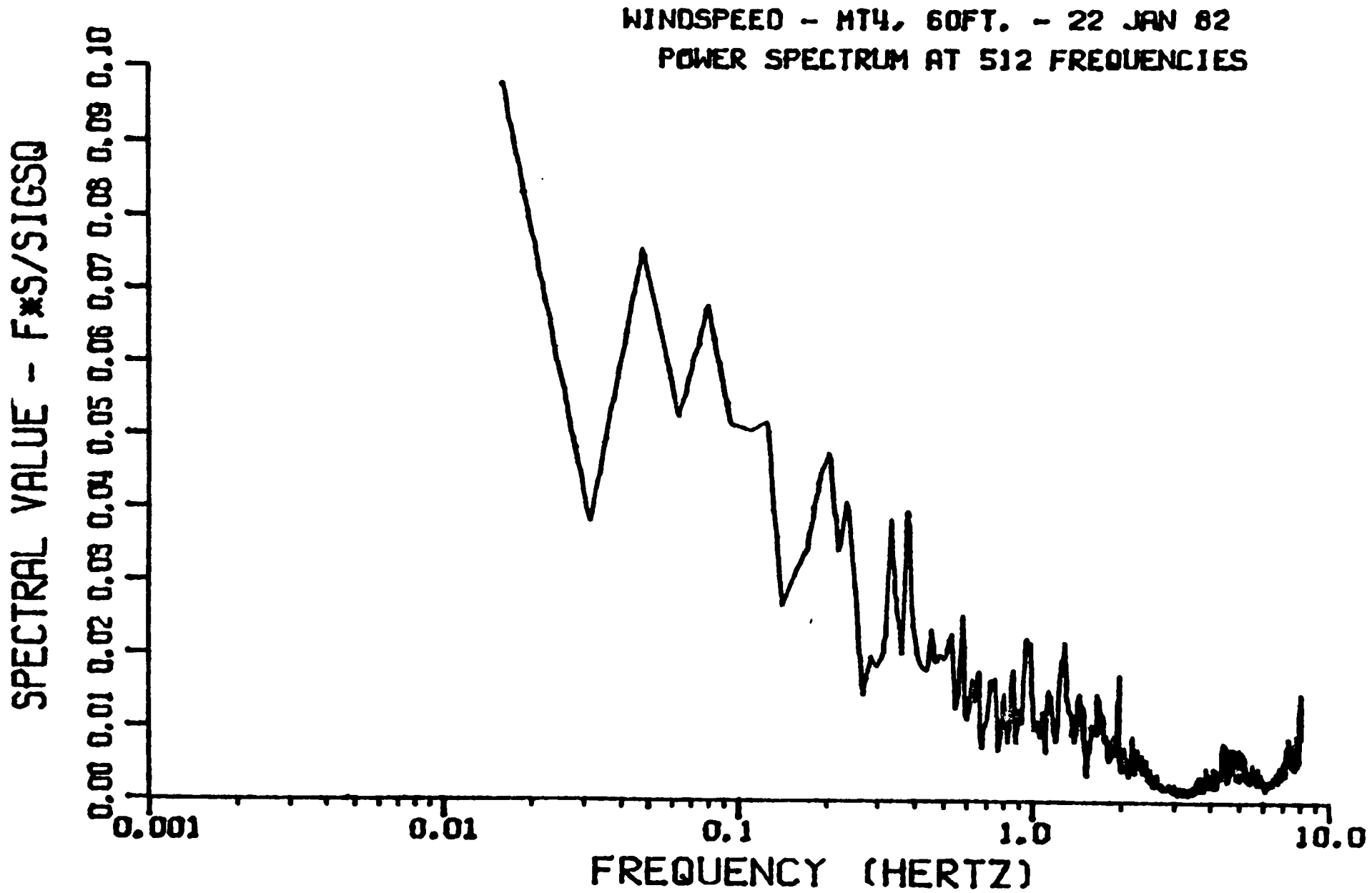


Figure 3.10 Wind Spectrum of Windspeed at 60 Foot Level of Meteorological Tower 4

CHAPTER IV

ANALYSIS OF STRUCTURAL RESPONSE DATA

In this chapter the theoretical relationships and methods of analyzing real wind structural response data are presented. The techniques discussed are illustrated insofar as is feasible with computations on data from the EPRI wind experiment in Oklahoma City. Many of the actual numerical results are limited, however, by the fact that no information about the properties of the towers was available during this study. Accordingly, the only calculations that are performed are for determining fluctuating response relationships. The stiffness and flexibility properties of the towers are considered to be unknown and are not included in the computations illustrated.

In the first section methods of estimating peak structural responses are given. These methods include separate calculations for mean or steady response and for fluctuating or dynamic response. In the second section computations that help to evaluate frequency response functions for real structures and the degree to which one load parameter contributes to a single response parameter are presented. This

analysis also relates to the linearity of the relationship between particular input and output quantities. In the third section illustrative results are shown only between one input parameter (load) and one output or response parameter (strain). The two choices made for these computations are the load in the northwest I-string, channel 45, whose time history is shown in Fig.4.1, and the strain in the vertical angle of the west tower leg, channel 53, whose time history shown in Fig.4.2. Channel 53 is used to predict the peak of the response.

4.1 Structural Peak Response

Structural response to wind loading is composed of a mean (static) response and a fluctuating (dynamic) response. For a time period, T, the average peak response, $\hat{R}$, can be estimated by (9)

$$\hat{R} = \overline{R} + K \sigma_R \qquad (4.1)$$

in which $\overline{R}$ is the mean response based on the mean windload on the structure;

σ_R is the standard deviation of the fluctuating response about the mean value; and

K is a statistical peak factor.

4.1.1 Mean Response

The structural response of a transmission line system comes from two sources: response due to wind on the cables and response due to wind on the towers themselves. The total mean tower response is written as:

$$\overline{R} = d_{tc}\overline{P}_c + d_{tt}\overline{P}_t \tag{4.2}$$

in which $\overline{P}_c$ and $\overline{P}_t$ are the mean wind pressures acting on the cables and the towers, respectively, and d_{tc} and d_{tt} are the structural influence coefficients which translate the mean wind pressures on the cables and the towers, respectively, into the mean structural response, $\overline{R}$.

With regard to the EPRI data, use of this equation could not be made herein because structural information needed to calculate the structural influence coefficients was missing. However, the mean wind pressures could have been determined from the wind speeds and the mass density of the air.

4.1.2 Fluctuating Response

Several steps needed to handle the fluctuating part are shown in Fig.4.3. The first step in the analysis involves the transformation of the gust spectrum, Su(f), into the force spectrum, $S_F(f)$, by multiplying by the aerodynamic admittance function $\chi^2(f)$. The second step involves the determination of the response spectrum, $S_R(f)$, by

multiplying the force spectrum by the mechanical admittance function, $H^2(f)$. In Fig.4.3, the aerodynamic admittance function and the mechanical admittance function are both frequency response functions used in different ways. The third step is to calculate the variance of the response, σ_R, from the area under the $S_R(f)$. The final step is to estimate a peak value of the fluctuating part by multiplying the root mean square value, σ_R, by a peak factor, K, and adding to the mean, $\bar{R}$, to obtain the overall expected peak, $\hat{R}$.

4.2 Basic Theory For Fluctuating Behavior: Cross Spectra And Frequency Response And Coherence Functions

Frequency response functions and coherence functions are obtained from relationships between cross spectra, input spectra and output spectra. After frequency response functions are calculated, the theoretical output spectra can be calculated by frequency response functions and input spectra as shown in Fig.4.3. The coherence function is used to evaluate the accuracy of the results which are based on the assumed linear relationship between input and output. No results are given in this section, just theories for arbitrary time series, x(t) and y(t).

4.2.1 Cross Spectra

Estimates of cross-spectral density for pairs of discrete

time series x(r) and y(r) can be obtained by the same computational technique used for power spectral density estimates (see Section 3.3). The cross spectral density estimates are calculated as follows:

$$Sxy(n) = \frac{2T}{N} \left(X^{*}(k) - Y(k)\right)$$

$$= Cxy(n) - iQxy(n) \qquad (4.3)$$

where a star * means the complex conjugate of the quantity that is starred. The real part of Eq. 4.3 is called the coincident spectral density function, or the co-spectrum for short, and the imaginary part is called the quadrature spectral density function, or the quad-spectrum for short.

It is more convenient to calculate two discrete Fourier transforms at the same time than to calculate two transforms separately. Two discrete time series, x(r) and y(r), may be considered to be the real and imaginary parts of a complex function z(r):

$$z(r) = x(r) + iy(r) \qquad r=0,1,2,\ldots,(N-1) \qquad (4.4)$$

for this purpose. Then the discrete Fourier transform of z(r) is

$$Z(k) = \sum_{r=0}^{N-1} (x(r) + iy(r))\, e^{-i2\pi rk/N} \qquad (4.5)$$

and X(k) and Y(k) are calculated by the following formulas:

$$X(k) = \frac{(Z(k) + Z^*(N-k))}{2} \tag{4.6}$$

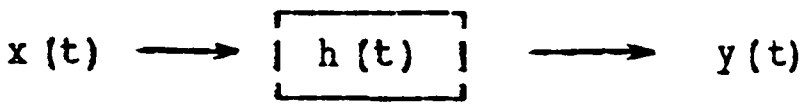
$$Y(k) = \frac{(Z(k) - Z^*(N-k))}{2i} \tag{4.7}$$

By frequency averaging or ensemble averaging, cross-spectral density estimates can be calculated by X(k) and Y(k). Normally the absolute value, $|Sxy(n)|$, or the squared absolute value, $|Sxy(n)|^2$, and the phase angle, $\theta xy(n)$, are the final results desired.

4.2.2 Frequency Response Function

A frequency response function can be called a transfer function. In the case of structures, the frequency response function is the reciprocal of a mechanical impedance function and is normally calculated from structural stiffness and mass properties. It might represent a linear filter in an electrical circuit, where a filter can be interpreted very generally as any linear operation definable by a convolution integral. In a variety of situations the frequency response function might simply represent some unexplained, but useful, linear relation between two arbitrary time histories.

For a single input-single output system as depicted by the following diagram,



the weighting function, or unit impulse function, $h(t)$, is defined as the response of the system to a unit impulse input as a function of the time, t, from the occurrence of the impulse. For mechanical systems, it is necessary that $h(t)=0$ for $t<0$, since the response must follow the input. The system output $y(t)$ for an arbitrary input $x(t)$ is given by the convolution integral

$$y(t) = \int_0^\infty h(\tau)x(t-\tau)d\tau \qquad (4.8)$$

The value of the output $y(t)$ at any time t is given as a weighted (infinite) sum over the entire past history of the input $x(t)$.

A linear system may alternatively be characterized by its frequency response function, $H(f)$, which is defined as the Fourier transform of $h(\tau)$. The input and output variables may then be related by the following equation

$$Y(f) = H(f)\ X(f) \qquad (4.9)$$

where X(f) and Y(f) are, respectively, the Fourier transforms of x(t) and y(t). H(f) contains both amplitude magnification and phase-shift information about the relationship between Y(f) and X(f).

Assume that a linear system with a single input and a single output is subjected to a random input, x(t), which is a representative member from a stationary random process with a zero mean. Then two relations between the power spectral density functions and the cross spectral density functions are

$$Sy(f) = |H(f)|^2 \; Sx(f) \qquad (4.10)$$

and

$$Sxy(f) = H(f) \; Sx(f) \qquad (4.11)$$

From these two equations, with measurements of the input power spectrum, Sx(f), and the cross power spectrum, Sxy(f), the frequency response function for a linear system is completely determined, including both gain (amplification) and phase. The transfer function estimate, H(f), obtained in this way is only the "least squares" approximation to the "true" nonlinear transfer function when the system is nonlinear.

4.2.3 Coherence Function

An extremely useful parameter in evaluating the accuracy

and usefulness of linear relations is the coherence function. For a single input-single output system with a noise-free input, x(t), the total output, y(t), may contain noise n(t), along with the noise-free output, w(t). In this case the output power spectrum also has two components:

$$Sy = Sn + Sw \tag{4.12}$$

where Sw is related to the input power spectrum Sx through the frequency response function,

$$Sw = |H|^2 Sx. \tag{4.13}$$

These equations imply that Sw is the portion of the total output power related to the input. The fraction of the total power accounted for by Sw is

$$\frac{Sw}{Sy} = \frac{|H|^2 Sx}{Sy} = \frac{|Sxy|^2}{Sx^2} \frac{Sx}{Sy} = \frac{|Sxy|^2}{Sx\ Sy} = \gamma_{xy}^2 \tag{4.14}$$

From this relation, the ordinary coherence, γ_{xy}, between the noise-free input x(t) and the total output y(t), represents the fraction of the power of the output that is accounted for by a linear relation with the input. The coherence function attains a theoretical maximum of unity at all frequencies for the case of ideal, non-noise, linear systems. If the coherence function is less than unity, the system is nonlinear or contains noise.

4.3 Calculation Of Fluctuating Response

This section uses the equations of section 4.2 to carry out the steps of Fig.4.3 with particular application to the load in the northwest I-string and the strain response in the west leg (the time histories shown in Figures 4.1 and 4.2).

4.3.1 Aerodynamic Admittance Function

For a given body immersed in a wind flow, the information on fluid velocity fluctuations is converted into information on resultant forces and moments by some empirical coefficients. The net drag force consists of the resultant over a given body's surface of all components of elemental forces that are aligned with the drag, or along wind, direction. The time-varying drag force on a body completely enveloped by a flow is conventionally given by the formula

$$F_D(t) = \frac{1}{2} \rho U^2(t) B^2 C_D \qquad (4.15)$$

where ρ is the mass density of air;

$U(t)$ is the along wind speed;

B is a typical body dimension; and

C_D is the drag coefficient in a steady or low-frequency wind.

Representing the windspeed as the sum of the mean component, U, and fluctuating component, u(t), the relation between the drag force spectrum and the along-wind gust spectrum can be derived(20) by means of the autocorrelation function of the drag force function. The result is

$$S_F(f) = \rho^2 U^2 B^4 C_D^2 \, Su(f) \tag{4.16}$$

This equation is valid over the range of frequencies contained in the gust spectrum provided all effects remain perfectly correlated. In practical conditions where this assumption does not hold, an adjustment factor or aerodynamic admittance factor is included to preserve the validity.

$$S_F(f) = \rho^2 U^2 B^4 C_D^2 \, Su(f) \, \chi^2(f) \tag{4.17}$$

where $\chi^2(f)$ is the aerodynamic admittance function.

The aerodynamic admittance function depends on the body shape and dimensions and on the characteristics of the turbulence. For a given body it is a frequency dependent function and can be found by experiment. It is shown schematically in Fig.4.4. For low frequencies $\chi^2(f)$ is about unity, but it falls below unity at frequencies in the range of interest for the effects of winds on structures.

4.3.2 Mechanical Admittance Function

After the force spectrum $S_F(f)$ is obtained by means of Eq. 4.17 the response spectrum for the response quantity R is obtained by multiplying $S_F(f)$ by the frequency response function, or mechanical admittance factor, $H^2(f)$:

$$S_R(f) = H^2(f)\, S_F(f) \tag{4.18}$$

The mechanical admittance function, $H^2(f)$, which relates $S_R(f)$ to $S_F(f)$ is normally determined from an analysis using the stiffness, mass, and damping characteristics of the structure. For a complex multiple-degree-of-freedom structure, evaluation of this frequency response function is a difficult task. One of the benefits of taking measurements at a full scale test site is that by measuring specific load and response quantities, an empirical $H^2(f)$ of the structure that applies to these quantities can be determined and compared to the analytical function.

For the transmission towers at the OKC site for which results are being used for illustration, the structural properties necessary to calculate the mechanical admittance were not made available for this project. Therefore only the measured $H^2(f)$ can be predicted. Using Eq. 4.11 of section 4.2.2, the mechanical admittance can be determined from the cross spectrum, $S_{FR}(f)$, and the ordinary force spectrum, $S_F(f)$, as follows:

$$H(f) = \frac{S_{FR}(f)}{S_F(f)} \tag{4.19}$$

Then the square of the H(f) spectrum can be used in Eq.4.18 to obtain for S_R (f) results.

Channel 45, the load on the northwest insulator (whose time history is shown in Fig.4.1), and channel 53, the strain in the west vertical leg of tower 287 (whose time history is shown in Fig.4.2), are used to illustrate these steps. Thus the force spectrum, S_F (f), is the spectrum for channel 45, which is shown in Fig.4.5, and the cross spectrum is between channels 45 and 53, as shown in Fig.4.6. Using these quantities in Eq.4.19, the resulting mechanical admittance or frequency response function, H(f), is shown in Fig.4.7. This plot, as mentioned earlier, gives the amplitude of the admittance, including both real and imaginary parts. The phase angle, θ_{FR} (f), between the real and imaginary parts is shown in Fig.4.8.

The mechanical admittance shown in Fig.4.7 does not look encouraging. Its oscillations are large in relation to its mean values, and no clear shape revealing the natural frequency or frequencies of the system appears. This is not an entirely surprising result since this empirical curve is

derived from twc spectra (Figures 4.5 and 4.6) which both show strong oscillations. Perhaps further smoothing by frequency averaging should be considered to help reveal a possible peak or hump in the curve. It should also be noted that the units of the measured quantities (load and strain) have not been used to normalize this function so that it approachs unity at the left (as frequency approaches zero).

The phase angle plot of Fig.4.8 also reveals a rather random relationship between the measured load (channel 45) and the measured strain (channel 53). It oscillates over the entire normalized range from zero to 1.0 in the units of the figure, which represents zero to 2 π radians or zero to 360 degrees. Both of these results indicate that there was too much noise in comparison to the signals in the measurements considered, and that many other forces not coherent with the force illustrated contributed to the strain illustrated. The lack of coherence between the load and strain quantities considered is treated further in Section 4.3.3 below. The methods of analysis used to develop the relationships just discussd are valid despite the poor results.

In a wind design or analysis, the mechanical admittance is a characteristic of the structure and may be used to predict the effect of any loading. Thus, for a different

given loading having a spectrum $S'_F(f)$, the resulting strain spectrum would be, using Eq.4.10,

$$S'_R(f) = H^2(f)\, S'_F(f) \tag{4.20}$$

The use of this relationship can be illustrated with the data considered herein by multiplying the calculated admittance function (Fig.4.7) by the original force spectrum, Fig.4.5, to get the strain response spectrum that would be obtained by analysis-type steps. When this is done, the spectrum of Fig.4.9 is obtained.

Comparison of Fig.4.9 to the response spectrum obtained directly from channel 45, Fig.4.10, reveals that much smaller amplitudes of $S_R(f)$ are obtained from Eq.4.10 than from treating the strain response time series directly. The difference may be small for measurements on a single-degree-of-freedom system containing little noise. The large differences observed between Figures 4.9 and 4.10 may be attributed to noise in the measurements, contributions to the strain from other forces (which are like noise components insofar as the dependence of the one strain on the one load considered), errors in the spectral estimates, and possible non-linearity between the input (load) and output (strain) considered.

4.3.3 Coherence Function

The coherence defined by Eq.4.14 can be used to evaluate the accuracy and usefulness of the measured relationship between any two input and output quantities such as the load and strain channels just considered. Letting

$$\gamma_{FR} = \frac{|S_{FR}|^2}{S_F\, S_R} \tag{4.21}$$

and using the functions of Figures 4.5, 4.6 and 4.10, the coherence function between channels 45 and 53 is found to vary as shown in Fig.4.11. The values of coherence in this plot are seen to be very small. This means that the fraction of the total variance in the output (strain) that is accounted for by a linear relation with the one input (load) considered is small. This agrees with the observations made above and may be attributed to the same factors: possible noise in the measurements, errors in spectral estimates, non-linearity in the structural behavior, or contributions of other inputs (loads) in the multiple-degree-of-freedom system.

Before leaving the plots of Figures 4.5 and 4.10, it should be pointed out that there are important common features in the two. Most obvious are the major peaks near 1 Hz ad 5 Hz and the rise at the high-frequency limit.

These features might be associated with natural frequencies of the tower-cable system, but other possibilities also exist. One is aliasing, which can be concentrated in one or more frequency ranges to produce a peak; another is the influence of filtering. The data shown were passed through a 7-point Butterworth filter which might produce peaks in the high-frequency range. this appears to be most likely for the 5 Hz and Nyquist frequency rises because they show up in the wind (see Fig.3.10) data as well as the load and strain data. The strong peaks in Figures 4.5 and 4.10 near 1 Hz are not apparent in the wind data, however, and seem to indicate some natural frequency of the system.

A final note worth making is that the load measurements (Fig.4.5) are sensitive to possible tower response just like strains, because the loads are measured between the cables and the towers. In other words, movement of the tower would pull on the loads cells between the insulators and the cables just as forces on the cables would pull the load cells. Thus the loads measured are not independent of the tower, or completely coupled from the tower. This may explain the similarity in the peaks of Figures 4.5 and 4.10 even though the coherence is small as shown in Fig.4.11.

4.3.4 Peak Factor

The mean square value, or variance, of the fluctuating

along wind response is obtained in an analysis or design as the area under the response spectrum calculated by Eq.4.20

$$\sigma_R^2 = \int_0^\infty S_R(f)\, df \tag{4.22}$$

Generally this integration is carried out in two parts, a low-frequency part caused by relatively long duration gusts where $H^2(f)$ is approximately 1.0, (called the background part), and a higher-frequency part caused by the shorter duration gusts in the range of the fundamental frequency of the structure where $H^2(f)$ has a peak (called the resonant part).

The final step in the analysis outlined in Fig.4.3 involves multiplying the root mean square value, σ_R, obtained from Eq.4.22 by a peak factor, K, to give the expect peak value of R(t). To yield the expected value cf the largest peak occurring in the time interval T of a normally distributed stationary time series with a zero mean, the peak factor K is calculated approximately by the following equation(20),

$$K = (2 \ln \nu T)^{1/2} + \frac{0.557}{(2 \ln \nu T)^{1/2}} \tag{4.23}$$

and

$$\nu = \left[\frac{\int_0^\infty f^2 S_R(f)\,df}{\int_0^\infty S_R(f)\,df} \right]^{1/2} \qquad (4.24)$$

is the cycling rate of the process, which is calculated from the spectral values $S_R(f)$. Usually the value of K is about 3 to 4.

Applying these steps to the strain response in the west tower leg (channel 53), the spectral density estimates of Fig.4.10 are first used in Eq.4.24 to evaluate the cycling rate, ν. The resulting value is 2.05 Hz. Then this value is used along with the measurement duration, T, of 1,024 seconds (17.07 minutes) to determine K, which turns out to be 4.05. Finally, using the measured mean, $\bar{R}$=142.2, and the measured standard deviation, σ_R=39.9, for this channel, the average peak response calculated from Eq.4.1 is

$$\hat{R} = \bar{R} + K\sigma_R = 142.2 + 4.05 \times 39.9 = 303.8 \ \mu in/in.$$

It may be noted that if the calculated spectral values of Fig.4.9 are used instead of those of Fig.4.10 the cycling rate is 2.18, the peak factor is 4.07, and the response is 304.6. Thus, the peak results are insensitive to the $S_R(f)$ magnitudes, which are not in close agreement between Figures 4.9 and 4.10.

The peak response value, 303.8, is shown along with the 1/16-second peak and the 2-second average peak in Fig.4.2. It may be seen that the predicted peak is midway between the 1/16-second peak and the 2-second peak. This is entirely reasonable. The 1/16-second peak strain of 419.6 may be unrealistically high, unless the wind induces significant response in the higher natural modes of the structure. On the other hand, the 2-second average peak strain of 214.0 is probably too low an estimate of the significant peak strain in the structure because it ignores responses in natural frequencies of the structure higher than 0.5 Hz. Thus the predicted peak of 303.8 appears to be useful. (It may be noted that use of a 2-second average was adopted originally for wind channels since the response time of the wind sensors is one second or more. However the electrical strain gages used can respond as rapidly as the structure and the instrumentation systems themselves.)

4.3.5 Computer Program PSCROS For Fluctuating Structural Response

Program PSCROS is used to calculate the input spectrum, output spectrum, cross spectrum, frequency response function, coherence function and phase angle of two time series. The cycling rate is also calculated as one of the steps in this program, which is shown in part A.4 of Appendix A.

Two time series read from two data files are first centered. Then utilizing the International Mathematics and Statistical Libraries (IMSL) program FTFPS, the fast Fourier transform estimates of the power spectra and the cross spectrum of these two series are obtained. The frequency response function is calculated by Eq.4.19 from the estimates of the input power spectrum and the cross spectrum. Then Eq.4.20 is used to obtain the structure response spectrum (Fig.4.9) from the force spectrum. Using the measured spectrum, the cycling rate, ν, is calculated by Eq.4.24. All the calculated spectra, frequency response function, coherence function and phase angle are plotted by subroutine PSPLCT.

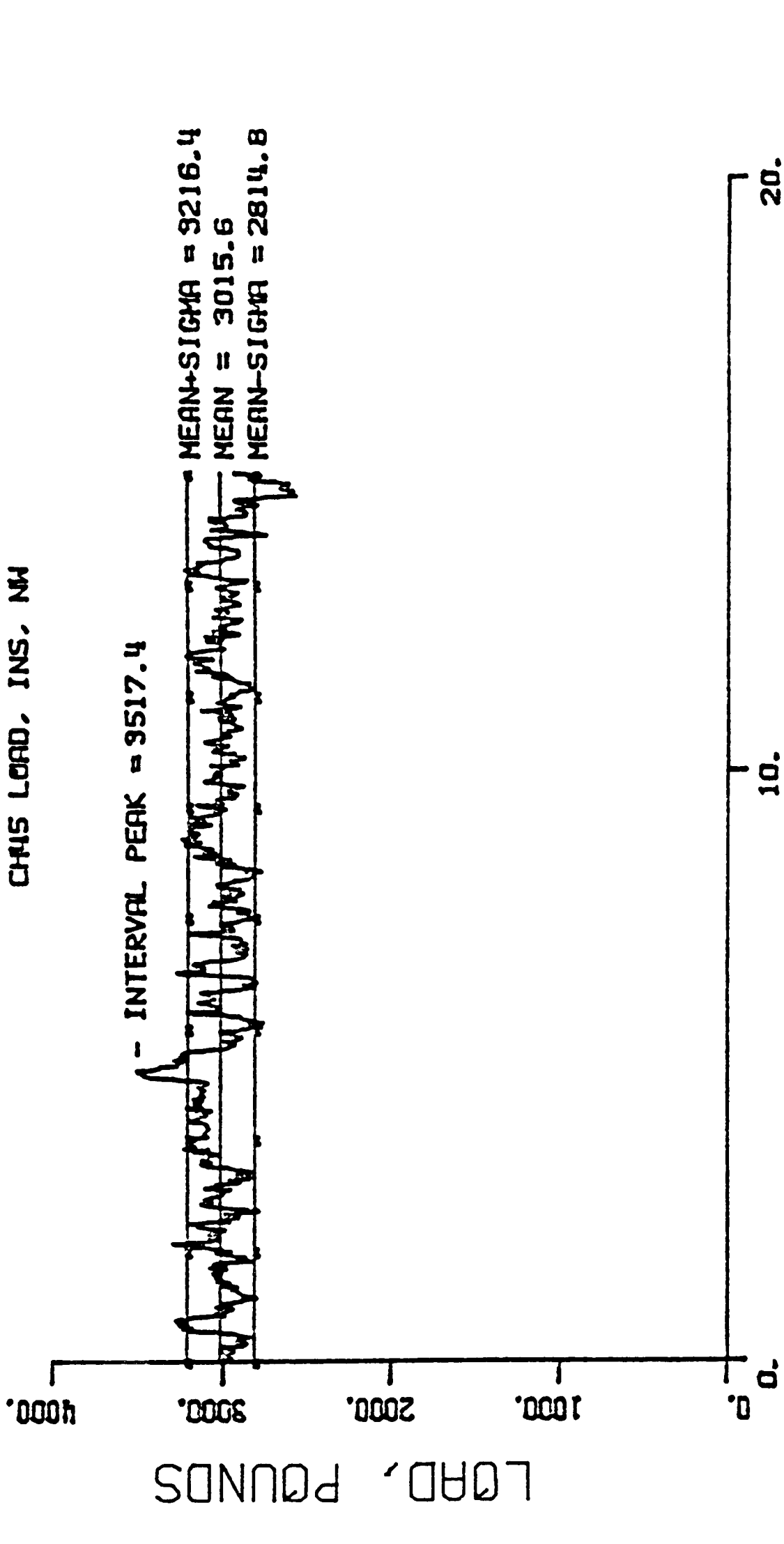


Fig. 4.1 Time History Plot of Channel 45, the Load on the Northwest Insulator of Tower 287

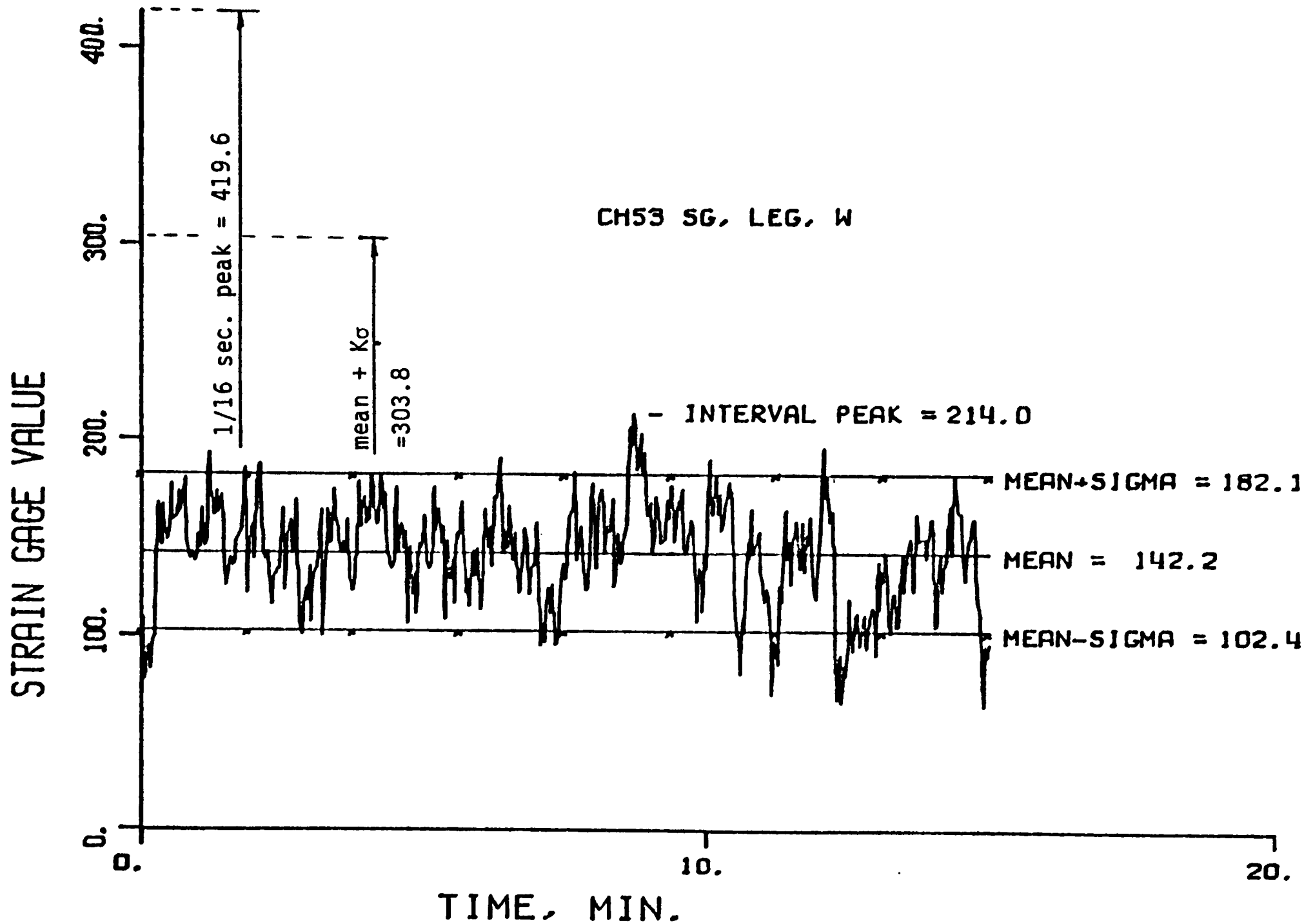


Fig.4.2 Time History Plot of Channel 53, the Strain in the West Vertical Leg of Tower 287

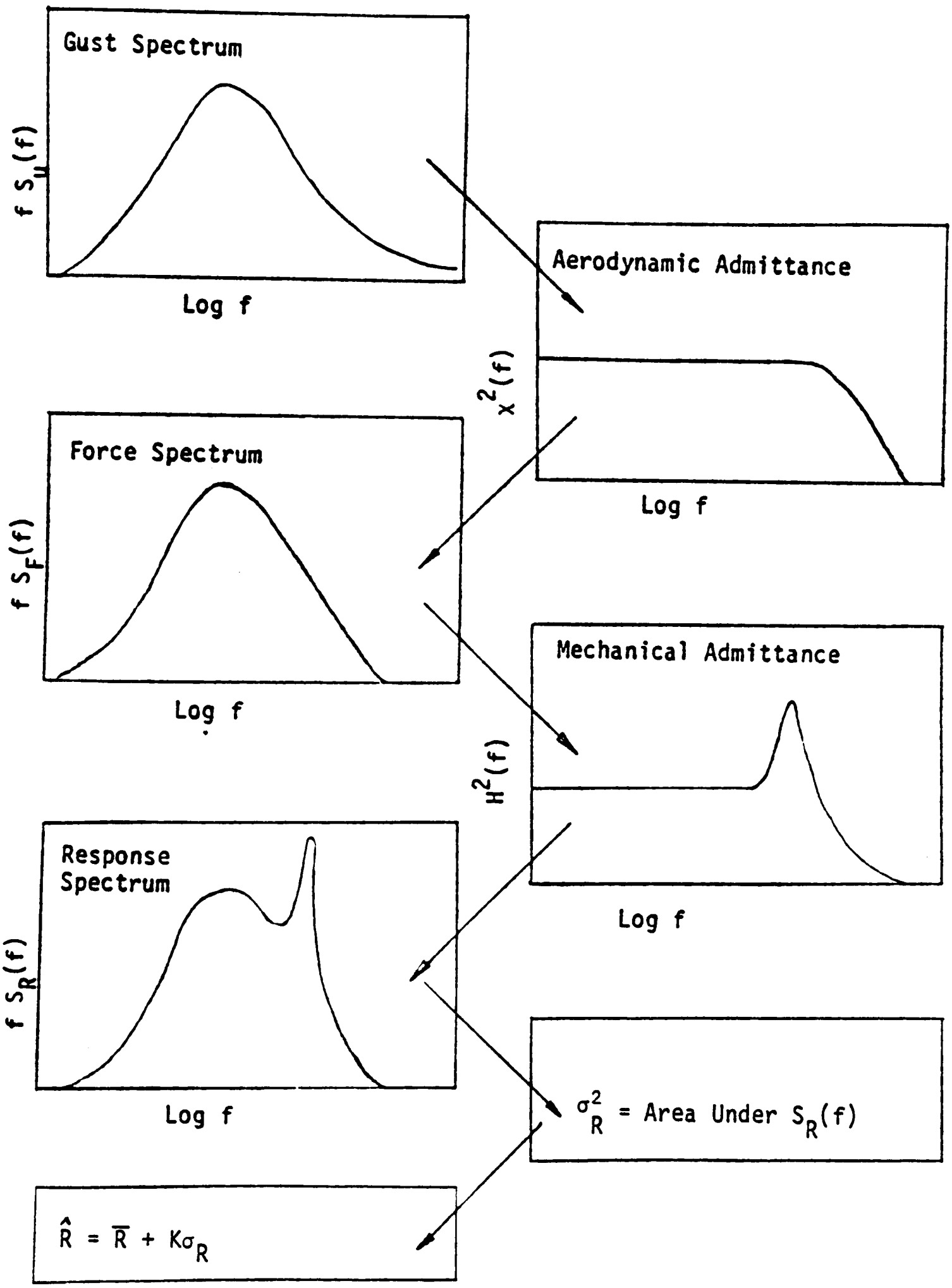


Fig.4.3 Elements of the Response Spectrum Analysis

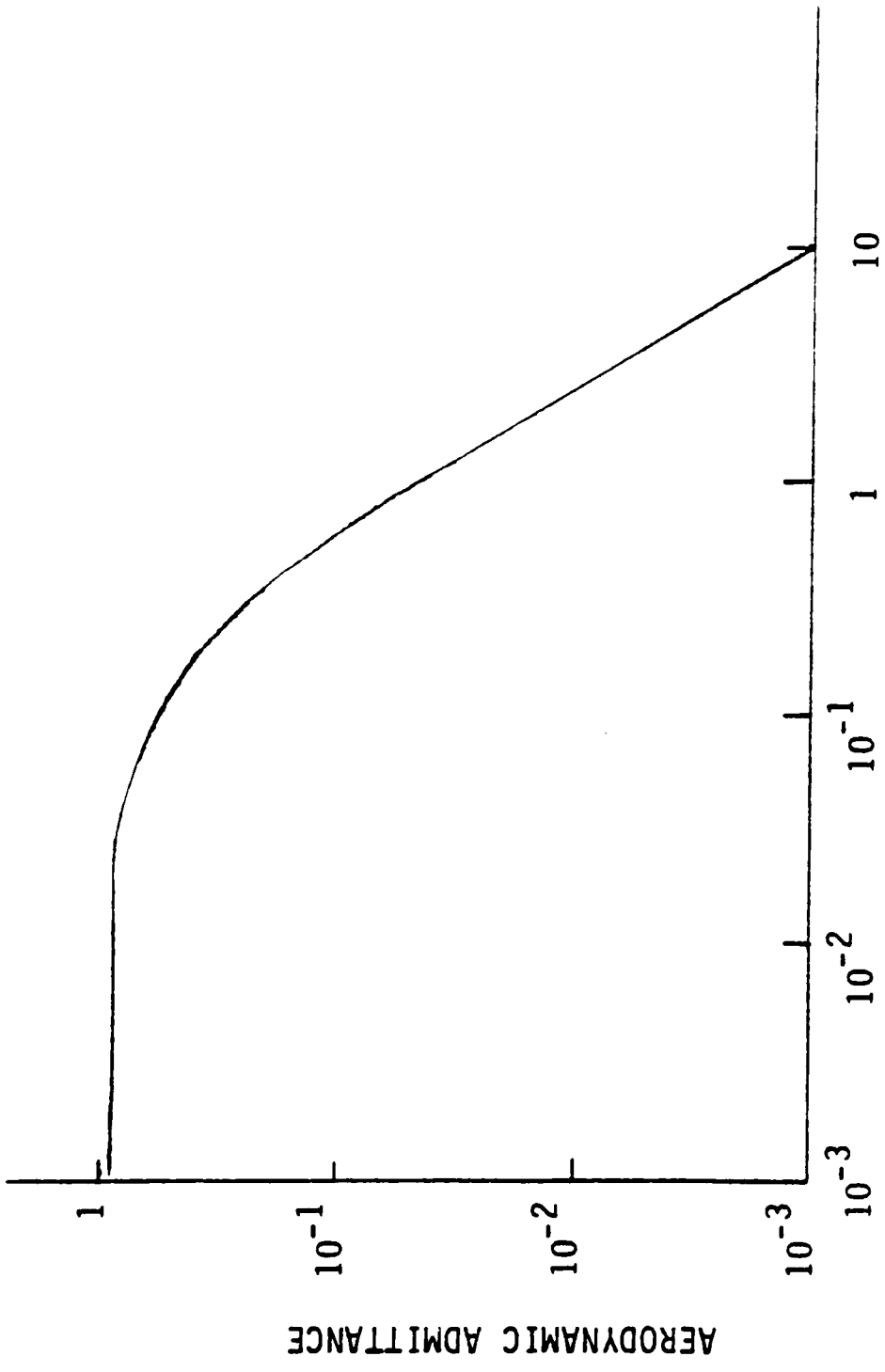


Figure 4.4 General Form of the Aerodynamic Admittance Function

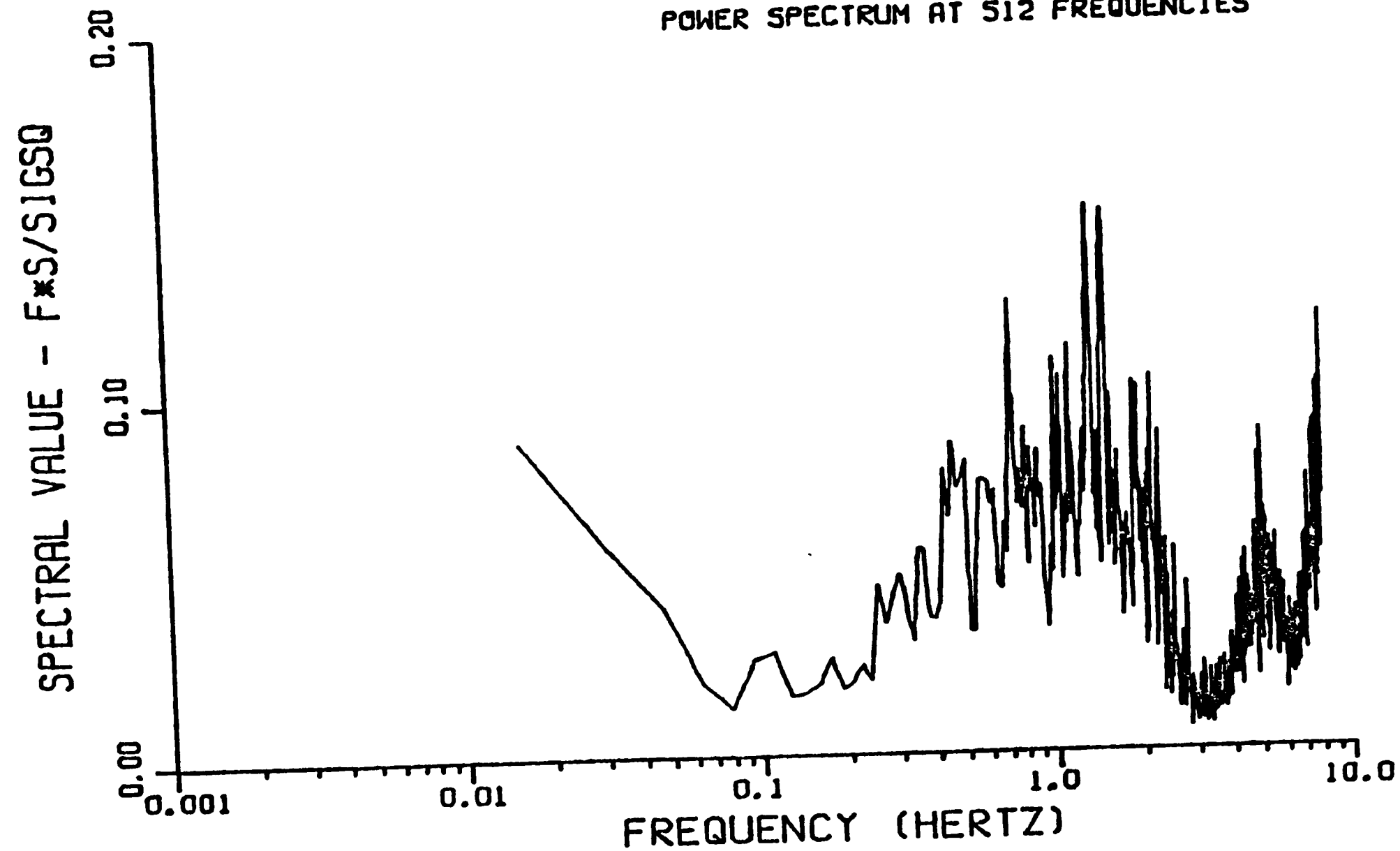


Figure 4.5 Power Spectrum of Channel 45, the Load on the Northwest Insulator of Tower 287

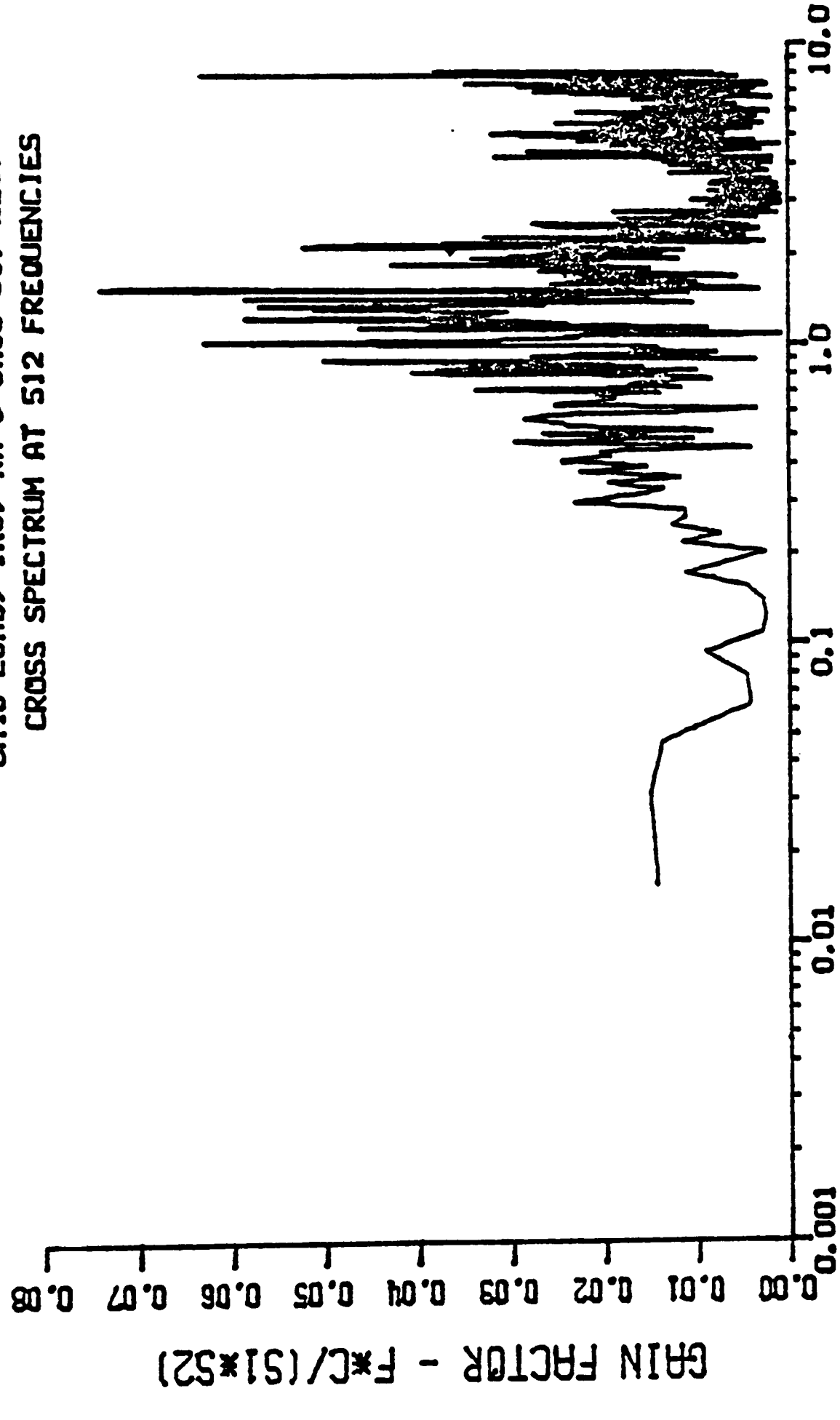


Figure 4.6 Cross Spectrum Between Channel 45, the Load on the Northwest Insulator, and Channel 53, the Strain in the West Vertical Leg, of Tower 287

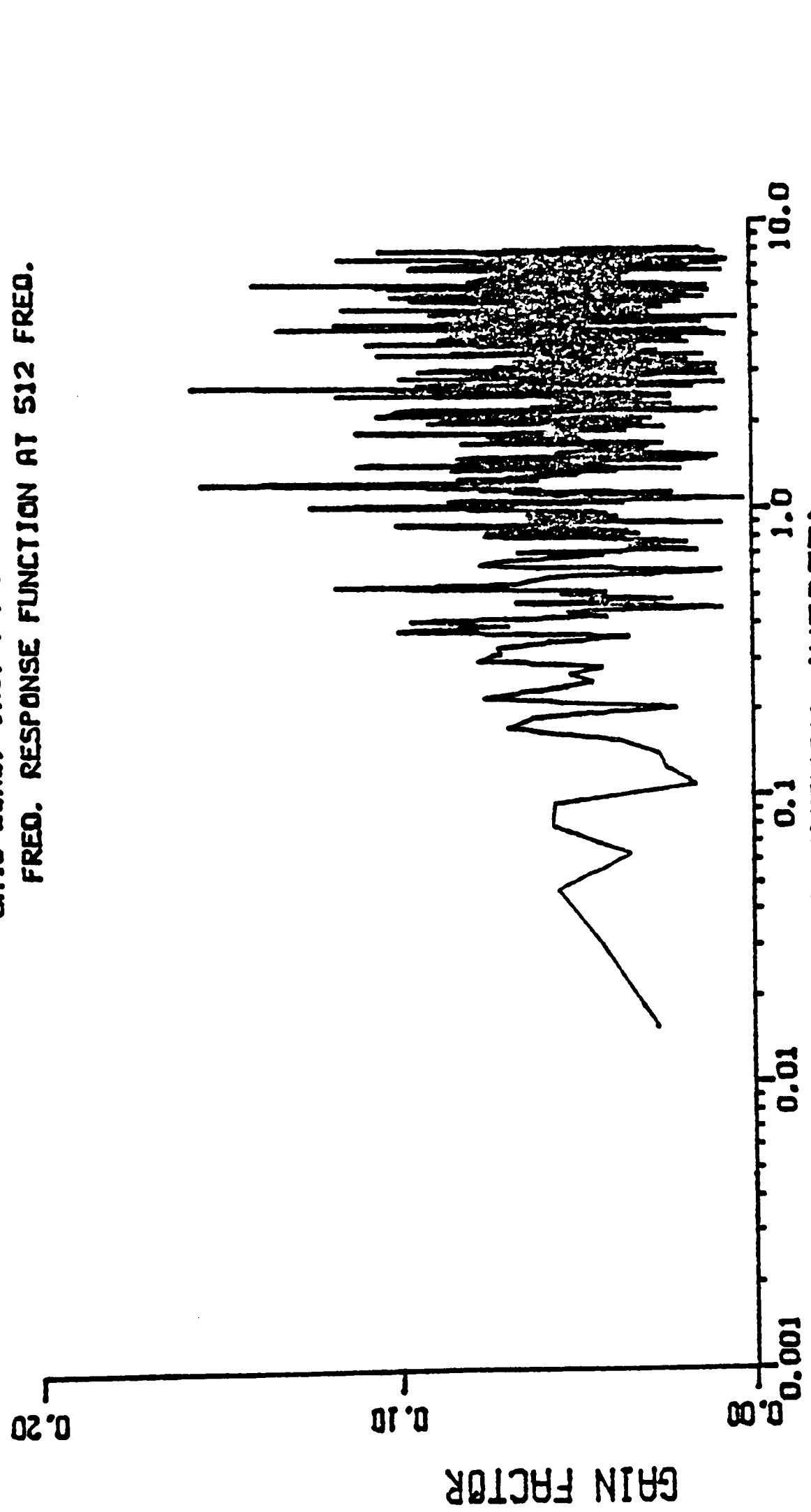


Figure 4.7 Frequency Response Function Between Channel 45, the Load on the Northwest Insulator, and Channel 53, the Strain in the West Vertical Leg, of Tower 287

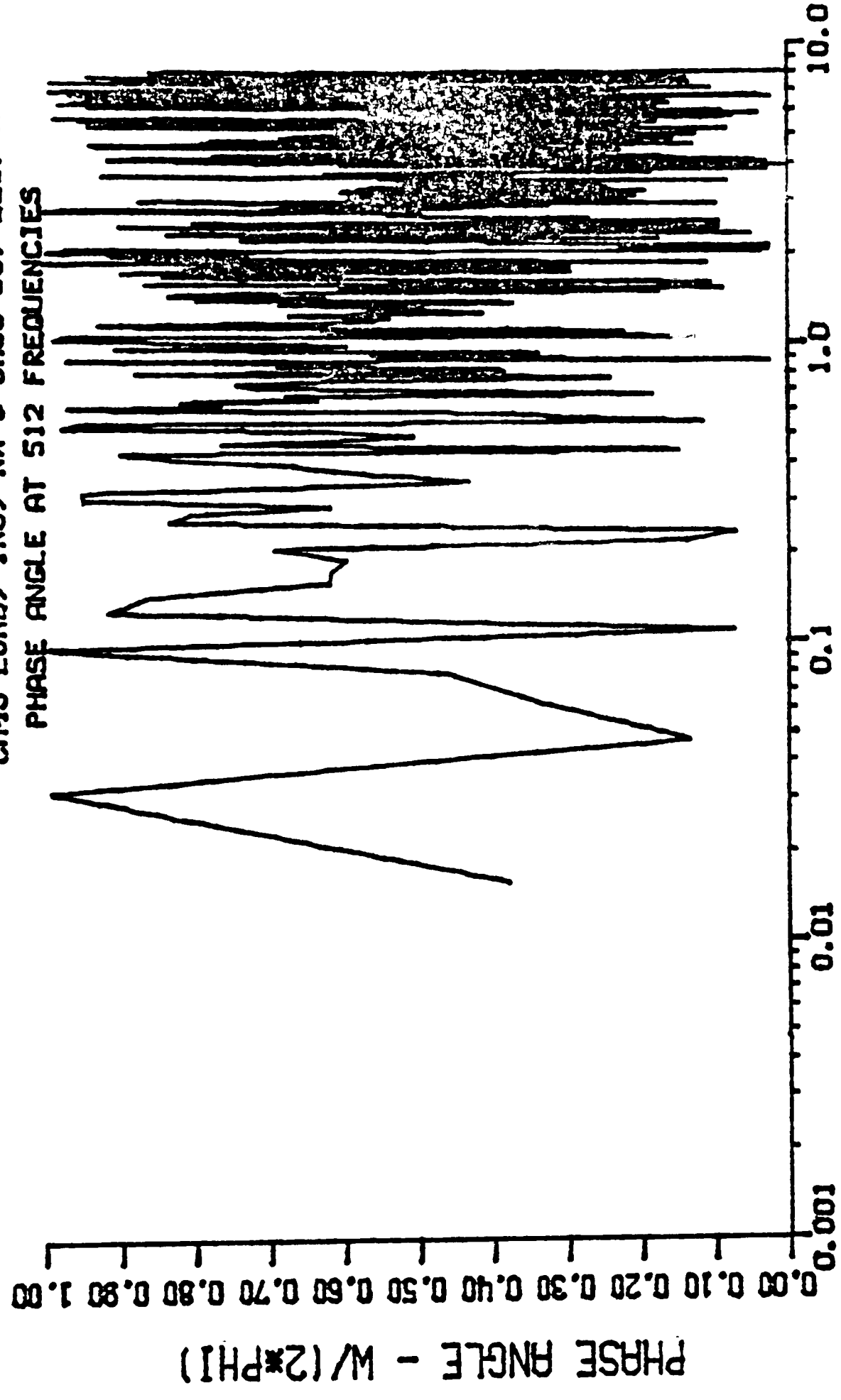


Figure 4.8 Phase Angle Between Channel 45, the Load on the Northwest Insulator, and Channel 53, the Strain in the West Vertical Leg, of Tower 287

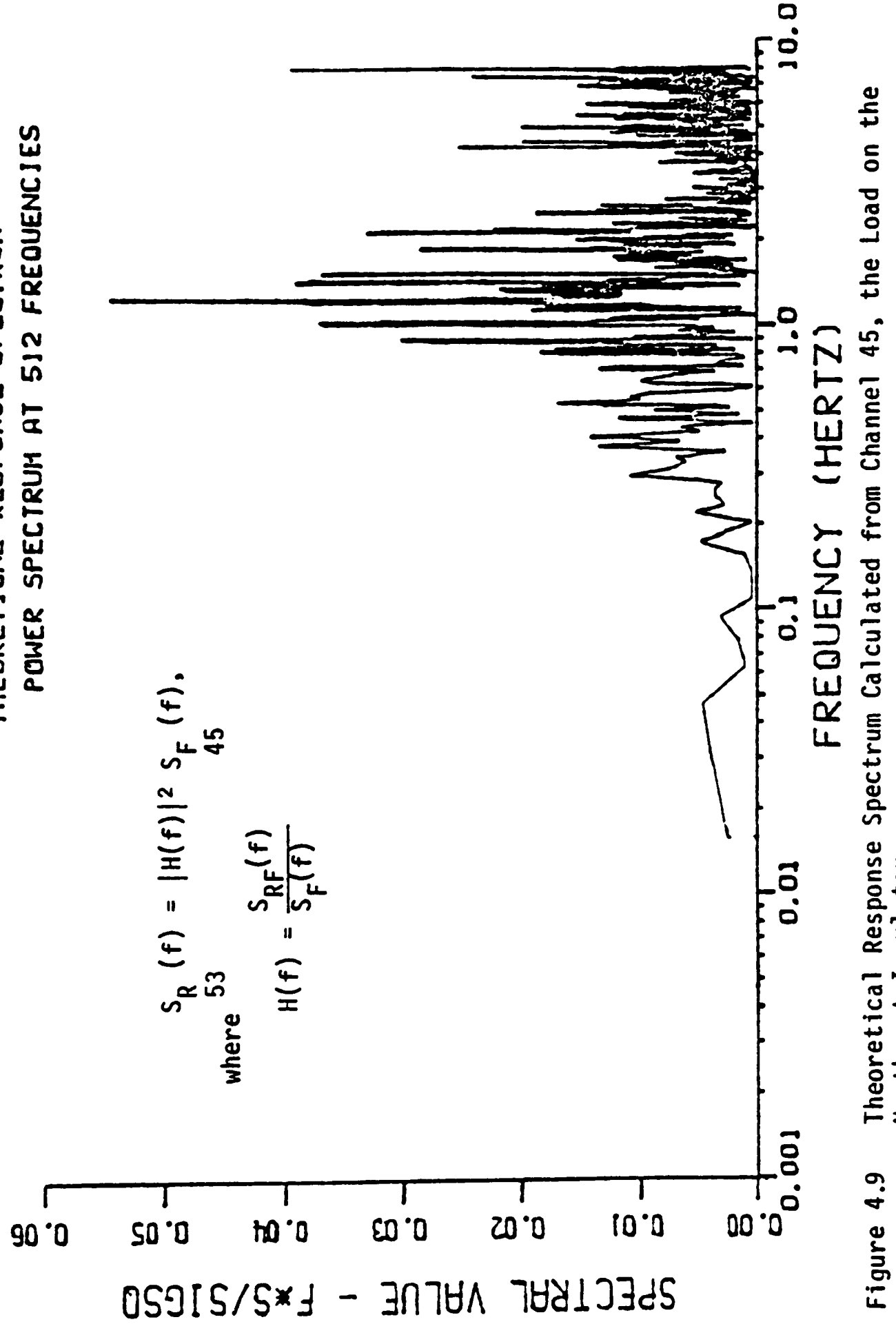


Figure 4.9 Theoretical Response Spectrum Calculated from Channel 45, the Load on the Northwest Insulator

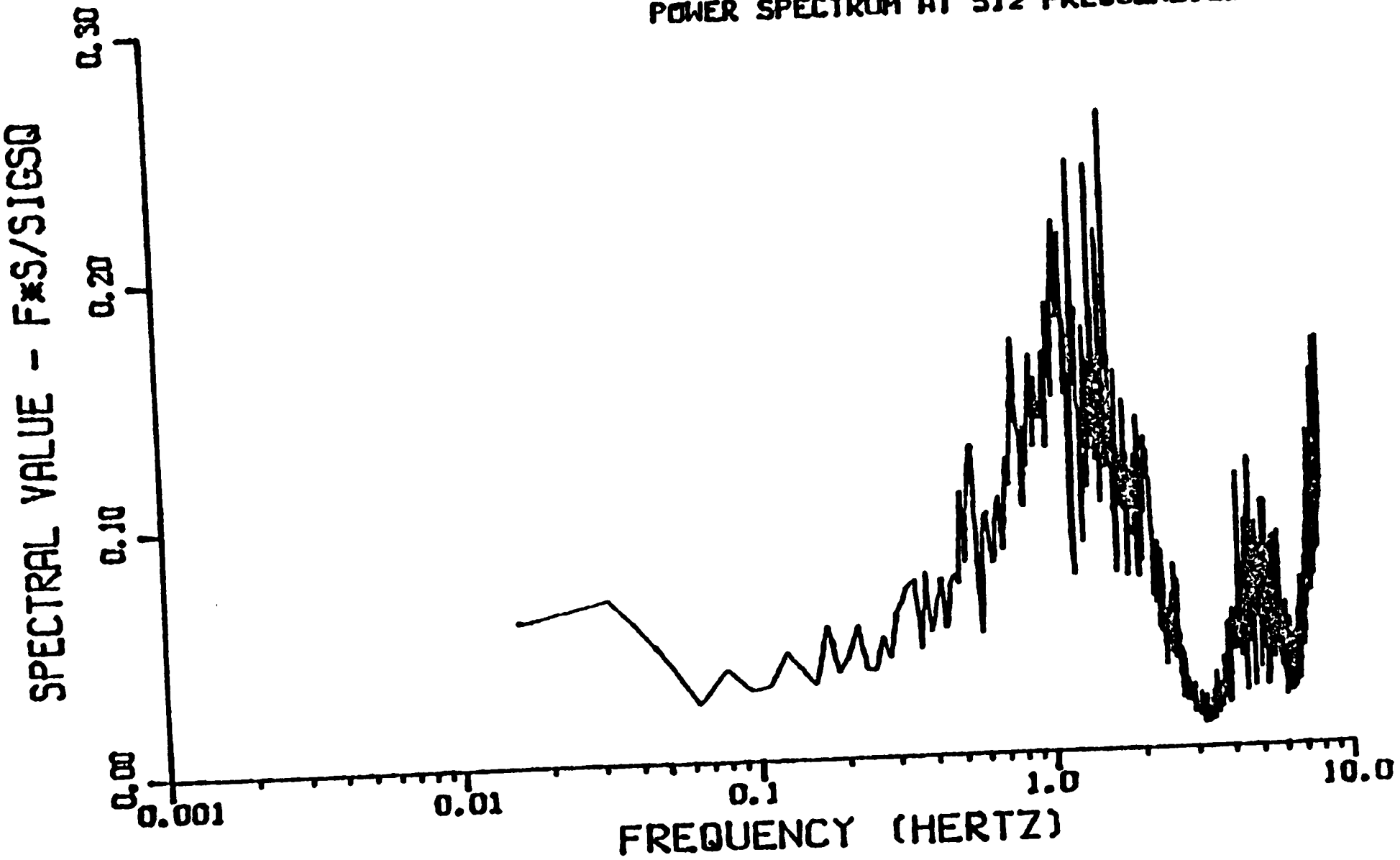


Figure 4.10 Power Spectrum of Channel 53, the Strain in the West Vertical Leg of Tower 287

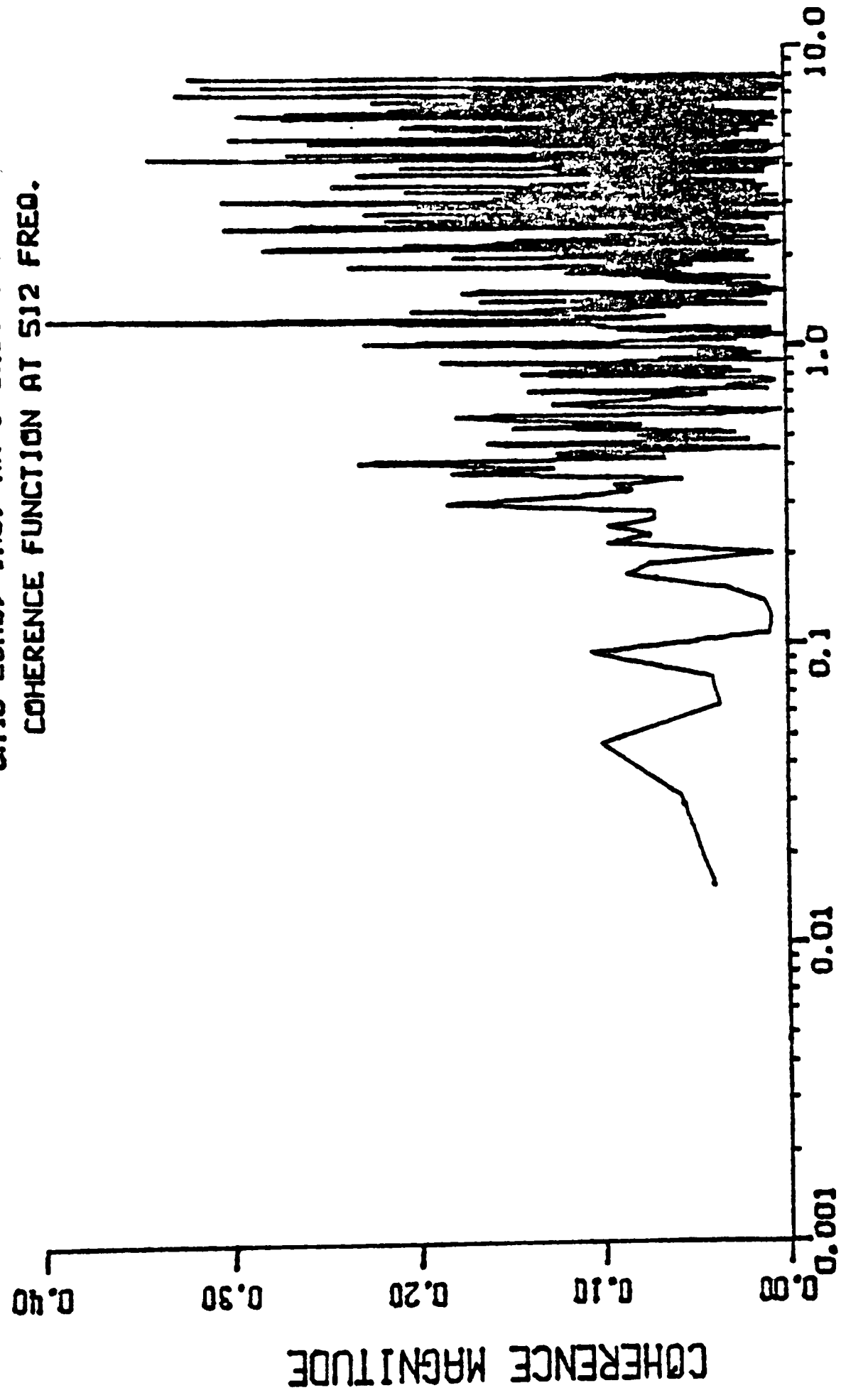


Figure 4.11 Coherence Between Channel 45, the Load on the Northwest Insulator, and Channel 53, the Strain in the West Vertical Leg, of Tower 287

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Basic wind data analysis procedures are discussed and reported in this thesis. The procedures are intended to help structural engineers gain valuable understandings of wind effects on structures. Particular attention is given to transmission tower systems. Sample calculations are presented for the procedures considered. The discussion concentrates on procedures to analyze real wind and structural response meaurements obtained in full-scale experiment.

The discretized wind data measured from transducers are passed through anti-aliasing filters to eliminate aliasing effects prior to being analyzed. The first task of the procedure to analyze data is validation of the data. This task includes time history plots, comparisons between channels to check for consistency, histograms and stationarity checks. Probability distribution and stationarity properties of the data and the reliability of the data acquisition system can be verified in this task. Second major task is the analysis of the wind data alone. This task includes determining mean wind profiles, turbulence intensities and wind spectra.

Site characteristics which determine the turbulence intensity and frequency content of the wind are expressed by the procedures in this task. The third major task is the analysis of the structural response data. If adequate wind data are available this task may include relating the input (wind) to the output (structural response) by power spectral density functions in the frequency domain. The coherence function, frequency response function and peak factor are examined in this task.

Some full scale transmission tower data obtained from the Oklahoma City site operated by the Electrical Power Research Institute are used to illustrate the application of these analysis procedures. Computer programs to carry out the computations described above are given in Appendix A.

5.1 Conclusions

Based on use of the analysis procedures developed, the following conclusions are made.

The validation methods employed proved to be effective and efficient. For example, in the data analyzed, several channels (specifically the windspeeds measured at the tops of all three transmission towers) proved to be unreliable because of inconsistences with other measurements. Similarly, checks on the probability distribution of the wind data through histogram plots and on stationarity of the

wind data through run test and trend test computations were readily carried out. The data proved to be normally distributed and stationary.

Analysis of the wind data was also accomplished effectively. Mean wind profile plcts by the power law and the logarithmic law compared reasonably well with one another, and the logarithmic law roughness length, power law exponent, and turbulence intensities were obtained in a straight-forward, unbiased manner. The wind spectrum plot was evaluated by a Fast Fourier Transform (FFT) technique(12) and showed a large amount of noise at frequencies abcve 0.5 Hz in the data used. Reliable values at frequencies below 0.01 Hz could not be obtained by the efficient FFT procedure without having records longer than the 17.07 minutes used.

Analysis of the structural response data was illustrated in terms of determining the effect of one input quantity (a load) on one output or response quantity (a strain) in the transmission tower system examined. The load considered was the total measured load at an I-string support fcr a conductor, and the strain considered was the longitudinal strain in one vertical leg at the base of the tower. The frequency respcnse function, H(f), and the coherence function, $\gamma_{xy}(f)$, were calculated from the power spectra of

the two individual quantities and the cross spectrum between them. The resulting functions indicated, as was expected, that the one load considered did not account to a high degree for the structural response parameter considered. There are apparently many loads in the multiple-degree-of-freedom system that contributed to the tower leg strain of interest, and there may be a measurable degree of nonlinearity between load and strain.

Another structural response parameter which can be calculated is the peak factor, K, which estimates the peak value of a random response variable in terms of the variance of that variable. For the leg strain response considered, K fell in the range expected.

5.2 Recommendations

The following recommendations for further studies are advanced.

First, more data should be recorded and further detailed analyses of the recorded data should be carried out to explore the usefulness of the analysis procedures discussed herein. Not enough computations have been carried out in this study to gain an in-depth appreciation for the accuracy or the validity of all the methods presented. In particular, several channels of data available from the OKC

site were unreliable or had high level of noise. It is noted that all field data can be expected to have some noise, and the extent to which noise problem generally will prevent useful computations and lessons about structural behavior remains to be determined. On the basis of the computations presented, the noise levels in the data need to be lower than in the data considered, or the signal levels need to be higher. Higher windspeeds approaching design windspeeds may help considerably to solve the noise problem.

Second, multiple-degree-of-freedom methods need to be used in analyzing structural response to winds. Such methods are available but they require information about the structural system which is not available for use in the present work. These analysis methods also depend on linear behavior of the system and conformity of the winds to simple statistical models (normal distribution and stationarity). The degrees to which these conditions hold for transmission tower systems need to be investigated.

Third, further study should be given to the aerodynamic admittance functions that relate to transmission tower systems. These functions can be studied as dependent on frequency, as in Ref. [20], and their agreement with simplified frequency-independent relations, as in Ref. [16], can be checked with the type of data available at the OKC

site. In particular, loads acting on transmission tower conductors, which are flexible cables with very long spans exposed to the wind, need to be understood in much more detail than at present.

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APPENDIX

LISTING OF PROGRAMS

A.1 TIMEHIST

```
C
C    PROGRAM TIMEHIST  -- FEBRUARY, 1982
C      PROGRAM TO PLOT THE TIME HISTORY OF A TIME SERIES
C      RECORDS, Y(T), AND CALCULATE ITS MEAN, STANDARD
C      DEVIATION, PEAK, INTERMEDIATE AVERAGES, AND MOVING
C      AVERAGES
C
       DIMENSION Y(16384),XLEGND(5),YLEGND(5),TITLE(10),
     1   XINT(900),YINT(900),VARINT(900),YMOVE(16384)
C
C              NOTATION:
C
C         TSPAN  = TOTAL TIME SPAN TO BE CONSIDERED, IN MIN.
C         DELTAT = TIME SPACING OF GIVEN DATA, IN SECONDS
C         TINT   = AVERAGING TIME INTERVAL FOR PLOTTING,
C                    IN SEC.
C         YINT(I)= AVERAGE OVER DISCRETE TIME INTERVAL I (OF
C                    LENGTH TINT)
C         XINT(I)= TIME AT CENTER OF DISCRETE TIME INTERVAL
C                  I
C         YPEAK  = OVERALL PEAK OF GIVEN DATA (AT SPACING
C                    DELTAT)
C         YINTPK = PEAK OFTHE DISCRETE INTERVAL AVERAGES (AT
C                    SPACING TINT)
C         YMOVE(I)=MOVING AVERAGE OVER TIME LENGTH TMOVE AT
C         TMOVE  = TIME SPAN FOR THE MOVING AVERAGE
C
C            SET DEFAULT VALUES OF PROGRAM QUANTITIES AND
C            OPTIONS                                      .
C
      DATA TSPAN,DELTAT,TINT,TMOVE /15.0, 0.0625, 2.0, 1.0/
      DATA XLEGND /'    ','    ','TIME',', MI','N.  '/
      DATA YLEGND /' MIN','DSPE','ED, ','MPH ','    '/
      DATA KTHIST,KPRINT,KPRVAL,KPRMOV /1,1,1,1/
C
C           READ EXTENT OF CALCULATIONS TO BE DONE WITH
C           KCALC
C              (KCALC = 0:  TIME HISTORY ONLY;
C                     = 1:  MOVING AVERAGE ONLY;
C                     = 2:  BOTH TIME HISTORY AND MOVING
C                           AVERAGE)
C           READ DESIRED CHANGES IN COMPUTATIONS TO BE DONE
C              (KHIST OR KMOVE NON-ZERO TO CHANGE FIRST
```

```
C                DATA LINE)
C
      READ(5,1000) KCALC,KHIST,KMOVE
 1000 FORMAT(8I10)
      IF (KHIST.EQ.0) GO TO 10
      READ(5,1010) TSPAN,DELTAT,TINT
 1010 FORMAT(8F10.3)
   10 IF(KMOVE.EQ.0) GO TO 20
      READ(5,1010) TMOVE
C
C           CAICULATE NUMBER OF DATA POINTS TO BE
C             CCNSIDERED IN TSPAN
C
   20 N = TSPAN*60./DELTAT + 0.1
C
C           READ AND ECHO PRINT DATA TO BE USED
C
      READ(5,1100) (YLEGND(I),I=1,5)
 1100 FORMAT(5A4)
      READ(1,1105) (TITLE(I),I=1,10)
 1105 FORMAT(10A4)
      READ(1,1010)  (Y(I),I=1,N)
      WRITE(6,2100) (TITLE(I),I=1,10)
 2100 FORMAT('1PROGRAM HIST - FEBRUARY, 1982'//
     1  1X,10A4,F10.5,///)
      WRITE(6,2110)
 2110 FORMAT(' FIRST PORTION OF DATA:'/)
      WRITE(6,1010) (Y(I),I=1,40)
      WRITE(6,2120) N,TSPAN
 2120 FORMAT(' ...'/' TOTAL NUMBER OF POINTS = ',I6/,
     1  ' TOTAL TIME SPAN = ', F10.2,' MINUTES'//)
C
C***** MAIN CALCULATION A.
C        IN A SINGLE PASS THROUGH THE DATA, CALCULATE THE
C        MEAN, YINT, AND THE VARIANCE, VARINT, IN EACH TIME
C        INTERVAL, PLUS COMING OUT WITH THE OVERALL MEAN,
C        VARIANCE, PEAK AT DELTAT, AND PEAK AMONG THE
C         YINT'S
C
C       1. SET UP BY FINDING THE NUMBER OF DISCRETE
C          INTERVALS NINT, AND THE NUMBER OF DELTAT POINTS
C          IN EACH, NPINT, PLUS INITIALIZING THE PEAK
C          VALUES YPEAK AND YINTPK, THE OVERALL Y SUM, THE
C          OVERALL Y-SQUARED SUM, AND THE COUNTERS WITHIN
C          EACH INTERVAL, KOUNT1 AND KOUNT
C
      IF(KCALC.EQ.1) GO TO 300
      NINT=TSPAN*60./TINT + 0.1
      NPINT=TINT/DELTAT + 0.1
      FNPINT = NPINT
      YPEAK = 0.
      YINTPK= 0.
      XINTPK= 0.
```

```
      YMIN   = C.
      YIMIN = C.
      XIMIN = C.
      YSUM   = 0.
      YSQSUM= C.
      KOUNT1=1
      KOUNT2=NPINT
C
C       2. BEGIN CYCLE OVER ALL NINT DISCRETE TIME
C            INTERVALS
C
      DO 210 I=1,NINT
      YISUM = C.
      YISSQ = 0.
C
C       3. CYCLE OVER POINTS AT DELTAT WITHIN EACH INTERVAL
C
      DO 200 J = KOUNT1,KOUNT2
      IF(Y(J).GT.YPEAK) YPEAK = Y(J)
      IF(Y(J).LT.YMIN) YMIN = Y(J)
      YISUM = YISUM + Y(J)
      YISSQ = YISSQ + Y(J)*Y(J)
  200 CONTINUE
C
C       4. FIND MEAN, YINT, AND VARIANCE, VARINT, FOR
C          INTERVAL AND ADD ITS SUMS INTO THE OVERALL SUMS
C
      XINT(I)=(FLOAT(I)-0.5)*TINT/60.
      YINT(I) = YISUM/FNPINT
      VARINT(I) = (YISSQ - YISUM*YISUM/FNPINT)/(FNPINT-1.)
      YSUM = YSUM + YISUM
      YSQSUM = YSQSUM + YISSQ
      IF(YINT(I).LE.YINTPK) GO TO 202
      YINTPK = YINT(I)
      XINTPK = XINT(I)
      GO TO 206
  202 IF(YINT(I).GE.YIMIN) GO TO 206
      YIMIN = YINT(I)
      XIMIN = XINT(I)
C
C       5. INCREMENT COUNTERS AND END LOOP OVER INTERVALS
C
  206 KOUNT1=KCUNT1 + NPINT
      KOUNT2=KCUNT2 + NPINT
  210 CONTINUE
C
C       6. CALCULATE THE OVERALL MEAN, VARIANCE AND
C          STANDARD DEVIATION
C
      FN=N
      YBAR = YSUM/FN
      SIGSQ = (YSQSUM - YSUM*YSUM/FN)/(FN-1.)
      SIGMA = SQRT(SIGSQ)
```

```
C
C         7. REVERSE SIGNS IF YBAR IS NEGATIVE
C
      IF(YBAR.GE.0) GO TO 300
      YBAR  = - YBAR
      YTEMP = YPEAK
      YPEAK = - YMIN
      YMIN  = - YTEMP
      YTEMP = YINTPK
      YINTPK= - YIMIN
      YIMIN = - YTEMP
      XTEMP = XINTPK
      XINTPK= XIMIN
      XIMIN = XTEMP
      DO 220 I=1,NINT
  220 YINT(I) = - YINT(I)
C
C****** MAIN CALCULATION B.
C         DETERMINE A MOVING AVERAGE OF THE DATA OVER A
C         TIME WINDOW OF TMOVE SECONDS
C
C         1. START BY DETERMINING THE NUMBER OF POINTS IN THE
C            MOVING AVERAGE, NPMOVE, AND CALCULATING THE INI-
C            TIAL SUM, YMSUM, AND AVERAGE, YMOVE(1)
C
  300 IF(KCALC.EQ.0) GO TO 400
      NPMOVE = TMOVE/DELTAT +0.1
      FNPM = NPMOVE
      NSTOP = N - NPMOVE
      YMSUM = 0.
      DO 305 I=1,NPMOVE
  305 YMSUM = YMSUM + Y(I)
      YMOVE(1) = YMSUM/FNPM
C
C         2. FOR EACH REMAINING DELTAT, OBTAIN THE MOVING SUM
C            BY DROPPING THE REAR Y AND ADDING THE FORWARD Y,
C            THEN FIND THE AVERAGE BY DIVIDING BY NPMOVE (=FN
C
      DO 310 I=1,NSTOP
      YMSUM = YMSUM - Y(I) +Y(I+NPMOVE)
  310 YMOVE(I+1) = YMSUM/FNPM
C
C***** OUTPUT OF RESULTS
C
  400 IF(KCALC.EQ.1) GO TO 410
      IF(KPRINT.EQ.0) GO TO 410
C
C         1. PRINT OVERALL RESULTS ALWAYS AND OTHERS ON OPTION
C
      WRITE(6,4000)(TITLE(I),I=1,10)
 4000 FORMAT('1RESULTS FOR ',10A4//)
      WRITE(6,4010) YBAR,SIGSQ,SIGMA,YPEAK,YINTPK,XINTPK
 4010 FORMAT(' MEAN, YBAR',17X,'= ',F10.3,/' VARIANCE,',
```

```
     0' SIGSQ',
     112X,'= ',F10.3/' STD. DEVIATION, SIGMA',6X,'= ',F10.3
     2/' INSTANT PEAK, YPEAK',8X,'= ',F10.3/' PEAK',
     3' DISCRETE MEAN,'
     4' YINTPK = ',F10.3/' CORRESPONDING TIME, XINTPK = ',
     5  F10.3//)
      IF(KPRVAL.EQ.0) GO TO 410
      WRITE(6,4020) TINT
 4020 FORMAT(' AVERAGES OVER ',F8.2, ' SECOND INTERVALS:'//
     1  ' INTERVAL   TIME (MIN)  INTERVAL MEAN'/)
      WRITE(6,4030)((I,XINT(I),YINT(I)),I=1,NINT)
 4030 FORMAT(I10,2F10.3)
C
C       2. PRINT MOVING AVERAGE VALUES ON OPTION
C
  410 IF(KCALC.EQ.0) GO TO 500
      IF(KPRMOV.EQ.0) GO TO 500
      WRITE(6,4050) TMOVE
 4050 FORMAT(///' MOVING AVERAGES FOR A ',F8.2,' SECOND',
     0' INTERVAL:'//,
     1  ' INTERVAL (AT DELTAT)   MOVING AVERAGE'//)
      WRITE(6,4060)((I,YMOVE(I)),I=1,100)
 4060 FORMAT(I15,F10.3)
C
C         PLOT TIME HISTORY WITH THPLOT
C
  500 IF(KCALC.EQ.1) CALL EXIT
      CALL THPLOT(XINT,YINT,NINT,TITLE,YLEGND,XLEGND,31,
     1  YBAR,SIGMA,YPEAK,YINTPK,XINTPK)
      CALL EXIT
      END
```

```
      SUBROUTINE ASCALE (YMAX,YINC,YTOP,NUM)
C
C     CALCULATION OF AN EVEN AXIS INCREMENENT (YINC) AND TOP
C     VALUE (YTOP) FOR PLOTTING ON EITHER AXIS ACCORDING TO
C     THE POWER OF TEN AND DECADE INTO WHICH THE MAXIMUM
C     VALUE (YMAX) FALLS
C
      DIV=1.E5
      DO 10 N=1,11
      TRIAL=YMAX/DIV
      IF(TRIAL.GT.1.0) GO TO 20
   10 DIV=DIV/10.
      GO TO 30
C
C     CHECK IF YMAX IS OUTSIDE THE SCALE RANGES CONSIDERED
C     (10**-5 TO 10**5); IF SO USE UNEVEN SCALE
C
   20 IF(N.EQ.1) GO TO 30
      YINC=10.**(6-N)
      NUM=YMAX/YINC+1
      YTOP=FLOAT(NUM)*YINC
      RETURN
C
C     YMAX OUTSIDE RANGE CONSIDERED
C
   30 WRITE(6,1030) YMAX
 1030 FORMAT('0ERROR IN ASCALE: YMAX = ',E20.6/)
      YINC=YMAX/10.
      YTOP=YMAX
      RETURN
      END
```

```
      SUBROUTINE THPLOT(X,Y,NINT,TITLE,YLEGND,XLEGND,IFILE,
     1  YBAR,SIGMA,YPEAK,YINTPK,XINTPK)
      DIMENSION X(900),Y(900),TITLE(10),YLEGND(5),
     1  XLEGND(5),XREF(11),YREF(11)
C
C     PLOT GRAPH OF TIME HISTORY WITH HOUSTON PLOTTER CALLS,
C     USING THAXIS FOR LINEAR X AND Y AXES
C
C         INITIATE FOR NEW PLOT AND SET ORIGIN
C
      CALL PLOTS(0.0,0.0,IFILE)
      CALL FACTOR(1.)
      CALL PLOT(2.0,1.5,-3)
C
C       DRAW AND LABEL ABSCISSA WITH SCALING
C
C          A. FIND EVEN INCREMENTS, XINC, LIMITING VALUE,
C             XLIM, AND NUMBER OF TIC MARKS, NXTICS, FOR X
C             AXIS
C
      CALL ASCALE(X(NINT),XINC,XLIM,NXTICS)
C
C          B. COMPUTE SCALE FACTOR, FX, AND TIC LENGTH,
C             XTICL,FOR X AXIS AND DRAW IT
C
      FX=XLIM/8.
      XTICL=8.0*XINC/XLIM
      CALL THAXIS(0.14,NXTICS,0.0,XINC,XTICL,XLEGND)
C
C         DRAW AND LABEL ORDINATE WITH SCALING
C
C           A. FIND EVEN INCREMENTS, YINC, LIMITING VALUE,
C              YLIM, AND NUMBER OF TIC MARKS, NYTICS, FCR Y
C              AXIS
C
      CALL ASCALE(YINTPK,YINC,YLIM,NYTICS)
C
C           B. COMPUTE SCALE FACTOR, FY, AND TIC LENGTH,
C              YTICL, FOR Y AXIS AND DRAW IT
C
      FY=YLIM/5.5
      YTICL=5.5*YINC/YLIM
      CALL THAXIS(0.14,NYTICS,90.0,YINC,YTICL,YLEGND)
C
C         COMPUTE SCALE FACTORS FOR PLOTTING X AND Y
C           VALUES AND PLOT LINE
C
   70 X(NINT+1)=0.0
      X(NINT+2)=FX
      Y(NINT+1)=0.0
      Y(NINT+2)=FY
      CALL LINE(X,Y,NINT,1,0,1)
C
```

```
C          PLOT AND LABEL THE MEAN, MEAN + SIGMA, AND MEAN -
C          SIGMA, USING XREF AND YREF VECTORS, STARTING WITH
C          THE MEAN
C
      NREF=9
      XFACT=X(NINT)/8.0
      DO 80 I=1,NREF
      XREF(I)=XFACT*FLOAT(I-1)
   80 YREF(I)=YBAR
      XREF(NREF+1)=0.0
      XREF(NREF+2)=FX
      YREF(NREF+1)=0.0
      YREF(NREF+2)=FY
      CALL LINE(XREF,YREF,NREF,1,0,1)
      XL1=X(NINT)/FX + 0.1
      YL1=YBAR/FY-0.1
      CALL SYMBOL(XL1,YL1,.14,'MEAN = ',0.0,7)
      XL2=XL1+0.9
      CALL NUMBER(XL2,YL1,.14,YBAR,0.0,1)
C          B. CHANGE LEVEL OF LINE TO YBAR + SIGMA AND PLOT
      DO 82 I=1,NREF
   82 YREF(I)=YBAR+SIGMA
      CALL LINE(XREF,YREF,NREF,1,1,4)
      YL1=YREF(NREF)/FY-0.1
      CALL SYMBOL(XL1,YL1,.14,'MEAN+SIGMA = ',0.0,13)
      XL2=XL1+1.5
      CALL NUMBER(XL2,YL1,.14,YREF(NREF),0.0,1)
C          C. CHANGE LEVEL OF LINE TO YBAR - SIGMA AND PLOT
      DO 84 I=1,NREF
   84 YREF(I)=YBAR-SIGMA
      CALL LINE(XREF,YREF,NREF,1,1,4)
      YL1=YREF(NREF)/FY-0.1
      CALL SYMBOL(XL1,YL1,.14,'MEAN-SIGMA = ',0.0,13)
      CALL NUMBER(XL2,YL1,.14,YREF(NREF),0.0,1)
C
C          LABEL INTERVAL PEAK, YINTPK
C
      XPEAK = XINTPK/FX+0.1
      YPEAK = YINTPK/FY-.07
      CALL SYMBOL (XPEAK,YPEAK,0.14,'- INTERVAL PEAK = ',
                   0.0,18)
      XPEAK = XPEAK + 2.1
      CALL NUMBER(XPEAK,YPEAK,0.14,YINTPK,0.0,1)
C
C          PRINT GENERAL PLOT INFORMATION FROM MIDDLE TO
C          UPPER RIGHT PORTION OF THE PLOT
C
      XTITLE=3.2
      YTITLE=5.7
      CALL SYMBOL(XTITLE,YTITLE,0.14,TITLE,0.0,40)
C
C          TERMINATE THIS PLOT
C
```

```
      CALL PLCT(0.0,0.0,999)
C
      RETURN
      END
```

```
      SUBROUTINE THAXIS (SIZE,NUM,THETA,YINC,F,AXLEGD)
      DIMENSION X1(10),Y1(10),X(10),Y(10),FNUM(50),
     1          AXLEGD(5)
      DATA X1/0.,0.,1.,1./,Y1/-0.14,0.,0.,-0.14/
      NDEC=2
      IF(YINC.GT.1.) NDEC=0
      HSIZE=1.5*SIZE
      HSHIFT=4.*HSIZE
      X(5)=0.0
      X(6)=1.0
      Y(5)=0.0
      Y(6)=1.0
      NUM1=NUM+1
      DO 105 I=1,NUM1
  105 FNUM(I)=YINC*(I-1)
      XLABEL=-0.2
      YLABEL=-0.40
      IF(THETA.EQ.0.0) GO TO 107
      YLABEL=-0.26
      CALL NUMBER(YLABEL,XLABEL,SIZE,FNUM(1),THETA,NDEC)
      GO TO 108
  107 CALL NUMBER(XLABEL,YLABEL,SIZE,FNUM(1),THETA,NDEC)
  108 DO 125 J=1,NUM
      DO 110 I=1,4
      Y(I)=Y1(I)
      X(I)=0.
  110 X(I)=(X1(I)+J-1)*F
      IF (THETA.EQ.0.0) GO TO 115
      CALL LINE(Y,X,4,1,0,0)
      GO TO 117
  115 CALL LINE (X,Y,4,1,0,0)
  117 XLABEL=X(4)-0.2
      YLABEL=Y(4)-0.26
      J1=J+1
      IF(THETA.EQ.0.0) GO TO 120
      YLABEL=Y(4)-0.12
      CALL NUMBER(YLABEL,XLABEL,SIZE,FNUM(J1),THETA,NDEC)
      GO TO 125
  120 CALL NUMBER(XLABEL,YLABEL,SIZE,FNUM(J1),THETA,NDEC)
  125 CONTINUE
      XL=(FLOAT(NUM)/2.-HSHIFT)*F
      YL=-HSHIFT
      IF(THETA.EQ.0.0) GO TO 130
      YL=0.14-HSHIFT
      CALL SYMBOL(YL,XL,HSIZE,AXLEGD,THETA,20)
      GO TO 140
  130 CALL SYMBOL(XL,YL,HSIZE,AXLEGD,THETA,20)
  140 RETURN
      END
/*
//GO.FT01F001 DD DSN=WYL.PV.UND.DLCH45,DISP=SHR,
//   VOL=SER=TPPAK1,DCB=(LRECL=80,BLKSIZE=3120,RECFM=FB),
//   UNIT=DASD
```

```
//GO.FT31F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.THL45.HOLD
//GO.SYSIN DD *

STRAIN GAGE VAIUE
//
```

A.2 HISTGRAM

```
C
C  HISTGRAM -- JULY, 1982
C    PROGRAM TO COMPUTE THE FREQUENCIES OF OCCURENCE OF
C    DIFFERENT DATA VALUES, Y, AND STORE THEM FOR PLOTTING
C    THE HISTOGRAM WITH A SEPARATE SAS PROGRAM
C
      DIMENSION D(16384),Y(16384),X(500),TITLE(10),XX(500)
C
C        SET DEFAULT VALUES OF PROGRAM QUANTITIES AND
C        OPTIONS AND PREPARE TO PLOT
C          IFILE1 FOR SPEED (XX(I)), IFILE2 FOR FREQUENCIES
C          (D(I)), USE THE SAME DATA NAME TO SAVE STORAGE
C
      DATA IFILE1,IFILE2/2,3/
      DATA NUM/30/
C
C          READ AND ECHO PRINT DATA FILE HEADER INFORMATION
C
   30 READ(1,1020) (TITLE(I),I=1,10),DELT,N
 1020 FORMAT(10A4,F10.5,I10)
      WRITE(6,1030) TITLE,DELT,N
 1030 FORMAT('1PROGRAM HISTOGRAM - SEP., 1982'//
     2  1X,10A4,F10.5,I10/)
      IF(WS.EQ.1.) GO TO 40
      READ(1,1035) ICHAN,NREC,ZERO,CALIB,IDUR
 1035 FORMAT(2I5,2E15.6,I5)
      WRITE(6,1037)ICHAN,NREC,ZERO,CALIB,IDUR
 1037 FORMAT('0ORIGINAL HEADER INFORMATION ON O.U. TAPE:'/,
     1  '   ICHAN    NREC    ZERO              CALIB          ',
     2  'IDUR'/,2I8,2E15.6,I5////)
C
C          READ (AND ECHO PRINT FIRST PART OF) DATA, D(I),
C          AT EQUALLY SPACED INTERVALS
C
   40 READ(1,1040) (D(I),I=1,N)
 1040 FORMAT(8F10.5)
      WRITE(6,1045)
 1045 FORMAT(' DATA'/)
      WRITE(6,1040) (D(I),I=1,40)
      WRITE(6,1047)  N
 1047 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
C
C        FIND DMAX, DMIN AND CALCULATE FREQUENCIES Y(I)
C
      DMAX = D(1)
      DMIN = D(1)
      DO 90 J=2,N
      IF(DMAX.GE.D(J)) GO TO 80
```

```
      DMAX = D(J)
   80 IF(DMIN.LE.D(J)) GO TO 90
      DMIN = D(J)
   90 CONTINUE
      DX = (DMAX-DMIN)/FLOAT(NUM)
      DO 110 J=1,NUM
      X(J) = DMIN+DX*(J-1)
      Y(J) = 0.
  110 CONTINUE
      DO 120 I=1,N
      J = (D(I)-DMIN)/DX+1
      Y(J) = Y(J)+1
  120 CONTINUE
      Y(NUM) = Y(NUM) + 1
C
C       TRANSFORM X(I) AND Y(I) SO THAT SAS CAN PLOT IT
C       INTO HISTOGRAM
C
      DO 410 I=1,NUM
      I4 = 4*I
      I3 = I4-1
      I2 = I4-2
      I1 = I4-3
      XX(I1) = X(I)
      XX(I2) = X(I)
      XX(I3) = X(I)+DX
      XX(I4) = XX(I3)
      D(I1)  = 0.
      D(I2)  = Y(I)
      D(I3)  = Y(I)
      D(I4)  = 0.
  410 CONTINUE
      NUM4 = 4*NUM
      WRITE(IFILE1,1040) (XX(I),I=1,NUM4)
      ENDFILE IFILE1
      WRITE(IFILE2,1090) (D(I),I=1,NUM4)
      ENDFILE IFILE2
 1090 FORMAT(8F10.2)
C
C          PRINT AND STORE DESIRED INFORMATION
C
  300 WRITE(6,2000)
 2000 FORMAT('1HISTOGRAM FREQUENCIES AND VALUES '/)
      WRITE(6,2010) TITLE
 2010 FORMAT(' ',10A4//'  FREQUENCY    DATA VALUE')
      WRITE(6,2020)
 2020 FORMAT('    ( NO. )      ( D UNITS)'/)
      WRITE(6,2030) ((Y(J),X(J)),J=1,NUM)
 2030 FORMAT(F10.4,F14.4)
      WRITE(6,2040) NUM
 2040 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
      CALL EXIT
      END
```

```
/*
//GO.SYSIN DD *

/*
//GO.FT01F001 DD DSN=WYL.PV.UND.D,DISP=SHR,UNIT=DASD,
//  VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,BLKSIZE=3120)
//GO.FT02F001 DD DSN=WYL.PV.UND.S,DISP=(NEW,CATLG,DELETE),
//  UNIT=DASD,VCL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,
//  BLKSIZE=3120),SPACE=(TRK,(10,1))
//GO.FT03F001 DD DSN=WYL.PV.UND.F,DISP=(NEW,CATLG,DELETE),
//  UNIT=DASD,VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,
//  BLKSIZE=3120),SPACE=(TRK,(10,1))
/*
//
```

```
*
*    COMMENT: SAS PROGRAM TO PLOT HISTOGRAM
*
// EXEC SAS,PLOT='PLT.PV.UND.HIS31011.HOLD'
//FIRST DD DSN=WYL.PV.UND.FRE11011,UNIT=DASD,DISP=SHR,
//   VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,BLKSIZE=3120)
//SECON DD DSN=WYL.PV.UND.SPE11011,UNIT=DASD,DISP=SHR,
//   VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,BLKSIZE=3120)
//SYSIN DD *
GOPTIONS COLORS=(BLACK,BLUE,RED) HSIZE=11.0 VSIZE=8.0
     HPOS=50 VPOS=36;
DATA YYFREQ;
DO XX=13.788 TO 40.BY 0.29023;
  YY=.399/3.996*EXP(-(XX-26.82)**2./(2.*3.996**2.))*14268.;
OUTPUT;END;
DATA FREQ;
  INFILE FIRST;
    INPUT Y @ @;
      LABEL Y=FREQ.;
DATA SPEED;
  INFILE SECON;
    INPUT X @ @;
      LABEL X=SPEED;
DATA NEW; MERGE FREQ SPEED YYFREQ;
TITLE HISTOGRAM OF WINDSPEED AT MT4,60FT. ;
PROC PRINT;
PROC GPLOT;
PLOT Y*X=1 YY*XX=2/OVERLAY HAXIS=13 TO 43 BY 3 VAXIS=0. TO
  2400 BY 400;
    SYMBOL1 I=JOINT;
    SYMBOL2 I=I3;
//
```

A.3 STATCHEK

```
C
C   PROGRAM STATCHEK----FOR LEVEL OF SIGNIFICANCE EQUALS
C                        TO 0.05
C
      DIMENSION X(512),XBAR(20),D1(20),D2(20),DAVG(20),
     1          IA(20),ITITLE(10)
C-------P1 IS CUMULATIVE PDF FOR ALPHA EQUAL TO 0.05
      DATA P1/1.96/
      READ(5,1010)  (ITITLE(I),I=1,10),L,M,N
      READ(5,1020)  (X(I),I=1,L)
      WRITE(6,1030) (ITITLE(I),I=1,10),L,M,N
      WRITE(6,1005)
 1005 FORMAT(/'0X  =')
      WRITE(6,1035) (X(I),I=1,10)
 1010 FORMAT(10A4,3I5)
 1020 FORMAT(8F10.3)
 1030 FORMAT('1PROGRAM RUNTEST - FEBRUARY, 1982'////1X,
     1 10A4/////' DATA NUMBER   DATA PER INTERVAL   ',
     2 'INTERVALS'//5X,I5,10X,I5,13X,I5//)
 1035 FORMAT(1X,8F10.3)
      WRITE(6,1037) L
 1037 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I5)
C
C-------CALCULATE XBAR, SIBMASQ AND XMEAN
C
      N1 = N-1
      DO 10 I=1,N1
      SUMX=0.
      DO  9 J=1,M
      JM=I*M-M+J
    9 SUMX=SUMX+X(JM)
      XBAR(I)=SUMX/M
   10 CONTINUE
      MN1=M*N1
      MN =MN1+1
      SUMX = C.
      DO 15 I=MN,L
      SUMX = SUMX+X(I)
      XBAR(N) = SUMX/(L-MN1)
   15 CONTINUE
      WRITE(6,1040)
 1040 FORMAT(/'0XBAR  ='/)
      WRITE(6,1050) (XBAR(I),I=1,N)
 1050 FORMAT(1X,8F10.3)
      XBASUM=0.
      XSQSUM=0.
      DO 20 I=1,N
      XBASUM=XBASUM+XBAR(I)
```

```
   20 XSQSUM=XSQSUM+XBAR(I)*XBAR(I)
      XMEAN=XBASUM/N
      SIGSQ=(XSQSUM-XBASUM*XBASUM/N)/(N-1)
      WRITE(6,1060) XMEAN,SIGSQ
 1060 FORMAT(/'0MEAN     = ',F10.3/'0VARIANCE = ',F12.4//)
C
C-------RUN TEST
C        LARGE    NUMBER OF X VALUES LARGER THAN MEAN VALUE
C        SMALL    NUMBER OF X VALUES SMALLER THAN MEAN VALUE
C        R        LARGE PLUS SMALL
C
      LARGE=0
      ISMALL=0
      IF(XBAR(1)-XMEAN) 120,110,110
  110 LARGE=1
      II=2
      GO TO 130
  120 ISMALL=1
      II=2
      GO TO 160
  130 IF(XBAR(II)-XMEAN) 150,140,140
  140 II=II+1
      IF(II.GT.N) GO TO 190
      GO TO 130
  150 ISMALL=ISMALL+1
      II=II+1
      IF(II.GT.N) GO TO 190
      GO TO 160
  160 IF(XBAR(II)-XMEAN) 170,180,180
  170 II=II+1
      IF(II.GT.N) GO TO 190
      GO TO 160
  180 LARGE=LARGE+1
      II=II+1
      IF(II.GT.N) GO TO 190
      GO TO 130
  190 IR=LARGE+ISMALL
      WRITE(6,1070) LARGE,ISMALL,IR
      RMEAN = FLOAT(N)/2.+1.
      RSIGSQ = FLOAT(N*(N-2))/4./(FLOAT(N)-1.)
      RDEVIA = P1*RSIGSQ**.5
      L1 = IFIX(RMEAN-RDEVIA)
      LL = IFIX(RMEAN+RDEVIA)
      IF(IR.GT.L1.AND.IR.LE.LL)  GO TO 194
      IF(IR.LE.L1.OR.IR.GT.LL)  GO TO 195
  194 WRITE(6,1072) L1,LL
      GO TO 196
  195 WRITE(6,1073) L1,LL
 1070 FORMAT(/'1RUN  TEST '///
     1 '0LARGE =   ',I6/'  SMALL =   ',I6/'   R   =   ',I7/)
 1072 FORMAT(/'0RUN TEST IS OK.  (',I4,' < R < = ',I4,' )')
 1073 FORMAT(/'0RUN TEST IS N.G.  ( R < = ',I4,' , OR ',
     1 'R > ',I4,')')
```

```
  196 CONTINUE
C
C--------TREND TEST
C         H(I,J)=1, IF X(I).GT.X(J)          H(I,J)=0, OTHERWISE
C         A(I)=SUM(H(I,J))                   A=SUM(A(I))
C
      ISUMA=0
      N1=N-1
      DO 230 I=1,N1
      IA(I)=0
      J=I+1
  200 IF(XBAR(I)-XBAR(J)) 210,210,220
  210 J=J+1
      IF(J.GT.N) GO TO 230
      GO TO 200
  220 IA(I)=IA(I)+1
      J=J+1
      IF(J.GT.N) GO TO 230
      GO TO 200
  230 ISUMA=ISUMA+IA(I)
      WRITE(6,1075)
      N1 = N-1
      WRITE(6,1080)(IA(I),I=1,N1)
      WRITE(6,1090) ISUMA
      TMEAN = FLOAT(N*(N-1))/4.
      TSIGSQ = FLOAT(N*(2*N+5)*(N-1))/72.
      TDEVIA = P1*TSIGSQ**.5
      L1 = IFIX(TMEAN-TDEVIA)
      LL = IFIX(TMEAN+TDEVIA)
      IF(ISUMA.GT.L1.AND.ISUMA.LE.LL) GO TO 240
      IF(ISUMA.LE.L1.OR.ISUMA.GT.LL) GO TO 250
  240 WRITE(6,1092) L1,LL
      GO TO 260
  250 WRITE(6,1093) L1,LL
 1075 FORMAT(/'1TREND  TEST '//' A(I)=')
 1080 FORMAT(1X,8I10)
 1090 FORMAT(/'0A  =  ',I10)
 1092 FORMAT(/'0TREND TEST IS OK.  ( ',I4,' < A < = ',I4,
     1 ' )')
 1093 FORMAT(/'0TREND TEST IS N.G.  (A <=',I4,', OR A >',
     1 I4,' )')
  260 CONTINUE
      CALL EXIT
      END
```

A.4 PSCROS

```
C
C   PSCROS  --  JANUARY, 1982
C     PROGRAM TC COMPUTE THE POWER SPECTRA ,CROSS SPECTRUM,
C     FREQUENCY RESPONSE FUNCTION, COHERENCE FUNCTION AND
C     PHASE ANGLE OF TWO VECTORS, Y1(T) AND Y2(T), AND
C     PLOT THEM WITH HOUSTON PLOTTER INSTRUCTIONS
C     (PLOT CAN ALSO BE DONE ON TEKTRONIX)
C
      DIMENSION Y1(16384),Y2(16384),PSY1( 520),PSY2( 520),
     1  FREQ( 520),FLOG( 520),PSCAL1( 520),TITLE(10),
     2  PSCRSC(520),PHASE(520),COHR(520),FRESP(520),
     3  PSCROS(1026),IWK(33),WK(1024),PSCAL2(520),PSO(520)
      COMPLEX CWK(1026)
C
C         SET DEFAULT VALUES OF PROGRAM QUANTITIES AND
C         OPTICNS AND PREPARE TO PLOT
C
      DATA WS /0./
      DATA L,IND /1024,1/
      DATA KPROR,KPRLIN,KPRLOG /0,0,1/
      DATA KPLOR,KPLLIN,KPLLOG /0,0,1/
      DATA KDUPAX/1/
      DATA LCODE,NSYMB /0,1/
C
C         READ DESIRED CHANGES IN COMPUTATION, PRINT, AND
C         PLOT PROCEDURES
C
    1 READ(5,1000) KCOMP,KPRINT,KPLOT
 1000 FORMAT(8I10)
      IF(KCOMP.EQ.0) GO TO 10
      READ(5,1010) L
 1010 FORMAT(I10)
   10 IF(KPRINT.EQ.0) GO TO 20
      READ(5,1010) KPROR,KPRLIN,KPRLOG
   20 IF(KPLOT.EQ.0) GO TO 30
      READ(5,1010) KPLOR,KPLLIN,KPLLOG
C
C       CALL SUBROUTINE CALC TO CENTER THE TIME SERIES
C
   30 CALL CALC(1,Y1,SIGSQ1,DELT,N,TITLE,NPAD,L,WS)
      CALL CALC(2,Y2,SIGSQ2,DELT,N,TITLE,NPAD,L,WS)
C
C           CALL SUBROUTINE TO OBTAIN POWER SPECTRUM
C           IN UNITS OF Y1 SQUARED
C
      WRITE(6,1085)L,N,NPAD,IND,Y1(1),Y2(1)
 1085 FORMAT(' CHECK PRINT PRIOR TO CALLING FTFPS ',
     1  'SUBRCUTINE:'/8X,'L',9X,'N',7X,'NPAD',8X,'IND',3X,
```

```
     2   'Y1(1)',6X,'Y2(1)'/4I10,2F10.5)
         CALL FTFPS(Y1,Y2,NPAD,L,IND,PSY1,PSY2,PSCROS,IWK,WK,
        1CWK,IER)
C
C            CALCULATE FREQUENCIES, COHERENCE AND SPECTRAL
C            ORDINATES IN REAL UNITS
C
         NFREQ = L/2 + 1
         IF(WS.EQ.1.) GO TO 80
         DO 70 J=1,NFREQ
         NFRJ = NFREQ+J
         PHASE(J) = PSCROS(NFRJ)
      70 COHR(J) = PSCROS(J)/PSY1(J)/PSY2(J)
      80 DO 90 J=1,NFREQ
         FREQ(J) = (FLOAT(J)-1.)/(FLOAT(L)*DELT)
         PSY1(J) = PSY1(J) * DELT
      90 PSY2(J) = PSY2(J) * DELT
C
C            SCALE SPECTRUM ORDINATES TO FREQ*PSY1/SIGSQ
C
         DO 100 J=1,NFREQ
         PSCAL1(J) = FREQ(J)*PSY1(J)/SIGSQ1
     100 PSCAL2(J) = FREQ(J)*PSY2(J)/SIGSQ2
     102 SIG12 = (SIGSQ1*SIGSQ2)**0.5
         DO 103 J=1,NFREQ
         PSCROS(J) = (PSCROS(J))**0.5 * DELT
         PSCRSC(J) = FREQ(J)*PSCROS(J)/SIG12
     103 CONTINUE
C
C            CALCULATE LOGRITHM OF FREQUENCIES AND FREQ.
C            RESPONSE FUNCTION
C
     104 FLOG(1) = 0.0
         FRESP(1) = PSCROS(1)/PSY1(1)
         DO 105 J=2,NFREQ
         FRESP(J) = PSCROS(J)/PSY1(J)
     105 FLOG(J)=ALOG10(FREQ(J))
C
C          CALCULATE SY(W) (OUTPUT SPECTRAL DENSITY BY FREQ.
C          RESPONSE FUNCTION AND INPUT SPECTRAL DENSITY) AND
C          ITS AREA
C
         DO 95 I=1,NFREQ
         PSO(I) = PSY1(I)*FRESP(I)**2.
      95 CONTINUE
         ASUM = (PSO(1)+PSO(NFREQ))/2.
         NFREQ1 = NFREQ-1
         DO 96 I=2,NFREQ1
      96 ASUM = ASUM+PSO(I)
         A = ASUM*FREQ(2)*2.
         ASUM1 = PSO(NFREQ)*FREQ(NFREQ)**2./2.
         DO 97 I=2,NFREQ1
      97 ASUM1 = ASUM1+PSO(I)*(FREQ(I))**2.
```

```
      A1 = ASUM1*FREQ(2)*2.
      V = (A1/A)**.5
      WRITE(6,1110) A,A1,V
 1110 FORMAT(//' CALCULATE CYCLING RATE '/
     1    ' AREA (OUTPUT SPECTRUM)                    = ',F20.5/
     2    ' AREA (MULTIPLIED BY FREQ. SQUARE)  = ',F20.5/
     3    ' CYCLING RATE                                = ',F20.5//)
C
C          PRINT AND STORE DESIRED INFORMATION
C
C     A. PRINT ORIGINAL POWER SPECTRUM (UNSCALED)
C
      IF(KPROR.EQ.0) GO TO 110
      WRITE(6,2000)
 2000 FORMAT('1POWER SPECTRUM FREQUENCIES AND VALUES -',
     1  ' UNSCALED'/)
      WRITE(6,2010) TITLE
 2010 FORMAT('  ',10A4//'  FREQUENCY        SPECTRUM VALUE')
      WRITE(6,2020)
 2020 FORMAT('    (HERTZ)      (SQ. OF Y1 UNITS)'/)
      WRITE(6,2030) ((FREQ(J),PSCROS(J)),J=1,40)
 2030 FORMAT(F10.4,F14.4)
      WRITE(6,2040) NFREQ
 2040 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
C
C  B. PRINT SCALED POWER SPECTRUM ON LINEAR FREQUENCY AXIS
C
  110 IF(KPRLIN.EQ.0) GO TO 120
      WRITE(6,2100)
 2100 FORMAT('1SCALED POWER SPECTRUM ON LINEAR FREQEUENCY',
     1  ' AXIS'/)
      WRITE(6,2010) TITLE
      WRITE(6,2120)
 2120 FORMAT('    (HERTZ)          (HERTZ)'/)
      WRITE(6,2030) ((FREQ(J),PSCRSC(J)),J=1,40)
      WRITE(6,2130) NFREQ
 2130 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
C
C     C. PRINT SCALED POWER SPECTRUM ON LCG FREQUENCY AXIS
C
  120 IF(KPRLOG.EQ.0) GO TO 200
      WRITE(6,2200)
 2200 FORMAT('1SCALED POWER SPECTRUM ON LOG FREQUENCY',
     1  ' AXIS'/)
      WRITE (6,2010) TITIE
      WRITE(6,2220)
 2220 FORMAT(' (LOG HERTZ)        (HERTZ)'/)
      WRITE(6,2030) ((FLOG(J),PSCRSC(J)),J=1,40)
      WRITE(6,2230) NFREQ
 2230 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
      WRITE(6,2300)
 2300 FORMAT('1PHASE ANGLE OF CROSS SPECTRUM ON LOG',
     1  'FREQUENCY AXIS'/)
```

```
      WRITE (6,2010) TITLE
      WRITE(6,2320)
 2320 FORMAT(' (LOG HERTZ)        (NONE)'/)
      WRITE(6,2030) ((FLOG(J),PHASE(J)),J=1,40)
      WRITE(6,2230) NFREQ
      WRITE(6,3100)
      WRITE(6,3110) COHR
      WRITE(6,3120)
      WRITE(6,3110) FRESP
 3100 FORMAT(' COHERENCE FUNCTION'//)
 3110 FORMAT(1X,8F13.5)
 3120 FORMAT(' FREQUENCY RESPONSE FUNCTION')
C
C           PLOT DESIRED INFORMATION
C
  200 IF(KPLLOG.EQ.0) GO TO 300
      KLOGAX=1
      FLOG(1)   = FLOG(2)
      PSCAL1(1) = PSCAL1(2)
      PSCAL2(1) = PSCAL2(2)
      PSCRSC(1)= PSCRSC(2)
      PHASE(1) = PHASE(2)
      COHR(1) = COHR(2)
      FRESP(1) = FRESP(2)
      CALL PSPLOT(FLOG,PSCAL1,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,13,KLOGAX,-3,2.)
      CALL PSPLOT(FLOG,PSCAL2,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,14,KLOGAX,0,1.)
      CALL PSPLOT(FLOG,PSCRSC,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,15,KLOGAX,0,1.)
      CALL PSPLOT(FLOG,PHASE,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,16,KLOGAX,0,1.)
      CALL PSPLOT(FLOG,COHR,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,17,KLOGAX,0,1.)
      CALL PSPLOT(FLOG,FRESP,NFREQ,LCODE,NSYMB,KDUPAX,
     1  TITLE,18,KLOGAX,0,1.)
  300 CALL EXIT
      END
```

```
      SUBROUTINE CALC(NR,Y1,SIGSQ,DELT,N,TITLE,NPAD,L,WS)
      DIMENSION Y1(400),Y2(400),TITLE(10)
C
C    SUBROUTINE TO CENTER THE TIME SERIES
C       READ AND ECHO PRINT DATA FILE HEADER INFORMATION
C       TITLE -- TITLE OF TIME SERIES
C       DELT  -- TIME INTERVAL OF DATA
C       N     -- TOTAL NUMBER OF DATA
C
   30 READ(NR,1020)(TITLE(I),I=1,10),DELT,N
 1020 FORMAT(10A4,F10.5,I10)
      WRITE(6,1030) TITLE,DELT,N
 1030 FORMAT('1PROGRAM PSPEC - JANUARY, 1982'//
     2  1X,10A4,F10.5,I10/)
      IF(WS.EQ.1.) GO TO 40
      READ(NR,1035)ICHAN,NREC,ZERO,CALIB,IDUR
 1035 FORMAT(2I5,2E15.6,I5)
      WRITE(6,1037)ICHAN,NREC,ZERO,CALIB,IDUR
 1037 FORMAT('0ORIGINAL HEADER INFORMATION ON O.U. ',
     1'TAPE:'/,'   ICHAN    NREC   ZERO           CALIB  ',
     2  '       IDUR'/,2I8,2E15.6,I5///)
C
C          READ (AND ECHO PRINT FIRST PART OF) DATA, Y1(T),
C          AT EQUALLY SPACED INTERVALS
C
   40 READ(NR,1040)(Y1(I),I=1,N)
 1040 FORMAT(8F10.5)
      WRITE(6,1045)
 1045 FORMAT(' DATA'/)
      WRITE(6,1046)(Y1(I),I=1,40)
 1046 FORMAT(1X,8F15.5)
      WRITE(6,1047) N
 1047 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)

C
C          CALCULATE AND PRINT THE MEAN, YBAR; VARIANCE,
C          SIGSQ AND STANDARD DEVIATION, SIGMA1
C
      YSUM = 0.0
      YSQSUM = 0.0
      FN = N
      DO 50 I = 1,N
      YSUM = YSUM + Y1(I)
   50 YSQSUM = YSQSUM + Y1(I)*Y1(I)
      YBAR = YSUM/FN
      SIGSQ = (YSQSUM - YSUM*YSUM/FN)/(FN-1.)
      WRITE(6,1055)YBAR,SIGSQ
 1055 FORMAT(/'0MEAN     = ',F12.4//' VARIANCE = ',F12.4//)
      SIGMA1 = SIGSQ ** 0.5
C
C          CENTER THE TIME SERIES BY SUBTRACTING THE MEAN,
C          AND PRINT
C
```

```
      DO 60 I=1,N
   60 Y1(I) = Y1(I)-YBAR
      WRITE(6,1057)
 1057 FORMAT('1CENTERED TIME SERIES DATA: '//)
      WRITE(6,1046)(Y1(I),I=1,40)
      WRITE(6,1060) N
 1060 FORMAT(' ...'//' NUMBER OF DATA POINTS = ',I6)
C
C          PAD THE DATA WITH ZEROES TO THE RIGHT IF N IS
C          NOT EQUALLY DIVISIBLE BY L
C
      NPAD = N
      IF(N/L*L.EQ.N) GO TO 80
      NPAD = N + L - MOD(N,L)
      NP1 = N + 1
      DO 70 I=NP1,NPAD
   70 Y1(I) = C.0
   80 RETURN
      END
```

```
      SUBROUTINE YSCALE (YMAX,YINC,YTOP,NUM)
C
C     CALCULATION OF AN EVEN Y-AXIS INCREMENENT (YINC) AND
C     TOP VALUE (YTOP) FOR PLOTTING ON THE Y AXIS ACCORDING
C     TO THE POWER OF TEN AND DECADE INTO WHICH
C     THE MAXIMUM VALUE (YMAX) FALLS
C
      DIV=1.E5
      DO 10 N=1,11
      TRIAL=YMAX/DIV
      IF(TRIAL.GT.1.0) GO TO 20
   10 DIV=DIV/10.
      GO TO 30
C
C     CHECK IF YMAX IS OUTSIDE THE SCALE RANGES CONSIDERED
C     (10**-5 TO 10**5); IF SO USE UNEVEN SCALE
C
   20 IF(N.EQ.1) GO TO 30
      YINC=10.**(6-N)
      NUM=YMAX/YINC+1
      YTOP=FLOAT(NUM)*YINC
      RETURN
C
C     YMAX OUTSIDE RANGE CONSIDERED
C
   30 WRITE(6,1030) YMAX
 1030 FORMAT('0ERROR IN YSCALE: YMAX = ',E20.6/)
      YINC=YMAX/10.
      YTOP=YMAX
      RETURN
      END
```

```
      SUBROUTINE PSPLOT(X,Y,NFREQ,LCODE,NSYMB,KDUPAX,TITLE,
     1  IFILE, KLOGAX,INIT,FLOGAX)
      DIMENSION X(131),Y(131),TITLE(10),SUBJ(10)
C
C       PLOT GRAPH OF POWER SPECTRUM WITH HOUSTON PLOTTER
C       CALLS, USING AXIS FOR LINEAR AXES AND CALLING LOGAX
C       FOR LOG AXES, REDRAW AXES UNLESS KDUPAX=0
C
      IF(KDUPAX.EQ.0) GO TO 70
C
C     INITIATE FOR NEW PLOT AND SET ORIGIN
C
      CALL PLOTS(0.0,0.0,IFILE)
      CALL FACTOR(1.)
      CALL PLOT(2.0,1.5,-3)
C
C       DRAW AND LABEL ABSCISSA
C          IF KLOGAX=0  DRAW LINEAR AXIS
C          IF KLOGAX=1  DRAW LOG-SCALED AXIS
C
      IF(KLOGAX.EQ.0) GO TO 30
      CALL LOGAX(1,IFILE)
C
C       CHANGE LOG FREQUENCY VALUE TO REAL DISTANCE FROM
C       ORIGIN
C
       DO 20 I=1,NFREQ
   20  X(I)=(X(I)-INIT)*FLOGAX
       GO TO 50
   30  CALL PSAXIS(0.14,8,0.0,1.,1.)
C
C      DRAW AND LABEL ORDINATE WITH SCALING
C
C      A. FIND MAXIMUM VALUE, YMAX, EVEN INCREMENTS, YINC,
C         AND LIMITING VALUE, YTOP, FOR Y AXIS
C
   50  YMAX=0.0
       DO 60 J=1,NFREQ
       IF(YMAX.GE.Y(J)) GO TO 60
       YMAX=Y(J)
   60  CONTINUE
       CALL YSCALE(YMAX,YINC,YTOP,NUM)
C
C      B. COMPUTE UNSCALED AXIS LENGTH, ALEN, AND SCALE
C         FACTOR, F, THEN DRAW Y AXIS
C
       ALEN=YTOP/YINC
       F=6.0/ALEN
       CALL PSAXIS(0.14,NUM,90.0,YINC,F)
C
C      COMPUTE SCALE FACTORS FOR PLOTTING X AND
C      Y VALUES, THEN PLOT LINE WITH OR WITHOUT
C      SYMBOLS, ACCORDING TO LCODE
```

```
C
   70 X(NFREQ+1)=0.0
      X(NFREQ+2)=1.0
      Y(NFREQ+1)=0.0
      Y(NFREQ+2)=YINC/F
      CALL LINE(X,Y,NFREQ,1,LCODE,NSYMB)
C
C     PRINT GENERAL PLOT INFORMATION ABOVE THE LAST VALUES
C     (IN MIDDLE TO UPPER RIGHT PORTION OF THE SPECTRUM)
C
      XTITLE=3.2
      YTITLE=6.32
      READ(5,1020)  (TITLE(I),I=1,10)
      CALL SYMBOL(XTITLE,YTITLE,0.14,TITLE,0.0,40)
      XTITLE=3.44
      YTITLE=YTITLE-0.32
      READ(5,1020) (SUBJ(I),I=1,10)
 1020 FORMAT(10A4)
      CALL SYMBOL(XTITLE,YTITLE,0.14,SUBJ,0.0,40)
      CALL PLOT(0.0,0.0,999)
C
      RETURN
      END
```

```
      SUBROUTINE LOGAX (LAST,IFILE)
C
CC      SUBROUTINE FOR LOG-SCALED HORIZONTAL AXIS
C
      DIMENSION X1(50),Y1(50),X(100),Y(100),NUM(50)
C
CC      SET X AND Y VALUES FOR LOG-SCALED HORIZONTAL AXIS
CC      INIT   THE FIRST LOGRITHMIC VALUE OF ABSCISSA (THE
CC             SMALLEST VALUE AVAILABLE IS -4)
CC      LAST   THE LAST LOGRITHMIC VALUE OF ABSCISSA (THE
CC             LARGEST VALUE AVAILABLE IS 4)
CC      F      SCALE FACTOR
C
      DATA INIT,F/-3,2./
      DATA NUM/'0.00','01  ','0.00','1   ','0.01','    ',
     1         '0.1 ','    ','1.0 ','    ','10.0','    ',
     2         '100.','0   ','1000','.0  ','1000','0.0'/
      DATA X1(1),X1(2)/0.,0./
      DO 101 I=3,28
      I33=I/3*3
      IF(I33.NE.I) GO TO 101
      C=FLOAT(I)/3.+1.
  101 X1(I)=F*ALOG10(C)
      DO 102 I=1,28
      Y1(I)=0.
      I31=(I-1)/3*3+1
      IF (I.NE.I31)  GO TO 102
      Y1(I)=-0.07
  102 CONTINUE
      Y1(1)=-0.14
      Y1(28)=-0.14
C
CC      PLOT AXIS
C
      LI=LAST-INIT
      SIZE=0.14
      X(29)=0.0
      X(30)=1.0
      Y(29)=0.0
      Y(30)=1.0
      XLABEL=-12./7.*SIZE
      YLABEL=-0.33
      INIT9=2*INIT+9
      CALL SYMBOL (XLABEL,YLABEL,SIZE,NUM(INIT9),0.0,4)
      XLABEL=XLABEL+24./7.*SIZE
      INIT9=INIT9+1
      CALL SYMBOL (XLABEL,YLABEL,SIZE,NUM(INIT9),0.0,3)
      DO 103 J=1,LI
      DO 104 I=1,28
      Y(I)=Y1(I)
      X(I)=0.
  104 X(I)=X1(I)+F*(J-1)
      CALL LINE (X,Y,28,1,0,0)
```

```
      XLABEL=X(28)-12./7.*SIZE
      YLABEL=Y(28)-0.19
      JI9=2*(J+INIT)+9
      CALL SYMBOL (XLABEL,YLABEL,SIZE,NUM(JI9),0.0,4)
      XLABEL=XLABEL+24./7.*SIZE
      JI9=JI9+1
  103 CALL SYMBOL (XLABEL,YLABEL,SIZE,NUM(JI9),0.0,3)
      XL=(FLOAT(LI)/2.-0.5)*F
      YL=-0.71
      HSIZE=1.5*SIZE
      CALL SYMBOL (XL,YL,HSIZE,'FREQUENCY (HERTZ)',0.0,17)
      RETURN
      END
```

```
C
C     SUBROUTINE PSAXIS (SIZE,NUM,THETA,YINC,F)
C
C     SUBROUTINE FOR NORMAL SCALE AXIS
C
      DIMENSION X1(10),Y1(10),X(10),Y(10),FNUM(50),
     1          TITLEY(10)
      DATA X1/0.,0.,1.,1./,Y1/-0.14,0.,0.,-0.14/
      NDEC=2
      IF(YINC.GT.1.) NDEC=0
      HSIZE=1.5*SIZE
      HSHIFT=4.*HSIZE
      X(5)=0.0
      X(6)=1.0
      Y(5)=0.0
      Y(6)=1.0
      NUM1=NUM+1
      DO 105 I=1,NUM1
  105 FNUM(I)=YINC*(I-1)
      XLABEL=-0.2
      YLABEL=-0.40
      IF(THETA.EQ.0.0) GO TO 107
      YLABEL=-0.26
      CALL NUMBER(YLABEL,XLABEL,SIZE,FNUM(1),THETA,NDEC)
      GO TO 108
  107 CALL NUMBER(XLABEL,YLABEL,SIZE,FNUM(1),THETA,NDEC)
  108 DO 125 J=1,NUM
      DO 110 I=1,4
      Y(I)=Y1(I)
      X(I)=0.
  110 X(I)=(X1(I)+J-1)*F
      IF (THETA.EQ.0.0) GO TO 115
      CALL LINE(Y,X,4,1,0,0)
      GO TO 117
  115 CALL LINE (X,Y,4,1,0,0)
  117 XLABEL=X(4)-0.2
      YLABEL=Y(4)-0.26
      J1=J+1
      IF(THETA.EQ.0.0) GO TO 120
      YLABEL=Y(4)-0.12
      CALL NUMBER(YLABEL,XLABEL,SIZE,FNUM(J1),THETA,NDEC)
      GO TO 125
  120 CALL NUMBER(XLABEL,YLABEL,SIZE,FNUM(J1),THETA,NDEC)
  125 CONTINUE
      XL=FLOAT(NUM)/2.*F-7.*HSIZE
      YL=-HSHIFT
      IF(THETA.EQ.0.0) GO TO 130
      XL=FLOAT(NUM)/2.*F-11.*HSIZE
      YL=0.14-HSHIFT
      READ(5,1020) (TITLEY(I),I=1,10)
 1020 FORMAT(10A4)
      CALL SYMBOL(YL,XL,HSIZE,TITLEY,THETA,26)
      GO TO 140
  130 CALL SYMBOL(YL,YL,HSIZE,'FREQUENCY (HERTZ)',THETA,17)
```

```
140 RETURN
    END
```

```
C
C       JCL FOR DATA FILES AND PLOT FILES
C       INPUT OF TITLES ALSO SHOWN
C
/*
//GO.FT13F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T345.HOLD
//GO.FT14F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T453.HOLD
//GO.FT15F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T54553.HOLD
//GO.FT16F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T64553.HOLD
//GO.FT17F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T74553.HOLD
//GO.FT18F001 DD UNIT=SYSTP,DISP=(NEW,CATLG,DELETE),
//   SPACE=(TRK,(5,5),RLSE),DSN=PLT.PV.UND.T84553.HOLD
//GO.SYSIN DD *

CH45 LOAD, INS, NW, TT287
SPECTRAL VALUE - F*S/SIGSQ
POWER SPECTRUM AT 512 FREQUENCIES
CH53 SG, LEG, W TT287
SPECTRAL VALUE - F*S/SIGSQ
POWER SPECTRUM AT 512 FREQUENCIES
CH45 LOAD, INS, NW & CH53 SG, LEG, W
GAIN FACTOR - F*C/(S1*S2)
CROSS SPECTRUM AT 512 FREQUENCIES
CH45 LOAD, INS, NW & CH53 SG, LEG, W
 PHASE ANGLE - W/(2*PHI)
PHASE ANGLE AT 512 FREQUENCIES
CH45 LOAD, INS, NW & CH53 SG, LEG, W
COHERENCE MAGNITUDE
COHERENCE FUNCTION AT 512 FREQ.
CH45 LOAD, INS, NW & CH53 SG, LEG, W
GAIN FACTOR
FREQ. RESPONSE FUNCTION AT 512 FREQ.
/*
//GO.FT01F001 DD DSN=WYL.PV.UND.DLCH45,DISP=SHR,UNIT=DASD,
// VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,BLKSIZE=3120)
//GO.FT02F001 DD DSN=WYL.PV.UND.DGCH53,DISP=SHR,UNIT=DASD,
// VOL=SER=TPPAK1,DCB=(LRECL=80,RECFM=FB,BLKSIZE=3120)
//
```