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Wind Turbulent Spectra for Design Consideration of Offshore Structures

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ABSTRACT

This paper reviews currently available information on turbulent wind spectra over a seaway. The results of comparisons of spectral densities constructed from measured data and those computed by various spectral formulations show a significant difference at low frequencies. In order to provide a reliable prediction technique throughout the entire frequency range, a spectral formulation is proposed for consideration in the design of offshore structures.

INTRODUCTION

One of the areas in which information is needed in order to establish more rational design of offshore structures is the estimation of unsteady wind fields (fluctuating turbulence) over the sea necessary to evaluate dynamic response of the structure in a seaway.

Currently available turbulent wind spectral formulations have been developed based primarily on wind data measured on land in order to provide information for vibration problems of buildings. It has been said that spectral density of turbulent wind over a seaway appears to be greater at lower frequencies than that computed by available spectral formulations (Bush and Panofsky 1968, Simiu and Scanlan 1978, among others). If this is the case, when a substantial amount of wind energy exists at a frequency close to the natural response frequency of the structure, the dynamic effect of turbulent winds on the structure's response can become a serious problem.

The purpose of this study is to review currently available information on turbulent wind spectra over a seaway, and derive a spectral formulation, if necessary, for design consideration of offshore structures. For this, available wind specta obtained from wind speed measurements over a seaway are compiled and compared with spectral density functions computed by available various spectral formulations. It is found that there is a significant difference at low frequencies where measured spectral densities are substantially greater than those computed by any of the spectral formulations.

References and illustrations at end of paper.

SPECTRAL PRESENTATION OF TURBULENT WINDS

The frequency and the spectral density function of turbulent winds are generally expressed in dimensionless form. In this paper, spectral formulations as well as the spectra obtained from measured data are all expressed in the following dimensionless form for comparison:

Dimensionless frequency:

$$f_* = fz \,/\, \bar{U}_z, \qquad (1)$$

Dimensionless spectral density:

$$S(f_*) = f\,S(f)/\,u_*^2\,, \qquad (2)$$

where
f = frequency in cps

z = height above sea level in meters

$\bar{U}_z$ = mean wind speed at height z in m/sec

$S(f)$ = spectral density function in m^2/sec

u_* = shear velocity in m/sec.

The following formulae for mean wind speed, $\bar{U}_z$, and friction velocity, u_*, are used for the dimensionless presentation of the spectral density function:

$$\bar{U}_z = \bar{U}_{10} + 2.5\, u_* \ln(z/10) \tag{3}$$

$$u_* = \sqrt{C_{10}}\, \bar{U}_{10}\,, \tag{4}$$

where $\bar{U}_{10}$ = mean wind speed at 10 m height in m/sec,

C_{10} = surface drag coefficient evaluated from wind measurements at 10 m height.

The surface drag coefficient, C_{10}, depends on mean wind speed, $\bar{U}_{10}$. The results of several studies on this subject are summarized and shown in Figure 1. Among others, Wu's results are based on data obtained for a wide range of wind velocities over a seaway; hence, his result shown in Figure 1 is used in the present study.

WIND SPECTRA OBTAINED FROM MEASUREMENTS OVER A SEAWAY

Several turbulent wind spectra have been obtained from wind speed measured over a seaway at various geographical locations. These are listed in Table 1 and the spectral density functions are compiled in Figure 2. It should be noted that some publications give data points only which are usually scattered over an unstable range at low frequencies. The average curves are drawn through these data points for the present study and they are shown in Figure 2.

The spectra shown in the figure are obtained from wind speeds of various severity, and from measurements at various heights above the water surface and at different geographical locations. Nevertheless, there is little scatter in the magnitude of the dimensionless spectral density functions except at very low frequencies.

The upper and lower bound curves are given for Eidsvik's wind spectrum. Eidsvik carried out an extensive analysis of turbulent wind spectra on a total of 3,660 wind speed time histories covering a mean wind speed range from 2 to 36 m/sec at 110 m height above the water surface. He classified the data into 15 wind speed groups and generated 15 spectra in sequence of increasing wind severity. However, only the largest and smallest wind spectra are shown in dimensionless form in Figure 2. For presenting Eidsvik's data in dimensionless form, the value of C_{10} is maintained constant, 1.5×10^{-3}, for all wind speeds, since this value was estimated through his measurements.

It is of interest to note that Eidsvik's upper and lower bound spectra encompass most of the other data obtained elsewhere. If we draw the average curve of Eidsvik's upper and lower-bound, then it represents approximately the average of all measured spectra presented in Figure 2.

TURBULENT WIND SPECTRAL FORMULATIONS

(a) Davenport spectral Formulation

The Davenport spectrum (Davenport 1961) is given in dimensionless form as

$$S(f_*) = \frac{4x^2}{(1+x^2)^{4/3}}\,, \tag{5}$$

where $x = 1{,}200\, f/\bar{U}_{10}$.

As can be seen in the above equation, the Davenport spectrum is not a function of height above the ground (or sea level); instead, it is a function of the mean wind speed at 10 m height.

(b) Harris Spectral Formulation

The original form of the Harris spectrum is given in the following form (Harris 1983):

$$\frac{f\, S(f)}{\sigma^2} = \frac{3.66x}{(1+6\pi^2 x^2)^{5/6}} \tag{6}$$

where σ^2 = mean square of turbulent wind fluctuations

$x = f\, L'/\bar{U}_z$

L' = characteristic length = $1.09\, L_u$

L_u = integral length scale

The characteristic length L' is chosen such that the spectral density function peaks at $x = L'/2\pi$. Vickery et al. (1985) state that the integral length scales, used to fit the Harris' formulation to the full scale data, range from 60 to 400 m and the mean value of L_u = 180 m is used to match the high frequency portion of the spectrum. They also suggest the ratio $\sigma/u_* = 2.45$ from the observed data. Thus, the Harris spectral formulation can be written as

$$S(f_*) = \frac{21.97x}{(1+6\pi^2 x^2)^{5/6}} \tag{7}$$

where $x = (1.09)(180)/\bar{U}_z$.

(c) Hino spectral Formulation

The original form of the Hino spectrum is given by (Hino 1971),

$$\frac{f\, S(f)}{\sigma^2} = \frac{0.475x}{(1+x^2)^{5/6}} \tag{8}$$

where σ^2 = mean square of wind turbulent fluctuations

$$x = \frac{10\, \sigma^3 (z/10)^{1-4\alpha}}{0.0275\, \bar{U}_{10} (\alpha \bar{U}_{10})^3}\, f$$

α = exponent of the power law governing the profile of mean wind speed.

By using the ratio $\sigma/u_* = 2.45$ given in connection with the Harris spectrum, we may write the Hino spectrum as follows:

$$S(f_*) = \frac{2.85x}{(1+x^2)^{5/6}}, \tag{9}$$

where $x = \dfrac{(5.34\mathrm{x}10^3)\ u_*^3\ (z/10)^{1-4\alpha}}{\alpha^3\ \bar{U}_{10}^4}\ f$.

Computations are carried out by choosing $\alpha = 0.16$ in the present study.

(d) Kaimal spectral Formulation

Kaimal et al. (1972) develop a spectral formulation which includes the effect of dissipation rate for turbulent energy as a function of dimensionless height, denoted by z/L. Here, L is the Monin-Obukhov length which is a function of shear velocity as well as surface heat flux. L is negative with upward heat flux (which depends on the difference between surface temperature and the temperature aloft). $L < 0$ is unstable and can be observed in the daytime. The spectrum is given by,

$$S(f_*) = \frac{105 f_*}{(1+33\ f_*)^{5/3}}\ \phi^{2/3} \tag{10}$$

where

$$\phi = \begin{cases} 1+0.5\ |z/L|^{2/3} & \text{for } -2 \leqq z/L \leqq 0 \\ 1+2.5\ |z/L|^{3/5} & \text{for } 0 \leqq z/L \leqq 2\ . \end{cases}$$

$z/L = 0$ is called the stable condition.

(e) Kareem Spectral Formulation

Kareem (1985) proposes the following formulae from analysis of available wind data and spectral formulations:

$$S(f_*) = \frac{335\ f_*}{(1+71\ f_*)^{5/3}} \tag{11}$$

In the derivation of the spectral formulation, Kareem specifically considers the spectral density obtained at low frequencies as well as the agreement between the variance evaluated by integrating the spectrum and that obtained from measured data.

(f) Simiu and Leigh Spectral Formulation

Simiu and Leigh (1983) suggest the following empirical spectral formulation for design of offshore structures:

$$S(f_*) = \begin{cases} a_1 f_* + b_1 f_*^2 + d_1 f_*^3 & \text{for } f_* < f_m \\ c_2 + a_2 f_* + b_2 f_*^2 & \text{for } f_m < f_* < f_s \\ 0.26\ f_*^{-2/3} & \text{for } f_* > f_s \end{cases} \tag{12}$$

where,

$$a_1 = \frac{4\ L_u\ \beta}{z}$$

$$\beta_1 = 0.26\ f_s^{-2/3}$$

$$b_2 = \frac{\frac{1}{3}\ a_1 f_m + \left(\frac{7}{3} + \ln\frac{f_s}{f_m}\right)\ \beta_1 - \beta}{\frac{5}{6}(f_m - f_s)^2 + \frac{1}{2}(f_m^2 - f_s^2) + 2f_m(f_s - f_m) + f_s(f_s - 2f_m)\ln\frac{f_s}{f_m}}$$

$$a_2 = -2\ b_2\ f_m$$

$$d_1 = \frac{2}{f_m^3}\left[\frac{a_1\ f_m}{2} - \beta_1 + b_2(f_m - f_s)^2\right]$$

$$b_1 = -\frac{a_1}{2f_m} - 1.5\ f_m d_1$$

$$c_2 = \beta_1 - a_2 f_s - b_2 f_s^2$$

L_u = integral scale length

$\beta = \sigma^2/u_*^2 = 6.0$

f_m = dimensionless frequency at which f S(f) is maximum

f_s = dimensionless frequency equivalent to the lower bound of the intertial subrange.

The Simiu and Leigh's spectral formulation is developed taking into consideration the wind energy over a seaway in the low frequency range. In particular, f S(f) becomes maximum at $f = f_m$, and the spectrum has a finite value at $f = 0$ given by

$$S(0) = 4(\sigma^2/\bar{U}_z)\ L_u \tag{13}$$

From analysis of many full scale measurements, Simiu and Leigh suggest that the magnitude of L_u ranges from 100 to 240 m for winds at 20-60 m above the sea surface. L_u is taken as 180 m in the present study.

Figure 3 shows all these spectral formulations. Included also in the figure for comparison is the average of all measured spectra shown in Figure 2. It should be noted that, as stated in the Introduction, many spectral formulations presented here are developed based on data measured primarily over land in an attempt to formulate turbulent wind energy in the relatively high frequency range, say $f_* > 0.1$. However, extension of the formulations is made here to see if they are still valid in the low frequency range for design consideration of offshore structures.

It can be seen in Figure 3 that there is no appreciable difference between measured spectra and those computed by spectral formulations for dimensionless frequency f_* greater than 0.03. However, a significant difference can be seen for f_* less than 0.03 where all measured spectral densities are greater than those computed by any of the spectral formulations.

Frequencies and periods corresponding to the dimensionless frequency $f_* = 0.03$ evaluated for mean wind speeds of 40, 60, and 80 knots at 30 m height above the sea surface (approximate location of the center of gravity for wind force of offshore structures) are tabulated in Table 2.

It can be seen in the table that the dimensionless frequency $f_* = 0.03$ for a mean wind speed of 40 knots corresponds to a natural response period of 48.6 sec. Thus, we may state that for a mean wind speed of 40 knots extreme care must be taken in applying the currently available wind spectral formulations for evaluating motions (surge and sway motions, for example) of floating units whose natural motion periods are greater than 48.6 sec. Similarly, for structures whose natural motion periods are greater than 32.4 sec. and 24.3 sec. care must be taken for mean wind speed of 60 knots and 80 knots, respectively.

PROPOSED SPECTRAL FORMULATION FOR TURBULENT WIND OVER A SEAWAY

For design consideration of offshore structures, the average wind spectra obtained from measured data over a seaway is expressed in the following mathematical formulation as a function of dimensionless frequency:

$$S(f_*) = \begin{cases} 583\, f_* & \text{for } 0 \leqq f_* \leqq 0.003 \\ \dfrac{420\, f_*^{0.70}}{(1+f_*^{0.35})^{11.5}} & \text{for } 0.003 \leqq f_* \leqq 0.1 \\ \dfrac{838\, f_*}{(1+f_*^{0.35})^{11.5}} & \text{for } f_* \geqq 0.1 \end{cases} \tag{14}$$

It is assumed in Eq. (14) that $S(f_*) = 583\, f_*$ for $f_* < 0.003$. This assumption is introduced because when $S(f_*)$ is converted to a dimensionless spectral density $S(f)$, it becomes infinite at $f = 0$. Since no information is available on turbulent wind energy at very low frequencies (approximately $f_* < 0.003$), the spectral densities for f_* less than 0.003 are modified such that the magnitude of the density will reduce linearly to zero at $f = 0$.

A comparison between the mathematical formulation given in Eq. (14) and the average of measured wind spectra is shown in Figure 4.

CONCLUSIONS

This paper reviews currently available information on turbulent wind spectra over a seaway and presents a spectral formulation for design consideration of offshore structures.

From comparison between wind spectra obtained from data measured over a seaway and those computed by available various spectral formulations, the following conclusions may be drawn:

(a) There is no appreciable difference between measured spectra and those computed by spectral formulations for dimensionless frequencies f_* greater than 0.03.

(b) A significant difference between measured and computed spectra exists for f_* less than 0.03 where all measured spectral densities are greater than those computed by any of the spectral formulations. This result is not surprising since currently available turbulent wind spectral formulations are developed based primarily on wind data measured on land.

Based on the above findings, the average wind spectra obtained from measured data over a seaway is obtained and presented in the mathematical formulation given in Eq. (14) for design consideration of offshore structures.

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REFERENCES

(1) Bush, N.E. and Panofsky, H.A.: "Recent Spectra of Atmospheric Turbulence", Quart. Journal Roy. Meteorol. Soc., Vol. 94, pp. 132-148, 1968.

(2) Davenport, A.G.: "The Spectrum of Horizontal Gustiness Near the Ground in High Winds", Quart. Journal Roy. Meteorol. Soc., Vol. 87, pp. 194-211, 1961.

(3) Garatt, J.R.: "Review of Drag Coefficients over Oceans and Continents", Month. Weather Rev., Vol. 105, pp. 915-929, 1977.

(4) Harris, R.I.: "The Nature of the Wind, The Modern Design of Wind-Sensitive Structures", Const. Ind. Res. & Inf. Assn., London, pp. 29-55, 1971.

(5) Hino, M.: "Spectrum of Gusty Wind", Proc. 3rd Conf. on Wind Effect on Buildings and Structures, Vol. 1, pp. 69-77, 1971.

(6) Kaimal, J.C. et al.: "Spectral Characteristics of Surface Layer Turbulence", Quart. Journal Roy. Meteorol. Soc., Vol. 98, pp. 563-589, 1972.

(7) Kareem, A.: "Structure of Wind Field over the Ocean", Proc. Int'l. Workshop on Offshore Winds and Icing, pp. 225-235, 1985.

(8) Large, W.G. and Pond, S.: "Open Ocean Momentum Flux Measurements in Moderate to Strong Winds", Journal Phy. Oceano., Vol. 11, pp. 324-336, 1981.

(9) Miller, B.I.: "A Study of the Filling of Hurricane Donna over Land", Month. Weather Rev., Vol. 92, pp. 389-406, 1964.

(10) Miyake, M. et al.: "Spectra and Cospectra of Turbulence over Water", Quart. J. Roy. Meteorol. Soc., Vol. 96, pp. 138-143, 1970.

(11) Pond, S. et al.: "Measurements of the Turbulent Fluxes of Momentum, Moisture, and Sensible Heat over the Ocean", Journal Atmosph. Sci., Vol. 28, pp. 901-917, 1971.

(12) Schmitt, K.F. et al.: "Structure of Marine Surface Layer Turbulence", Journal Atmosph. Sci., Vol. 36, pp. 602-618, 1979.

(13) Simiu, E. and Scanlan, R.H.: "Wind Effects on Structures", John Wiley & Sons, Inc. New York, 1978.

(14) Simiu, E. and Leigh, S.D.: "Turbulent Wind Effects on Tension Leg Platform Surge", National Bur. Stand., Building Sci. Ser. 151, 1983.

(15) Smith, S.D.: "Thrust-Anemometer Measurements of Wind-Velocity Spectra and Reynolds Stress over a Coastal Inlet", Journal Mar. Res., Vol. 25, pp. 239-262, 1967.

(16) Smith, S.D.: Wind Stress and Heat Flux over the Ocean in Gale Force Winds", Journal Phy. Oceanography, Vol. 10, pp. 709-726, 1980.

(17) Takeda, A.: "Effects of Water Wave Motions on Spectral Characteristics of Wind Fluctuations in the Marine Atmospheric Surface Layer", Journal Meteorol. Soc. Japan, Vol. 59, No. 4, pp. 487-508, 1981.

(18) Vickery, P.J. et al.: "Gust Factor and Turbulence Measured at 50 m over the Sea Off Sable Island", Proc. Int'l. Workshop on Offshore Winds and Icing, pp. 196-213, 1985.

(19) Weiler, H.S. and Burling, R.W.: "Direct Measurements of Stress and Spectra of Turbulence in the Boundary Layer over the Sea", Journal Atmosph. Sci., pp. 653-664, 1967.

(20) Wu, J.: "Wind-Stress Coefficients over Sea Surface from Breeze to Hurricane", Journal Geophy. Res., Vol. 87, pp. 9704-9706, 1982.

Table 1 Measurements of turbulent winds over the sea

	Location	Height above sea surface in m.	Mean Wind speed in m/sec.
Eidsvik (1985)	Norwegian sea	110	2-36
Schmitt et al.(1979)	North Pacific	29	5.5-11.8
Miyake et al.(1970)	400 m offshore Vancouver, Canada	1.4-4.5	3.8-8.6
Takeda (1981)	1 km offshore Kanagawa, Japan	0.4-5.1	< 7
Pond et al.(1971)	Barbados Caribbean	8	3.9-7.2
Weiler & Burling(1967)	400 m offshore Vancouver, Canada	1.7-2.7	1.4-10.0
Smith (1967)	Nova Scotia Canada	1.6-4.2	6-22

Table 2 Frequency and period corresponding to $f_* = 0.03$ for $z = 30$ meters

	Mean wind speed at 30 m height above sea level (in kts)		
	40	60	80
Frequency (Hz)	0.021	0.031	0.041
Period (Sec.)	48.6	32.4	24.3

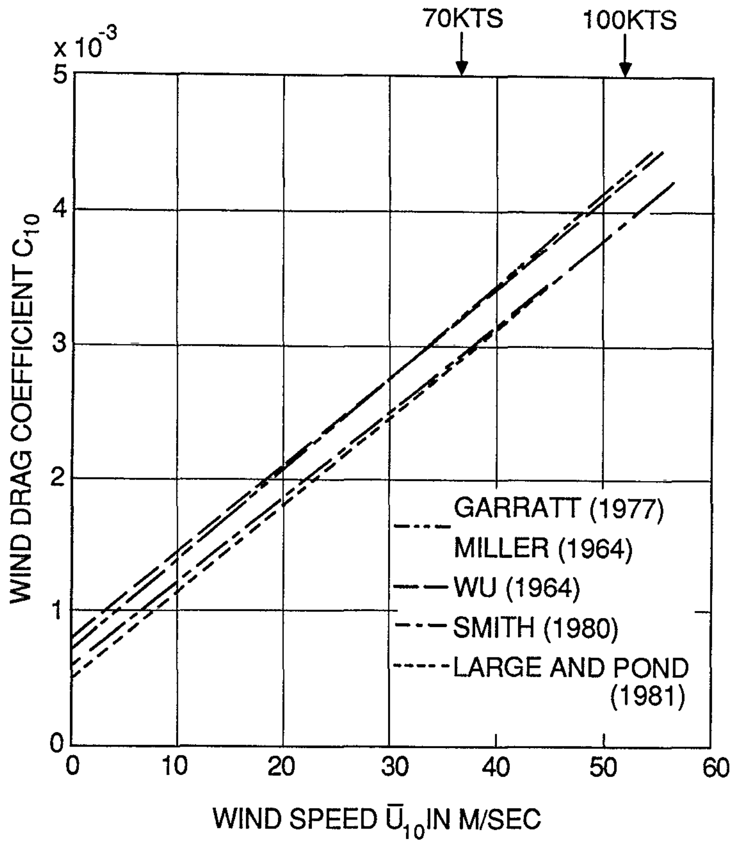

Figure 1 Wind drag coefficient, C_{10}, as a function of mean wind speed, $\bar{U}_{10}$

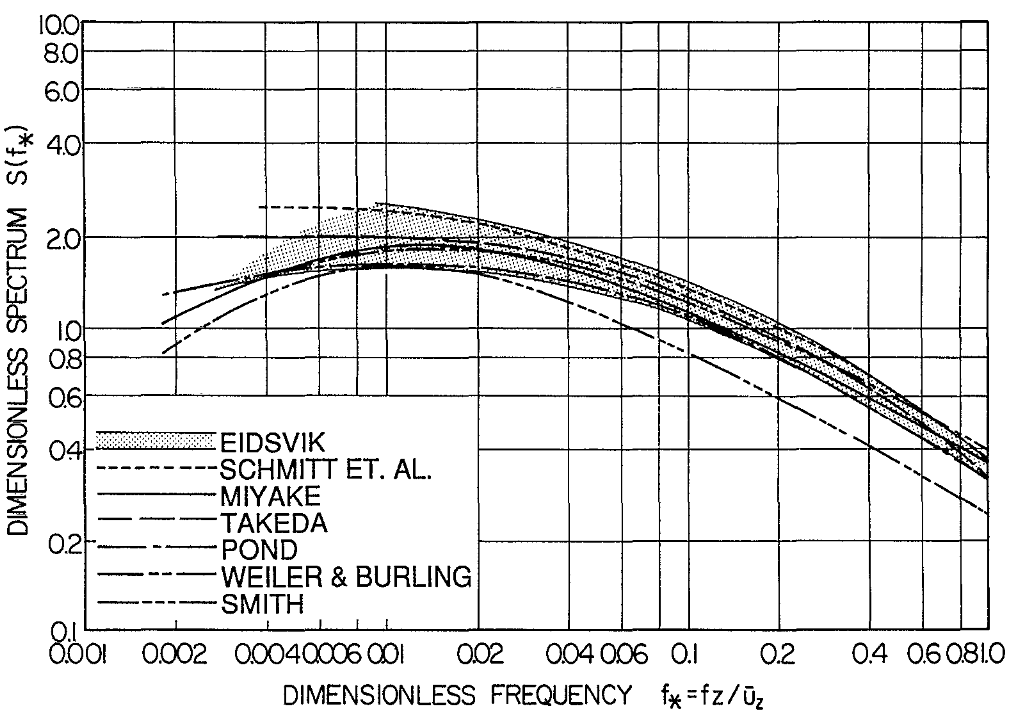

Figure 2 Comparison of turbulent wind spectra obtained from data measured over a seaway

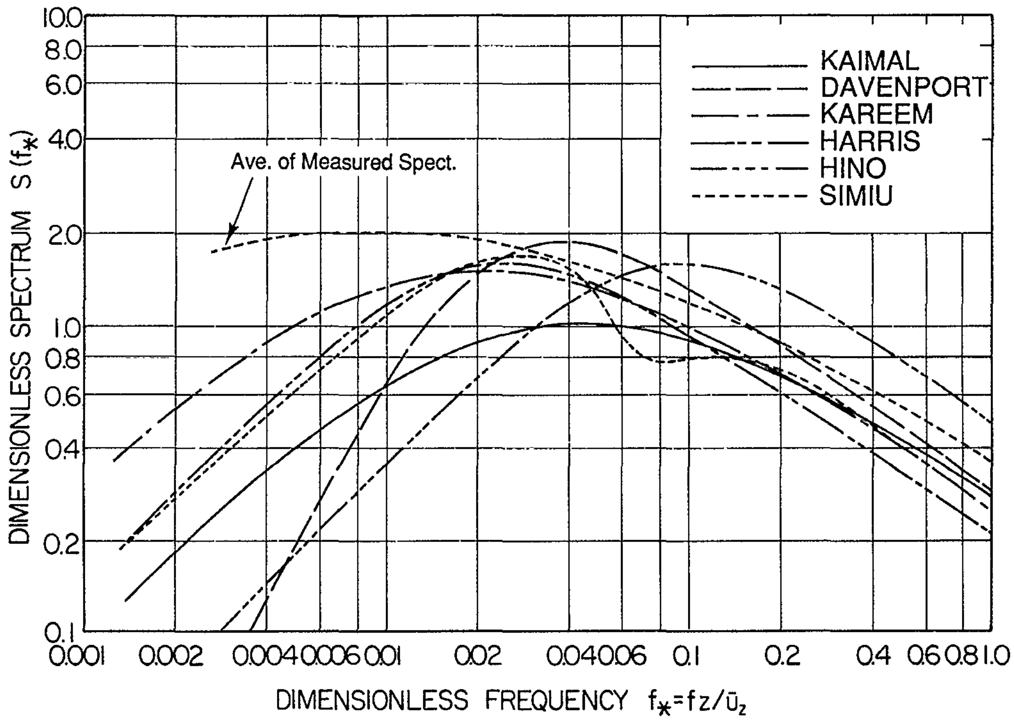

Figure 3 Comparison of various wind spectral formulations

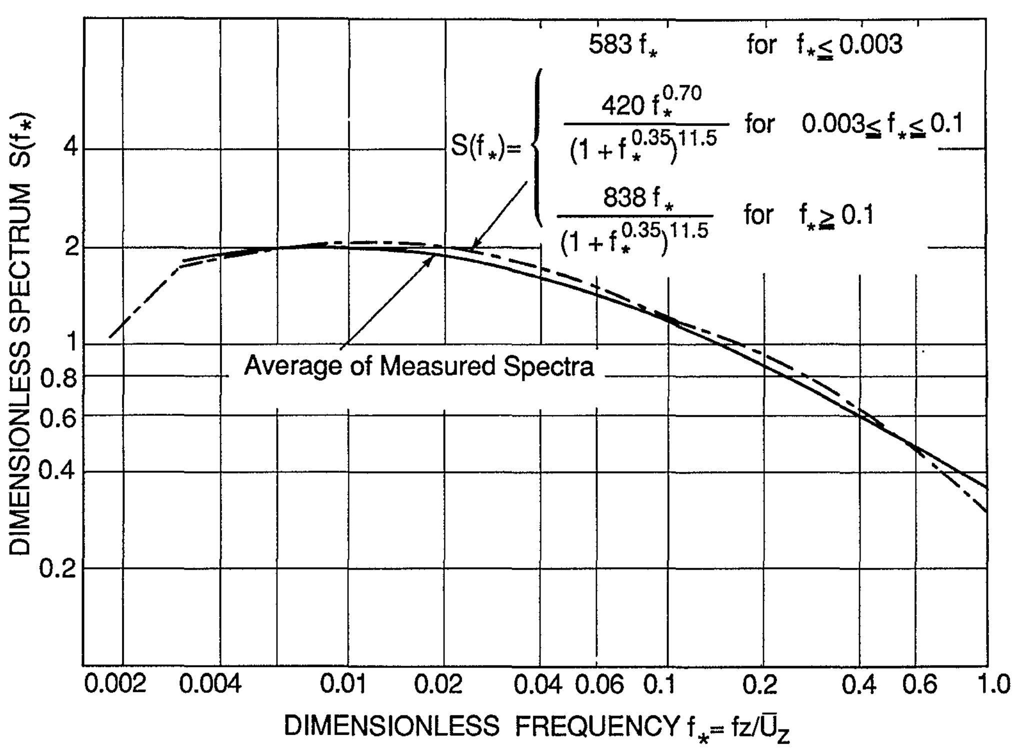

Figure 4 Mathematical presentation of average of measured wind spectra over a seaway