 

# Non-Deterministic Analysis of Wind Loads Effects on High-Rise Buildings

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**Abstract**

This paper studies the effect of wind turbulence component that should be described and analyzed in a stochastic form on tall building.

Wind turbulence has been modeled as a random process. Root mean squares (RMS) for building tip displacement has been determined for different heights and different aspect ratios of building plan. Based on computed RMS, it has been noted that different margins of safety should be used for different design parameters (i.e. building height and different aspect ratios).

**Keywords:** Root mean squares, frequency.

## *1. Introduction:*

One could distinguish between three types of excitation functions, namely, harmonic, periodic, and non-periodic, where the latter is also known as transient. The common characteristic of these functions is that their values can be given in advance for any time t. Such functions are said to be deterministic, and typical examples are shown in Figure (1). There is no difficulty in expressing the response to any arbitrary deterministic excitation in some closed form, such as the convolution integral (Meirovitch, 1975).

There are many physical phenomena, however, that do not lend to explicit time description. Examples of such phenomena are jet engine noise, the height of waves in a rough sea, the intensity of an earthquake, the intensity of wind, etc. The implication is that the value at some future time of the variables describing these phenomena cannot be predicted.

The response of a system to random excitation is also a random phenomenon. Because of the complexity involved, the description of random phenomena as functions of time does not appear as a particularly meaningful approach, and new methods of analysis should be adopted. Many random phenomena exhibit a certain pattern, in the sense that the data can be described in terms of certain averages. This characteristic of random phenomena is called statistical regularity. If the excitation exhibits statistical regularity, so does the response. In such cases, it is more feasible to describe the excitation and response in terms of probabilities of occurrence than to seek a deterministic description (Meirovitch, 1975). Solution techniques and SAP capabilities are generally described in heading and respectively.

Final different case studies that depict statistical effects of building height and aspect ratios have been considered in section.

## *2. Random Wind Process:*

2.1 Stationary Wind Process:

To establish a statistics modeling of wind fluctuation due to air turbulence, one should collect wind records of the type shown in the Figure (2). Each record is called a sample, and the total collection of samples is called the ensemble.

One could compute the ensemble average of the instantaneous pressures at time $t_1$. It could be also multiplied the instantaneous pressures in each sample at times and $t_1+\tau$, and average these results for the ensemble. If such averages do not differ as first choice in different values of $t_1$ then the random process described by the above ensemble is said to be stationary (Thomson, 1981).

Figure (3) shows a typical record of wind velocity obtained from measurements at three different heights of a mast. Stationarity over periods of 10 min to an hour is significant. The explanation of steadiness lies in the fact that processes generating the mean flow have time scales much, much greater than 1 hour. However, mean speed does vary with time and large fluctuations cover a period of several days (Stathopoulos, et al., 2007).

2.2 Statistical Description of Random Wind Function:

Wind velocity during an interval of time could be depicted as the Figure (4):

Several averages are useful in describing such a random function. The most common are the Mean value $\bar{x}$ which is defined as (Paz, et al., 2004):

$$\bar{x} = \frac{1}{T}\int_0^T \dot{x}(t)\,dt \qquad 1.1$$

and the mean square value $\bar{x}^2$ is defined as

$$\bar{x}^2 = \frac{1}{T}\int_0^T \dot{x}^2(t)\,dt \qquad 1.2$$

Both the mean and the mean-square values provide measurements for the average value of the random function $\dot{X}(t)$. The measure of how widely the function $x(t)$ differs from the average is given by its variance, $\sigma_x^2$ defined as:

$$\sigma_x^2 = \frac{1}{T}\int_0^T [\dot{x}(t) - \bar{x}]^2\,dt \qquad 1.3$$

when the expression under the integral is expanded and then integrated, it is found that:

$$\sigma_x^2 = \overline{\dot{x}^2} - (\bar{\dot{x}})^2 \qquad 1.4$$

which means that the variance can be calculated as the mean square minus the square of the mean.

As mean wind component has been studied in Chapter 3, then it will be excluded here by assuming that the mean value is zero, in which case variance is equal to the mean square value. The root mean square $RMS_x$, of the random function $\dot{X}(t)$ is defined as:

$$RMS_x = \sqrt{\overline{\dot{x}^2}} \qquad 1.5$$

The standard deviation $\sigma_x$, of the random function $\dot{X}(t)$ is the square root of the variance; hence from Equation (1.4) (Paz, et al., 2004).

$$\sigma_x = RMS_{\dot{x}} \qquad 1.6$$

2. 3 Probability Density Function:

Figure (5) shows a portion of a record of a random function $\dot{X}(t)$. If one wishes to determine the probability of $\dot{X}$ having a value in the range ($\dot{X}_1$, $\dot{X}_2$) a horizontal lines could be drawn through the values $\dot{X}_1$ and $\dot{X}_2$, and then the corresponding time intervals $\Delta t_i$. Are measured The ratio given by:

$$P(\dot{x}_1 \le \dot{x} \le \dot{x}_2) = \frac{\Delta t_1 + \Delta t_2 + \cdots \Delta tn}{T} \qquad 1.7$$

and calculated for the entire record length T, is the probability of $\dot{X}$ having a value between $\dot{X}_1$ and $\dot{X}_m$ at any selected time $t_i$ during the random process (Paz, et al., 2004).

Similarly, the probability of $\dot{X}(t)$ being smaller than a value $\dot{X}$ can be expressed as

 

$$P(\dot{x}) = p[\dot{x}(t) < x] = \lim_{T\to\infty} \frac{1}{T} \sum_i \Delta t_i \quad 1.8$$

where the time intervals $\Delta t_i$ are now those for which the function $\dot{\mathcal{X}}(t)$ has a value smaller than the specified.

The function of $P(\dot{\mathcal{X}})$ in the previous equation is known as the cumulative distribution function of the random function $\dot{\mathcal{X}}(t)$. This function could be plotted in the Figure (6) as a function of *x*. The cumulative distribution function is a monotonically increasing function for which:

$$P(-\infty) = 0, \quad 0 \le P\left(\dot{\mathcal{X}}\right) \le 1, \quad P(\infty) = 1 \quad 1.9$$

The probability that the value of the random variable is smaller than the value $x + \Delta x$ is denoted by $P(\dot{\mathcal{X}} + \Delta x)$ and that $x(t)$ takes a value between $x$ and $x + \Delta x$ is $P(\dot{\mathcal{X}} + \Delta x) - P(\dot{\mathcal{X}})$. This allows defining the probability density function as:

$$p(\dot{x}) = \lim_{n\to\infty} \frac{P(\dot{x}+\Delta x)-P(\dot{x})}{\Delta x} = \frac{dP(\dot{x})}{dx} \quad 1.10$$

Thus, the probability density function $p(\dot{\mathcal{X}})$ is represented geometrically by the slope of the cumulative probability function $P(\dot{\mathcal{X}})$. The functions $P(\dot{\mathcal{X}})$ and $p(\dot{\mathcal{X}})$ are shown in the Figure (6) From the previous equation, the probability that a random variable $\dot{\mathcal{X}}(t)$ has a value between $\dot{\mathcal{X}}$ and $\dot{\mathcal{X}} + dx$ is given by $p(\dot{\mathcal{X}})dx$, where $p(x)$ is the probability density function. Having prescribed $p(x)$, the probability of $\dot{\mathcal{X}}$ being in the range ($\dot{\mathcal{X}}_1$, $\dot{\mathcal{X}}_2$) at any selected time is given by

$$P\left(\dot{\mathcal{X}}_1 \le \dot{\mathcal{X}} \le \dot{\mathcal{X}}_2\right) = \int_{\dot{\mathcal{X}}_1}^{\dot{\mathcal{X}}_2} p\left(\dot{\mathcal{X}}\right) dx \quad 1.11$$

and is equal to the shaded area shown between $\dot{\mathcal{X}}_1$ and $\dot{\mathcal{X}}_2$ in the Figure (6). Similarly, the probability of $\dot{\mathcal{X}}$ being greater than $\dot{\mathcal{X}}_m$, that is, $P(|\dot{\mathcal{X}}| > \dot{\mathcal{X}}_m)$ could be represented as the two shaded tail areas in the same Figure. Since every real $\dot{\mathcal{X}}$ lies in the interval (∞,-∞), the area under the entire probability density function is equal to 1, that is:

$$\int_{-\infty}^{\infty} p(\dot{x})dx = 1$$

Thus, as $\dot{\mathcal{X}}$ tends to infinity in either direction $p(\dot{\mathcal{X}})$ should asymptotically diminish to zero (Paz, et al., 2004).

2. 4 Normal Distribution:

The most commonly used probability density function is the normal distribution, also referred to as the Gaussian distribution expressed by:

$$p(\dot{x}) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}(\dot{x}-\bar{\dot{x}})^2/\sigma^2} \quad 1.12$$

The Figure (7) shows the shape of this function. It may be observed that the normal distribution function is symmetric about the mean value $\bar{\dot{\mathcal{X}}}$ (Paz, et al., 2004).

In the Figure (8), the standard normal distribution is plotted non-dimensionally in terms of $(\dot{\mathcal{X}} - \bar{\dot{\mathcal{X}}})/\sigma$. The probability of $x$ being between $-\lambda_a\sigma$ and $\dot{\mathcal{X}} + \lambda_a\sigma$, where $\lambda_a$ is any positive number, is given by the equation.

 

$$P[\bar{\dot{x}} - \lambda_a\sigma < \dot{x} < \bar{\dot{x}} + \lambda_a\sigma] = \frac{1}{\sqrt{2\pi\sigma}}\int_{\bar{\dot{x}}-\lambda_a\sigma}^{\bar{\dot{x}}+\lambda_a\sigma} e^{-\frac{1}{2}(\dot{x}-\bar{\dot{x}})^2/\sigma^2}\,dx \quad 1.13$$

The previous Equation represents the probability that $\dot{x}$ lies within $\lambda_a$ standard deviations from $\bar{x}$. The probability of $\dot{x}$ lying more than $\lambda_a$ standard deviations from $\bar{x}$ is the probability of $|\dot{x} - \bar{x}|$ exceeding $\lambda_a$, which is 1.0 minus the value given by previous Equation. The following Table (1) presents numerical values for the normal distribution associated with $\lambda_a = 1, 2$, and 3 (Paz, et al., 2004).

### *3. Spectral Density Function:*

If a random process $\dot{x}(t)$ is normalized (or adjusted) so that the mean value of the process is zero, then, provided that $\dot{x}(t)$ has no periodic components, the autocorrelation function $R_{\dot{x}}(\tau)$ approaches zero as $\tau$ increases, that is:

$$\lim_{t\to\infty} R_{\dot{x}}(\tau) = 0 \quad 1.14$$

To expect that $R_{\dot{x}}(\tau)$ should satisfy the condition in Equations (1.15), then, Equations (1.16) and (1.17) can be used to obtain the Fourier transform $S_{\dot{x}}(\omega)$ of the autocorrelation function $R_{\dot{x}}(\tau)$ and its inverse as Equation (1.18):

$$\int_{-\infty}^{\infty}|F(t)|\,dt < \infty \quad 1.15$$

$$C(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(t)e^{-i\omega t}\,d\omega \quad 1.16$$

$$F(t) = \int_{-\infty}^{\infty} C(\omega)e^{i\omega t}d\omega \quad 1.17$$

In Equation (1.18), $S_{\dot{x}}(\omega)$ is called the spectral density function of $\dot{x}(t)$:

$$S_{\dot{x}}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_{\dot{x}}(\tau)e^{-i\omega a\tau}\,d\tau \quad 1.18$$

$$R_{\dot{x}}(\tau) = \int_{-\infty}^{\infty} s_{\dot{x}}(\omega)e^{i\omega\tau}d\omega \quad 1.19$$

The most important property of $S_{\dot{x}}(\omega)$ becomes apparent by letting $\tau = 0$ Equation (1.19). In this case:

$$R_{\dot{x}}(0) = \int_{-\infty}^{\infty} S_{\dot{x}}(\omega)d\omega \quad 1.20$$

which by Equation (1.21) is equal to mean square value of the function $\dot{x}(t)$ that is:

$$R(0) = \lim_{T\to\infty}\frac{1}{T}\int_0^T[\dot{x}(t)]^2dt = \overline{\dot{x}^2} \quad 1.21$$

$$\overline{\dot{x}^2} = \int_{-\infty}^{\infty} S_{\dot{x}}(\omega)d\omega \quad 1.22$$

The mean square value of a random process is therefore given by the area under the graph of the spectral density function as shown in the Figure (9). Consequently, the contribution of an incremental frequency $\Delta\omega$ to the mean square value is:

$$\Delta\overline{\dot{x}^2} = S_{\dot{x}}(\omega)\Delta\omega \quad 1.23$$

The spectra1 density of a given record can be obtained electronically by an instrument called a frequency analyzer or spectral density analyzer. The output of an accelerometer or other vibration transducer is fed into the instrument, which is essentially a variable frequency narrow-band filter with a spectral meter to display the filtered output. With this instrument, the experimenter searches for the predominant frequencies present in a vibration signal. The output of the spectral density analyzer is the contribution to the mean square value $\dot{x}^2$ of the input signal $\dot{x}(t)$ for a small range $\Delta\omega$ around the set frequency (Paz, et al., 2004).

When dealing with theory, the natural unit for the frequency is rad/sec. However, in most practical problems, the frequency is expressed in cycles per second or Hertz In the latter case, rewrite Equation (1.23) as:

$$\Delta\overline{\dot{x}^2} = S_{\dot{x}}(f)\Delta f \quad 1.24$$

where the frequency is in Hertz. Since $\Delta\omega = 2\pi\Delta f$, it is $S_{\dot{x}}(f)$:

 

$$S_{\dot{x}}(f) = 2\pi S_{\dot{x}}(\omega) \quad 1.25$$

when the spectral density function for the excitation is known. Its mean-square value may be determined from eq. (1.24) as:

$$\overline{x^2} = \int_{-\infty}^{\infty} S_x(f)df \quad 1.26$$

Figure (10) shows a plot of the various wind spectra, each spectrum being represented by a different symbol. The abscissa is a logarithmic scale, with frequency indicated in cycles per hour and the corresponding period in hours (Hoven, 1956).

In this steady, the spectrum density is ready without the need to find it by the equations of autocorrelation and Fourier series.

The distributions of spectral density function shown in Figure (10) are quite close to the Gaussian distributions (Hoven, 1956).

***4. SAP Random Wind Idealization:***

SAP procedures that are described in sub sections 4.1, 4.2 and 4.2 for frame modelling, shell modelling and mass modelling respectively. Main difference lies in wind load modelling.

4.1 Frame Element:

Frame element has been used in model of building beams and columns. The frame element is a very powerful element that can be used to model beams, columns, braces, and trusses in planar and three-dimensional structures. A Frame element is modeled as a straight line connecting two points. Each element has its own local coordinate system for defining section properties and loads, and for interpreting output.

Each Frame element may be loaded by gravity (in any direction), multiple concentrated loads, multiple distributed loads, strain and deformation loads, and loads due to temperature change. Element internal forces are produced at the ends of each element and at a user specified number of equally spaced output stations along the length of the element (CSI, 2009).

4. 2 Shell Elements:

SAP shell element that could accommodate arbitrary geometry, and which could interact with edge beams and supports, has been used in slab modelling for floors and roofs (Wilson, 2002). This element is a two-dimensional plate-bending element that is combined with a two-dimensional membrane element to produce a four-node shell element shown in Figure (11) (Wilson, 2002):

For this element, 24 by 24 local element stiffness matrix is formed in a local *xyz* system, and is then transformed to the global XYZ reference system. The shell element stiffness and loads could be added using the direct stiffness method to form the global equilibrium equations (Wilson, 2002).

In this study, Sap Shell element has been used to model slabs, floors and shear walls.

4.3 Mass Modelling

In SAP, mass and weight serve different functions. Mass is used for the inertia in dynamic analyses, and for calculating the built-in acceleration loads. Weight is a load that one defines and assign to one or more members, and could then be applied to one or more load cases.

SAP offers three different methods, shown in the interactive box below, to generate mass matrix see Figure (12):

With From Element and Additional Masses option, the program uses the following mass specifications:

1. Mass density specified for materials.
2. Additional line mass assigned to frame or cable objects.
3. Additional area mass assigned to area objects.

4. Mass specified for link properties.
5. Mass assigned directly to the joints.

With From Loads option, mass could be calculated from a scaled combination of load patterns. On the other hand, the absolute value of the net load acting in the global Z direction is divided by the acceleration due to gravity, in the current units, is used for the mass in the three translational directions.

The above two approaches could be combined together with From Element and Additional Masses and Loads option,

In this work, the applied load that consists of dead and live loads have been applied through From Loads option.

4. 4 Spatial Modelling of Wind Load:

This section defines spatial variation in terms of wind force that has been computed as pressure times a corresponding spot area.

4. 5 Temporal Modeling of Wind Load:

Temporal variation has been defined in terms of power spectral density and as shown in interactive box below Figure (13).

4. 6 Load Case Definition:

Finally, temporal and spatial time variation are merged together through load case definition Figure (14).

***5. Case Study:***

Within case studies of these sections, root mean square for wind turbulence has been determined based on SAP power spectral analysis for different:

- Heights.
- Aspect Ratio.

In the two case studies, following data have been used:

- SAP software has been used in modelling and time history analysis for all case studies. Frame element has been used in modelling of beams and columns. Shell element has been used in modelling of roofs and floors slabs.
- Floors superimposed dead load has been taken to be 2.5 kN/m2 and floors live load has been assumed 3.0 kN/m2, while roof superimposed dead load has been assumed 4.0 kN/m2 and roof live load has been assumed 1.5 kN/m2. Building self-weight has been computed automatically by the SAP. Partitions self-weight has been modelled as a line load with value of 1.5 kN/m.
- Mass modelled by SAP “From Loads Option” command, where whole dead load and 0.25 of live load have been used in mass computation.
- Mean wind speed has been assumed to be 45 m/sec with a sinusoidal time history.
- Material has been assumed as concrete with compressive strength of 28 MPa.
- All beams have been assumed to have 4.5 m span with 0.4m by 0.6m cross section.
- All columns have been assumed 3.0m high with 0.5m by 0.5m cross section (assumed for this case study).
- Slab thickness for floors, roofs, and shear walls has been assumed 0.2m.

- Damping ratio has been assumed 0.03 for all modes (Arkawa, et al., 2004).

5.1 Height versus Root Mean Square:

Five buildings with different heights of, 120, 180, 240 and 300 m have been considered. For all buildings, plan dimensions have been assumed 65m by 65m. Exposure B has been assumed with all heights with drag coefficient 1.18.

Results of above different heights are presented, summarized, and discussed in sub-sections below:

Variations of tip displacement root mean with building height have been summarized in the Table (2) and the Figure (15):

From The Table (2) and Figure (15), variation in tip displacement reaches the maximum value in height range of 250m. Then within this height range, permissible tip displacement has a larger margin of safety to counteract the larger uncertainty in wind turbulence that has been measured by RMS.

For example, Figure (16) shows Plan and Isometric for 100 Stories.

5.2 Different Aspect Ratio versus Root Mean Square:

Effect of aspect ratio for building plan on DLF for tip displacement and building base shear are considered in this section. Aspect ratio in this section is defined as follows:

$$\boldsymbol{Aspect\ Ratio = \lambda = \frac{plan\ dimension\ along\ wind\ direction\ \text{"}D\text{"}}{plan\ dimension\ across\ wind\ direction\ \text{"}B\text{"}}}$$

Four different “D” values (20, 40, 100, and 200) with constant “B” value of 20m have been considered. These lead to four different aspect ratios $\boldsymbol{\lambda}$ of 1, 2, 5, and 10. For each aspect ratio, corresponding drag coefficient “$C_D$” has been determined based available wind tunnel data (Simiu, et al., 1996).

Four different values of (20, 40, 100, and 200m) for along wind plan dimension “D” with a constant value of 20m for cross wind plan dimension “B” has been considered. This leads to four different aspect ratios $\boldsymbol{\lambda}$ of 1, 2, 5, and 10.

For each aspect ratio, corresponding drag coefficient “$C_D$” has been determined based on available wind tunnel data (Simiu, et al., 1996).Results of tip displacement RMS versus aspect ratio are summarized Figure (16).

From the Figure (17), variations in tip displacement, reach their maximum values in aspect ratio in range of 2. Then within this range of aspect ratio, permissible tip displacement should has a larger margin of safety to counteract the larger uncertainty in wind turbulence.

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TABLE 1: PROBABILITY FOR DIFFERENT $\lambda$ VALUES OF A NORMALLY DISTRIBUTED FUNCTION:

| $\lambda_a$ | $P\left[\bar{\dot{x}} - \lambda_a\sigma < \dot{x} < \bar{\dot{x}} + \lambda_a\sigma\right]$ | $P[\dot{x} - \bar{\dot{x}}] > \lambda_a\sigma$ |
|---|---|---|
| 1 | 68.3% | 31.7% |
| 2 | 95.4% | 4.6% |
| 3 | 99.7% | 0.3% |

TABLE 2 DIFFERENT HEIGHTS WITH TIP DISPLACEMENTS.

| Building Height(m) | Tip Disp. RMS (m) |
|---|---|
| 60 | 0.008 |
| 120 | 0.006 |
| 180 | 0.0115 |
| 240 | 0.0225 |
| 300 | 0.017 |

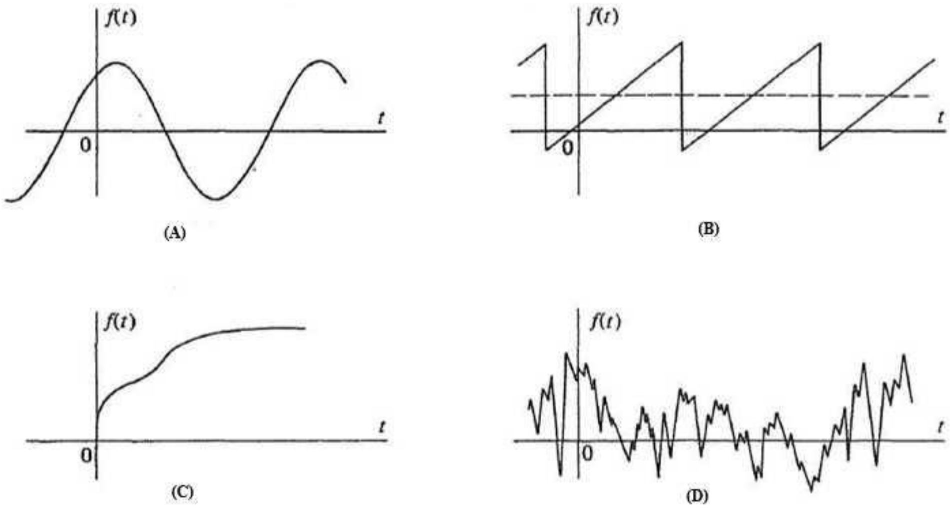


FIGURE 1 (A, B AND C) DETERMINISTIC FUNCTIONS AND (D) IS NON-DETERMINISTIC FUNCTIONS (MEIROVITCH, 1975).

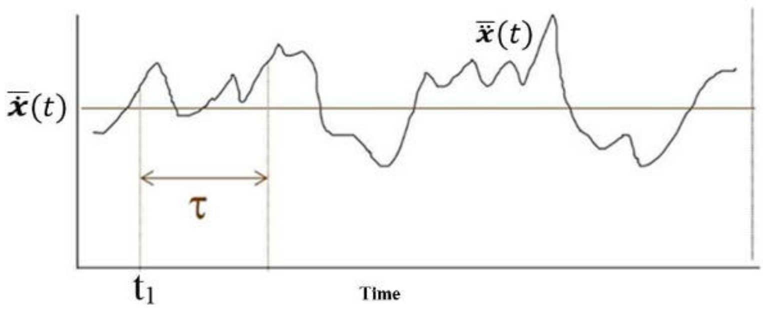


FIGURE 2 AN ENSEMBLE OF RANDOM TIME FUNCTIONS (THOMSON, 1981).

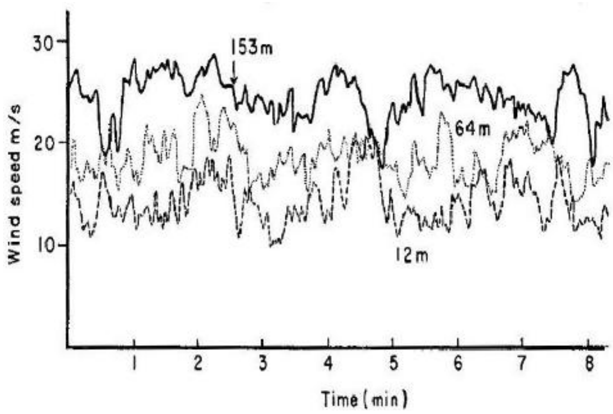


FIGURE 3 RECORD OF WIND SPEED AT THREE HEIGHTS ON 153 M MAST IN OPEN TERRAIN (STATHOPOULOS, ET AL., 2007).

 

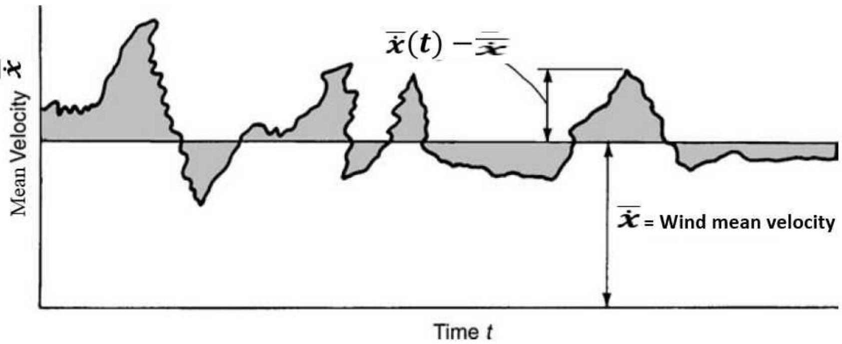


FIGURE 4 VARIATION OF WIND VELOCITY WITH TIME; AT ANY INSTANT $T$ (TARANATH, 2005).

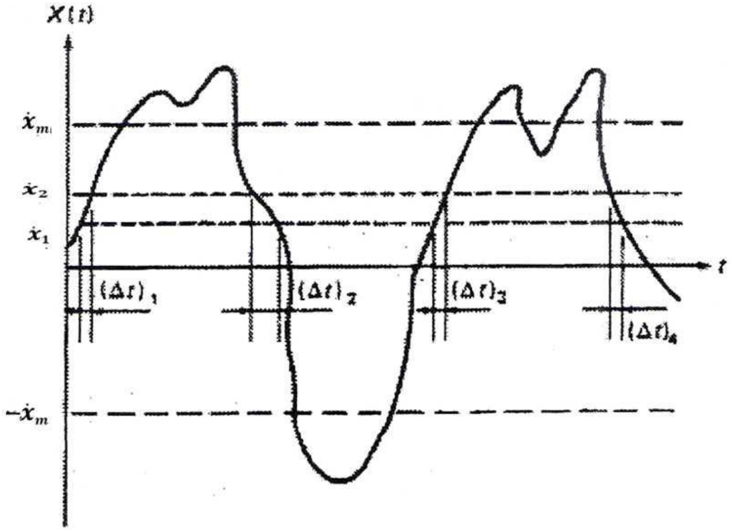


FIGURE 5 PORTION OF RANDOM RECORD SHOWING DETERMINATION OF PROBABILITIES (PAZ, ET AL., 2004).

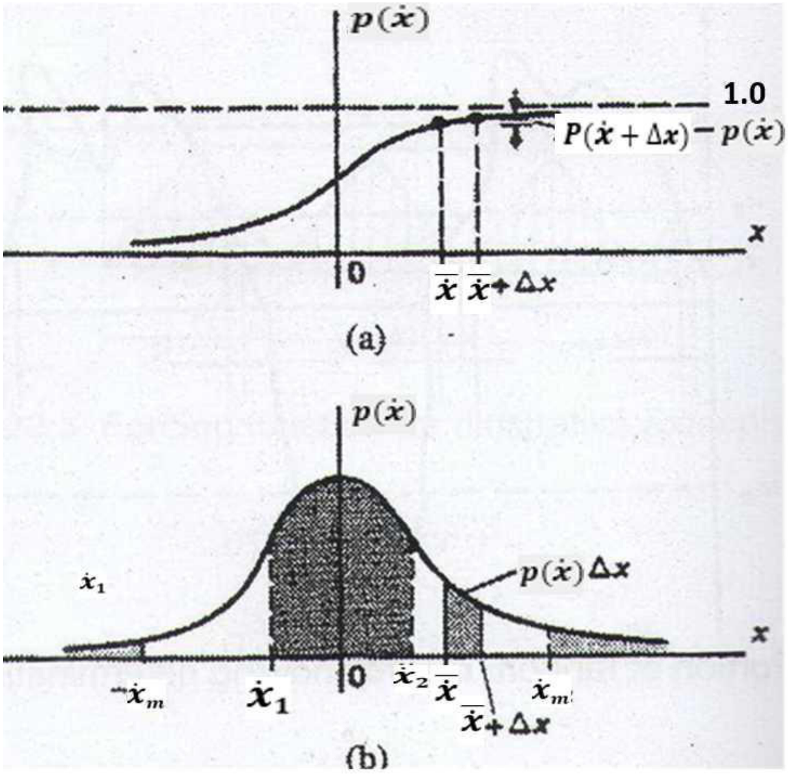


FIGURE 6 CUMULATIVE PROBABILITY FUNCTION P(X),(B) PROBABILITY DENSITY FUNCTION P(X) OF THE VARIABLE X=X(T) (PAZ, ET AL., 2004).

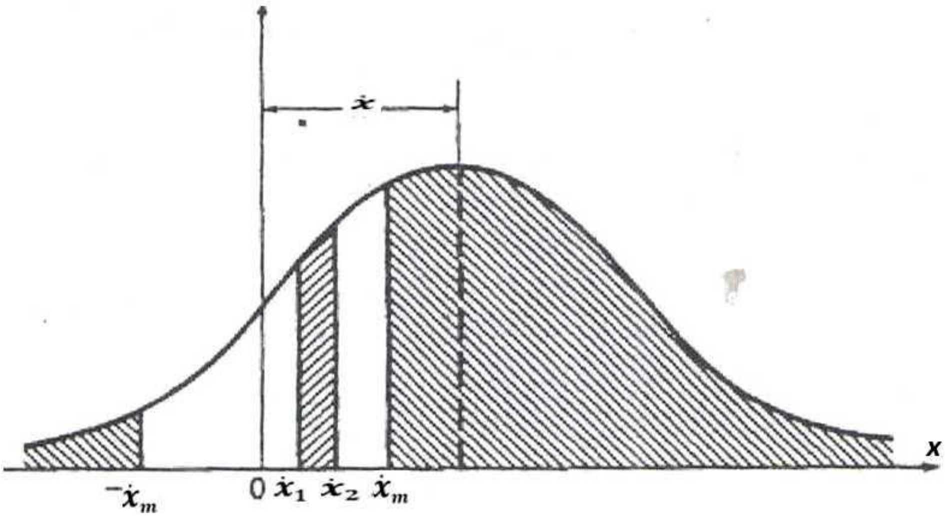


FIGURE 7 NORMAL PROBABILITY DENSITY FUNCTION (PAZ, ET AL., 2004).

 

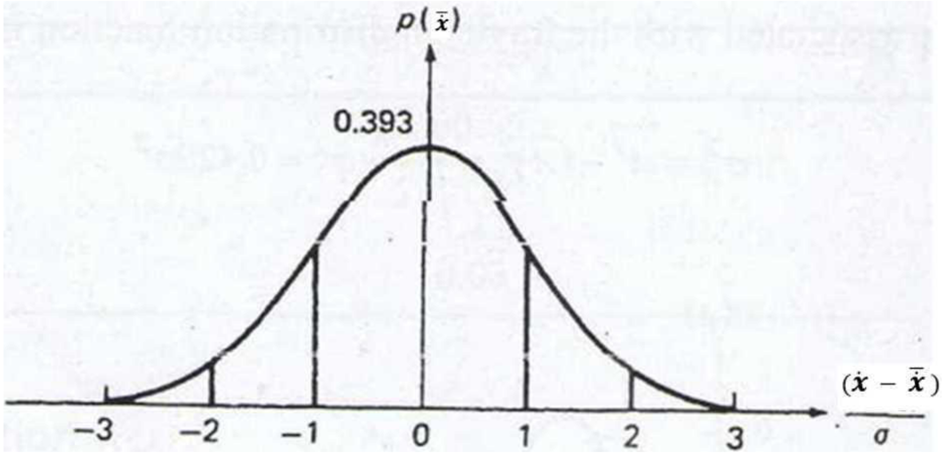

FIGURE 8 STANDARD NORMAL PROBABILITY DENSITY FUNCTION (PAZ, ET AL., 2004).

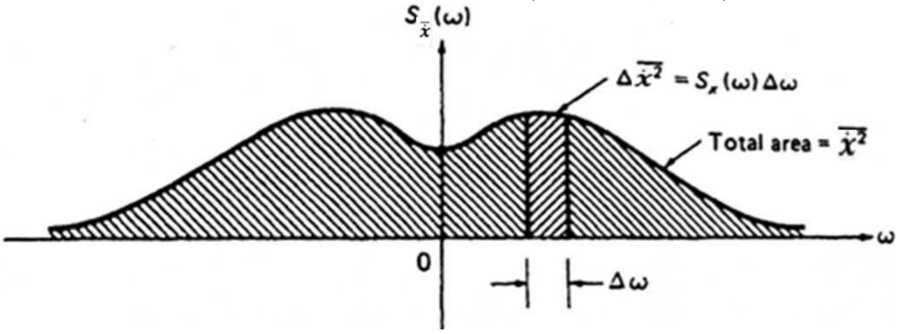

FIGURE 9 SPECTRAL DENSITY FUNCTION SHOWING AREA EQUAL TO MEAN SQUARE VALUE (PAZ, 1980).

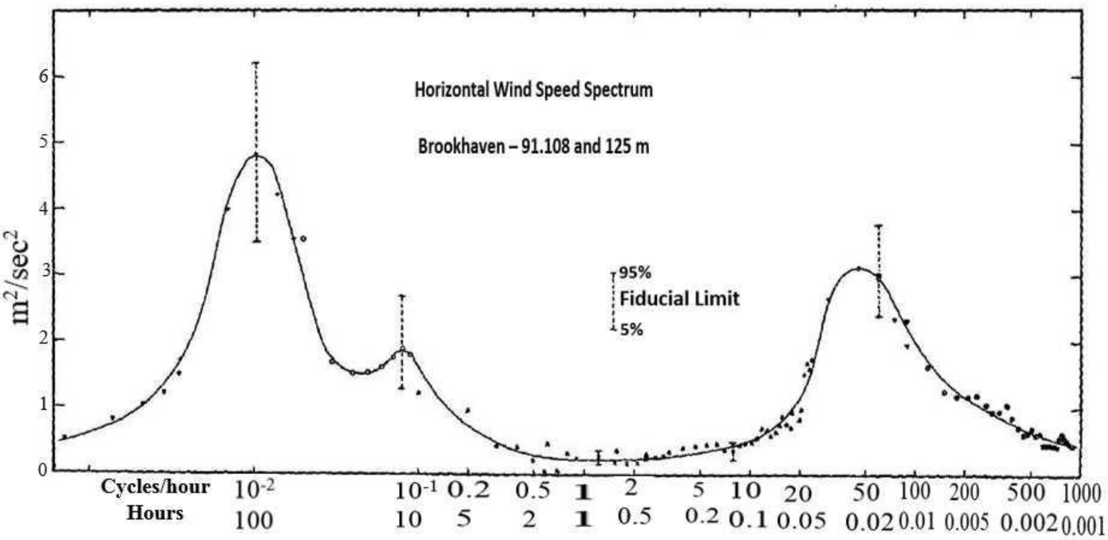

FIGURE 10 WIND SPEED SPECTRUM (HOVEN, 1956).

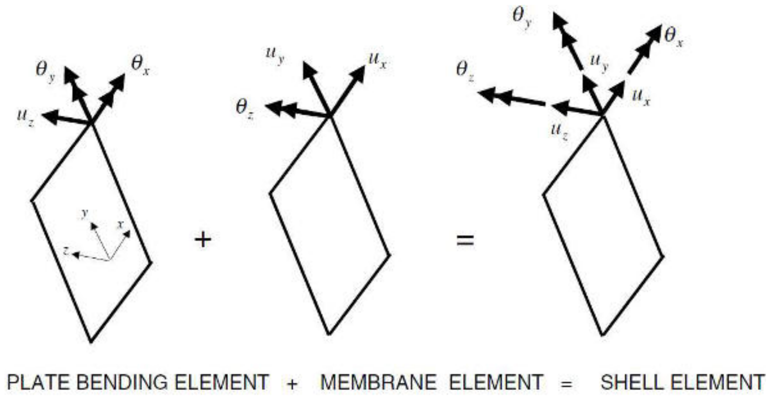


FIGURE 11 FORMATION OF FLAT SHELL ELEMENT (WILSON, 2002).

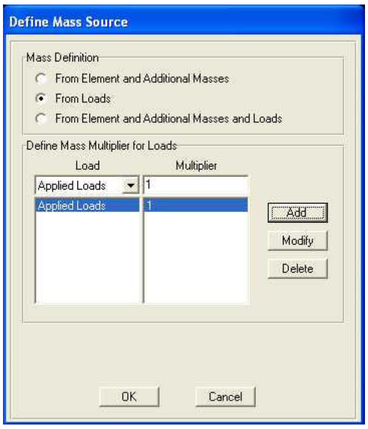


Figure 12 SAP Interactive Box for mass definition.

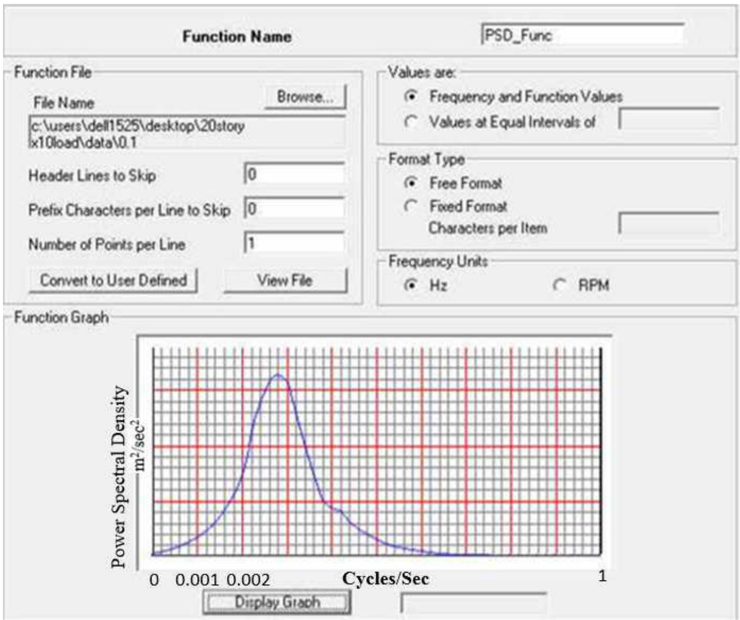


FIGURE 13 SAP MODELING FOR WIND POWER SPECTRAL DENSITY.

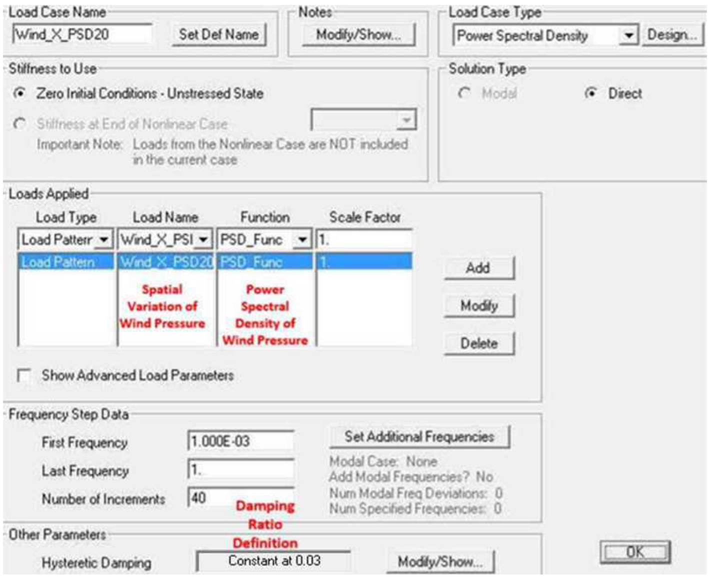


FIGURE 14 SAP LOAD CASE DEFINITION.

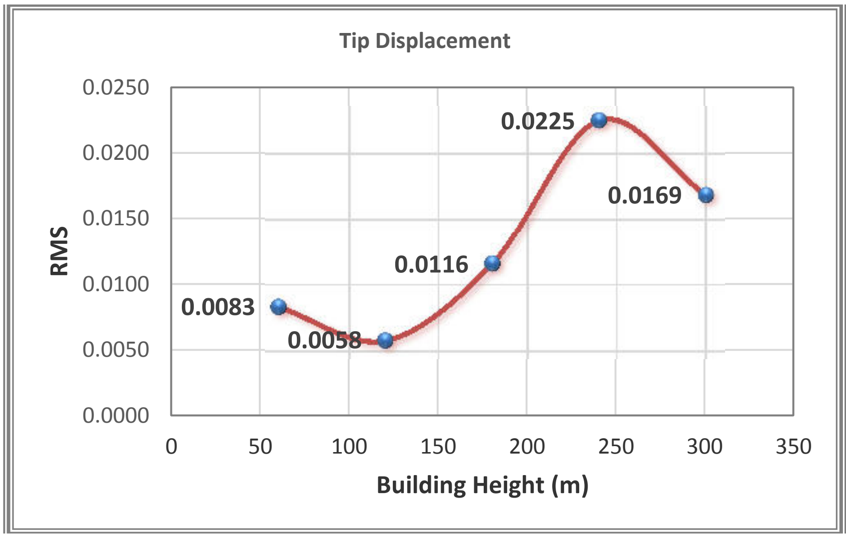


FIGURE 15 HEIGHT VERSUS ROOT MEAN SQUARE FOR TIP DISPLACEMENT.

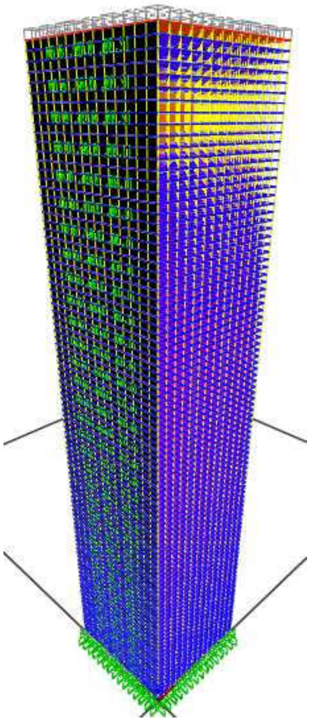

FIGURE 16 PLAN AND ISOMETRIC FOR 100 STORIES.

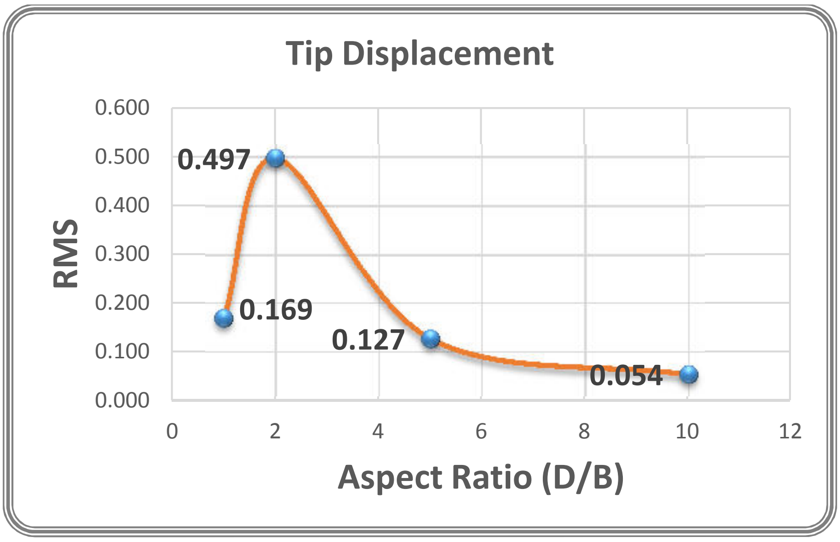


Figure 2 Different Aspect Ratios versus Root Mean Square for Tip Displacement.