Presented at the International Symposium on
WAVES'93, American Soc. Civil Engineers
1993.

ON HURRICANE-GENERATED SEAS

Michel K. Ochi*

Abstract

Two different situations in the relationship between wind speed and sea severity during hurricanes (and tropical cyclones) are clarified from analysis of measured data obtained by NOAA buoys. From analysis of 400 wave spectra obtained from measured data during hurricanes, a wave spectral formulation specifically applicable for hurricane-generated seas is derived in the form of the JONSWAP spectral formulation and as a function of significant wave height and modal frequency. A family of wave spectra which can be used for design of marine systems during hurricanes is also developed.

Introduction

Wind-generated seas during hurricanes are significantly different from those observed in ordinary storms because the input source of energy generating the waves is advancing at a speed of 5 to 12 knots. The rate of change of wind speed measured at a location in the moving path of a hurricane is much faster than that observed during an ordinary storm. The time duration, therefore, of a given wind speed during hurricane is extremely short in contrast to seas generated by ordinary winds blowing continuously for several hours with constant speed.

Many studies have been carried out on hurricane-generated seas, primarily through hindcasting and forecasting techniques. These include Cardone, Pierson and Ward (1976), Bretschneider and Tamaye (1976), Young and Sobey (1981), Ross and Cardone (1978) and Young (1988), among others. Although these studies provide valuable information for individual hurricanes, it is not possible

* Professor, Coastal and Oceanographic Engineering Department, University of Florida

to draw general conclusions regarding the severity of the sea and the shape of wave spectra during hurricanes.

The purpose of this study is to find the relationship between wind speed and sea severity during hurricanes in order to provide information on simultaneous loadings associated with winds and waves for the design and safe operation of ships and offshore structures. For this, analysis is carried out on measured data obtained by NOAA buoys deployed in the Gulf of Mexico and the Atlantic Ocean. It is also the purpose of this study to derive a wave spectral formulation specifically applicable for hurricane-generated seas. This is accomplished by analysis of 400 wave spectra obtained during hurricanes.

Sea Severity During Hurricanes

It is generally known that sea severity generated by hurricanes depends on several factors of the hurricane such as maximum sustained wind speed, radius of maximum winds, central pressure, forward speed, etc. The results of analysis of wind speed and sea severity during hurricanes, however, indicate that there exists a relatively simple relationship between the sea severity and mean wind speed. In fact, there are two different situations; one is the growing stage of hurricane-generated seas in which the wind speed is increasing at an extremely high rate but the sea severity is comparatively moderate, the other is the sea condition resulting from continuous winds of mild severity blowing for one week or longer then followed by a storm, usually a tropical cyclone.

We may first consider the sea condition at a given location as the hurricane approaches. We define this situation here as the growing stage of the hurricane. As an example, let us examine the relationship between wind and sea severity observed in Hurricane ELOISE. Figure 1 shows the track of Hurricane ELOISE taken from a report published by NOAA Data Buoy Office (NOAA 1975). The hurricane crossed the Gulf of Mexico and its center passed within 10 miles (16 kilometers) of Buoy EB 10 as shown in the figure. The relationship between the mean wind speed at a 10 meter-height and the significant wave height obtained by the buoy at one hour time intervals is shown in Figure 2.

The white circle in Figure 2 indicates the wind speed and significant wave height in the growing stage of the hurricane. It can be seen in the figure that the sea severity increases almost linearly with increase in wind speed during the growing stage, and becomes the severest (significant wave height 8.8 m) when the wind speed becomes maximum (35.2 m/sec, 68.6 knots) and is then followed by a transition stage. That is, the wind speed reduces in magnitude to a great extent (from 35.2 m/sec to 8 m/sec) within two hours when the hurricane eye passes near the buoy. The sea state follows the change in energy source by reducing in severity from a

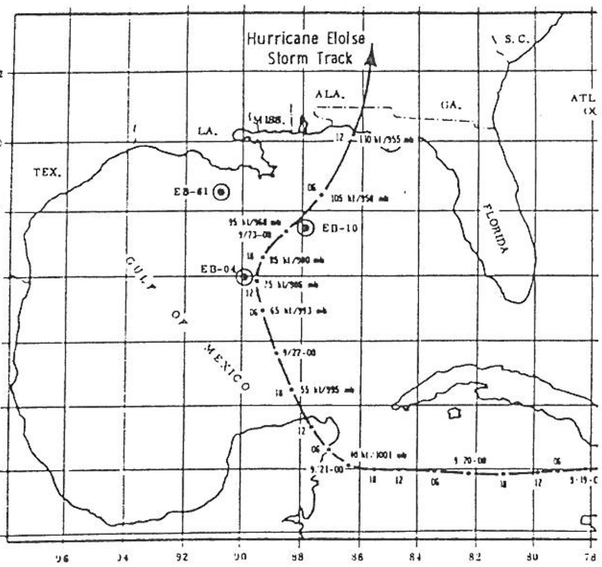

Figure 1:

Track of Hurricane ELOISE (From NOAA Data Report 1975)

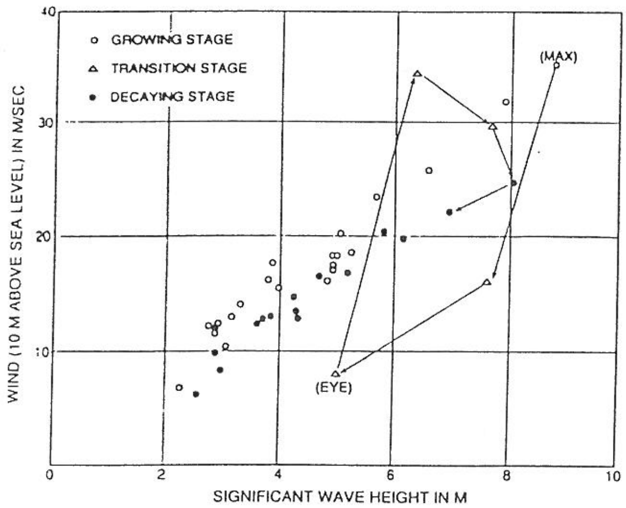

Figure 2:

Relationship between mean wind speed and significant wave height, Hurricane ELOISE

significant wave height of 8.8 m to 5.0 m. Then, during the following two hours, the wind speed as well as the sea state come back to nearly the same level as they were in the growing stage. After that, the sea severity reduces almost linearly with reduction in wind speed. Thus, it can be seen that the severity of sea state is subject to wind speed during the hurricane.

The wind speed - sea severity relationship during the growing stage of hurricanes is obtained for an additional five hurricanes and the results are summarized in Figure 3. The data shown in the figure are all measured by NOAA buoys in deep water. Some wind speeds measured at a 5-meter height above the buoy are converted to that for a 10 m height. Some wind speeds included in the figure were below hurricane level (33.5 m/sec, 65 knots) when they passed over the buoys, but the wind severity reached hurricane level later.

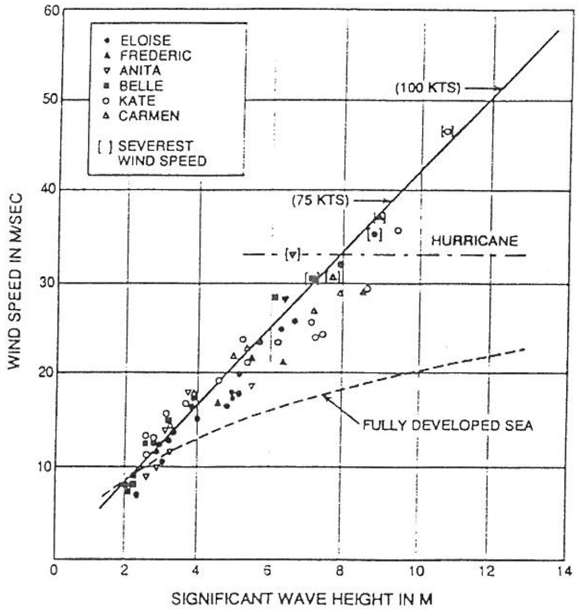

Figure 3:

Relationship between mean wind speed and significant wave height obtained in various hurricanes

As can be seen in Figure 3, the sea severity increases almost linearly with increase in wind speed during the growing stage of hurricanes. Since no appreciable scatter can be observed in the data, a probability analysis of data may not be required. By drawing the average line in the figure, the significant wave height during the growing stage of the hurricane can be simply obtained as a function of the mean wind speed at a 10 meter level as,

$$H_s = 0.235\, \bar{U}_{10}. \tag{1}$$

Included also in Figure 3 is the functional relationship between wind speed and significant wave height for fully-developed seas obtained from the Pierson-Moskowitz spectrum (1964). That is, the original Pierson-Moskowitz's spectral formulation for fully developed seas is given as a function of the mean wind speed referred to a 19.6 meter height above sea level. Under the assumption of a narrow-band spectrum, however, the formula can be presented as a function of significant wave height. Hence, we can drive the relationship between the mean wind speed and significant wave height for fully developed seas. By converting the wind speed to that at a 10 meter height, we have the following relationship:

$$H_s = 0.237\, (\bar{U}_{10}^2/g). \tag{2}$$

As expected, Figure 3 shows that the sea severity during the growing stage of a hurricane for a given wind speed is much less than that for fully developed seas. This is because the time duration of a given wind speed is extremely short during hurricanes in comparison with that required for fully developed seas.

Next, let us consider the sea condition resulting from continuous winds of mild severity blowing for one week or longer and then followed by storm, usually a tropical cyclone. In this case, the sea becomes severe. For example, before the tropical cyclone GLORIA passed near the NOAA Buoy 41002 in 1985, the sea condition (significant wave height) in that area was 2.5-4.0 meters for 10 days with consistently blowing winds of 7-11 m/sec. That is, the sea had the potential for being easily augmented in severity when GLORIA came to the area.

Figure 4 shows the relationship between the mean wind speed and significant wave height of GLORIA measured by the NOAA buoy. Included also in the figure is the functional relationship applicable for fully-developed seas given in Equation (2). As can be seen, the wind velocity-sea relationship is very close to that applicable for a fully-developed situation in this example. This does not imply, however, that the shape of the wave spectrum is very close to that of a fully-developed sea.

It is given by Pierson-Moskowitz that a sufficiently long time duration is prerequisite for generating the fully-developed wave spectrum. For example, at least 42 hours is required at a mean wind speed, U_{10} of 20 m/sec for a sea to become fully-developed and to have the spectral shape given by Pierson, Neumann and James (1955). It is not realistic to expect such a long sustained wind speed during a tropical cyclone. Therefore, even though the wind-wave relationship is close to that given in Eq.(2), the shape of the spectrum is different from that for a fully-developed sea as will be shown in the next section.

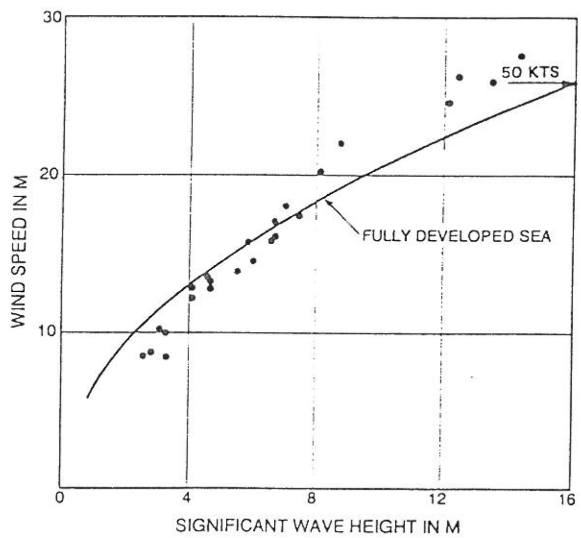

Figure 4:

Relationship between mean wind speed and significant wave height, Tropical cyclone GLORIA

Wave Spectra During Hurricanes

It is of considerable interest to examine the shapes of wave spectra during hurricanes, since the rate of change of wind speed is much shorter during hurricanes than that observed during ordinary storms. As an example, Figure 5 shows a comparison between a wave spectrum obtained during Hurricane ELOISE and various spectra obtained during ordinary storms in the North Atlantic. All spectra are obtained in deep water and have the same severity; significant wave height of 8.8 meters. As can be seen, the wave energy is concentrated primarily in the neighborhood of the peak frequency during the hurricane as contrasted with the energy being spread over a wide frequency range, including double peaks, for wave spectra obtained during ordinary storms.

One may expect the shape of wave spectra during hurricanes to be extremely random; however, the results of analysis of measured data in the open ocean have shown that there is a consistent trend in their shape, particularly in severe sea conditions. For example, Figure 6 shows a number of observations of modal frequency

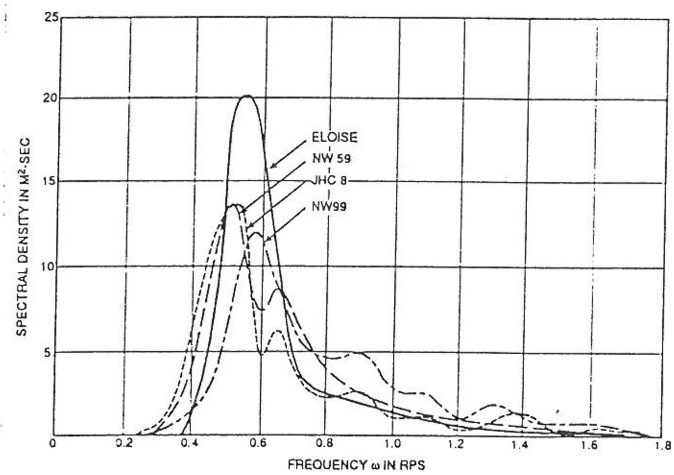

Figure 5:

Comparison between Hurricane ELOISE wave spectrum and wave spectra in ordinary storms having the same significant wave height, 8.8 m

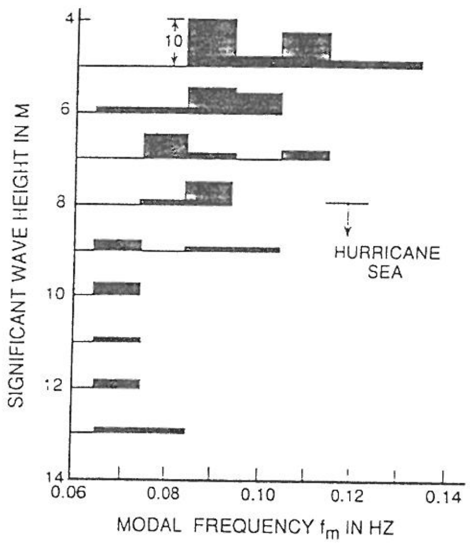

Figure 6:

Number of modal frequencies for specified significant wave height (From Foster 1982) of wave spectra for one-meter intervals of significant wave height. It can be seen that the location of modal frequencies during hurricanes is concentrated in the neighborhood of 0.07 Hz in severe seas.

Antani (1981) analyzed the shape of approximately 400 wave spectra obtained during hurricanes. In his analysis, the spectral shape is compared to various mathematical formulations such as the one-parameter (Pierson and Moskowitz 1964), the two-parameter, the three-parameter, the six-parameter (Ochi and Hubble 1976) and the JONSWAP spectra (Hasselmann et al. 1973). The parameters involved in these spectral formulations are determined so that the sum of the squared differences between the mathematical formulation and the observed spectra are minimal. The results of his analyses indicate that the six-parameter and the JONSWAP formulations well represent the wide variety of spectral shapes associated with the stages of growth, eye passage and decay of hurricane-generated seas.

Furthermore, Foster (1982) systematically analyzed the values of parameters involved in the JONSWAP spectral formulation and derived several significant conclusions. Based on the results of studies carried out by Antani and Foster, it is concluded that the shape of wave spectra during hurricanes can be well represented by the JONSWAP spectral formulations; however, the values of parameters involved in the formulation are different from those originally by Hasselmann as follows.

The JONSWAP spectral formulation is given as,

$$S(f) = \alpha \frac{g^2}{(2\pi)^4} \exp\left\{-1.25(f_m / f)^4\right\} \times \gamma^{\exp\left\{-(f - f_m)^2 / 2(\sigma f_m)^2\right\}}, \tag{3}$$

where

γ = peak-shape parameter, 3.30 as an average
α = $0.076\,(\bar{x})^{-0.22}$
σ = 0.07 for $f \le f_m$, and 0.09 for $f > f_m$
f_m = $3.5(g/\bar{U})(\bar{x})^{-0.33}$
$\bar{x}$ = dimensionless fetch = $gx/\bar{U}^2$
x = fetch length, and
$\bar{U}$ = mean wind speed.

The parameter α is a function of dimensionless fetch length which is extremely difficult to evaluate during hurricanes since the mean wind speed is continuously changing. It is obtained, however, that α can be well presented as a function of significant wave height, H_s, and modal frequency, f_m, as follows (Foster 1982):

$$\alpha = 4.5\, H_s^2\, f_m^4, \tag{4}$$

where the constant carries the units of $(\sec^2/\text{meter})^2$.

It is also found that the peak-shape parameter γ substantially deviates from the mean value 3.3 given in Eq. (3). Figure 7 shows the histogram of the peak-shape parameter evaluated by fitting the measured spectra by the JONSWAP formulation. As can be seen in the figure, the values of γ for hurricane-generated seas range from 0.60 to 4.0 which is significantly smaller than that obtained in the JONSWAP Project. It is noted that values of γ greater than 3.0 shown in the figure are primarily from the decay stage of a specific hurricane —— Hurricane BELLE.

Figure 8 shows the peak energy density, $S(f_m)$, obtained from measured data in hurricanes as a function of significant wave height. As can be seen, there is a strong correlation between the peak energy and significant wave height, and it can be presented by

$$S(f_m) = 0.75\, H_s^{2.34}. \tag{5}$$

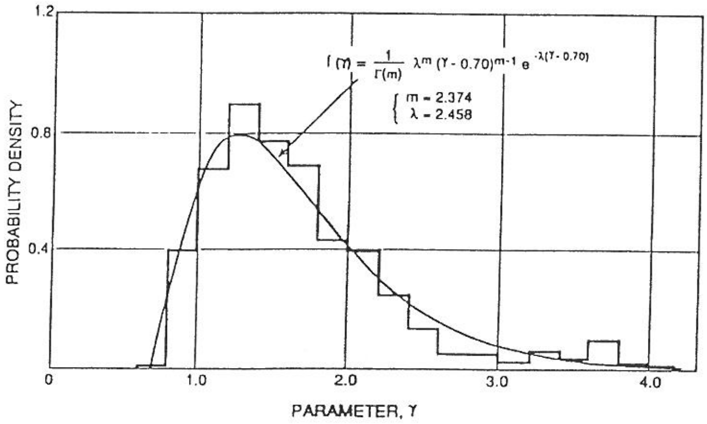

Figure 7:

Comparison of probability density function of Parameter of the JONSWAP spectrum (Data from Foster 1982)

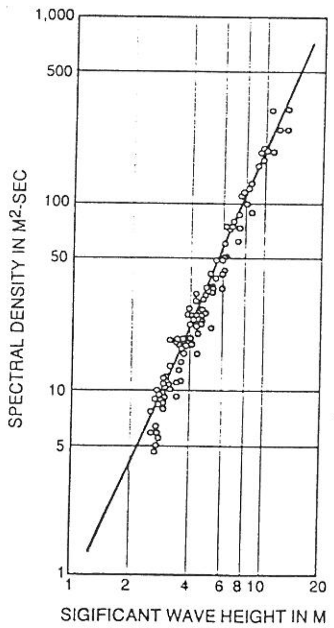

Figure 8:

Wave energy densities at modal frequency versus significant wave height (From Foster 1982)

On the other hand, the peak energy density of the JONSWAP spectrum can be obtained from Eq. (3) as

$$S(f_m) = \alpha \frac{g^2}{(2\pi)^4 f_m^5} e^{-1.25} \cdot \gamma . \tag{6}$$

Thus, from Eqs. (4) through (6), the peak-shape parameter can be expressed as a function of significant wave height and modal frequency as follows:

$$\gamma = 9.5 H_s^{0.34} f_m . \tag{7}$$

By using these relationships, we may derive a wave spectral formulation specifically applicable for hurricane-generated seas in the form of the JONSWAP formulation and as a function of significant wave height and modal frequency as follows:

$$S(f) = \frac{4.5}{(2\pi)^4} (H_s g)^2 (f_m^4 / f^5) \exp\left\{-1.25 (f_m / f)^4\right\}$$
$$\times \left(9.5 H_s^{0.34} f_m\right)^{\exp\left\{-(f - f_m)^2 / 2(\sigma f_m)^2\right\}} , \tag{8}$$

where the units are in meters and seconds. The above formula can also be written as a function of frequency ω as follows:

$$S(\omega) = \frac{4.5}{(2\pi)^4} (H_s g)^2 (\omega_m^4 / \omega^5) \exp\left\{-1.25 (\omega_m / \omega)^4\right\}$$
$$\times \left(\frac{9.5}{2\pi} H_s^{0.34} \omega_m\right)^{\exp\left\{-(\omega - \omega_m)^2 / 2(\sigma \omega_m)^2\right\}} . \tag{8'}$$

Figure 9 shows an example of comparison between Hurricane ELOISE and the spectral formulation given in Eq.(8'). Another two comparisons between the spectral formulation and spectra obtained during Hurricanes KATE and GLORIA are shown in Figures 10 and 11, respectively. Figure 10 is the case for a strong wind speed, 42.0 m/sec (81.7 knots), while Figure 11 is the case for a severe sea state, significant wave height of 14.3 meters. A good agreement between measure spectra and the formulation given in Eq.(8') can be seen in all these cases.

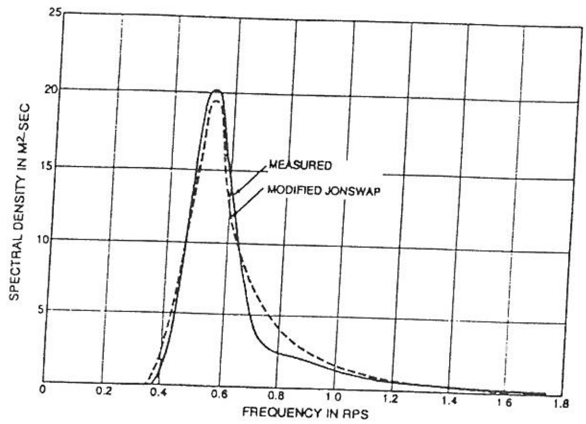

Figure 9:

Comparison between measured and modified JONSWAP spectra, Hurricane ELOISE (Significant wave height 8.8 m)

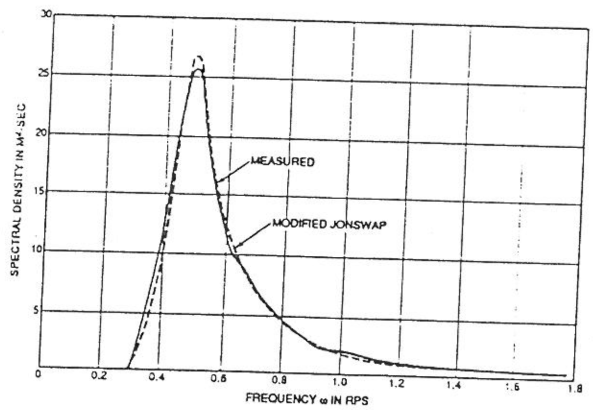

Figure 10:

Comparison between measured and modified JONSWAP spectra, Hurricane KATE (Significant wave height 10.0 m)

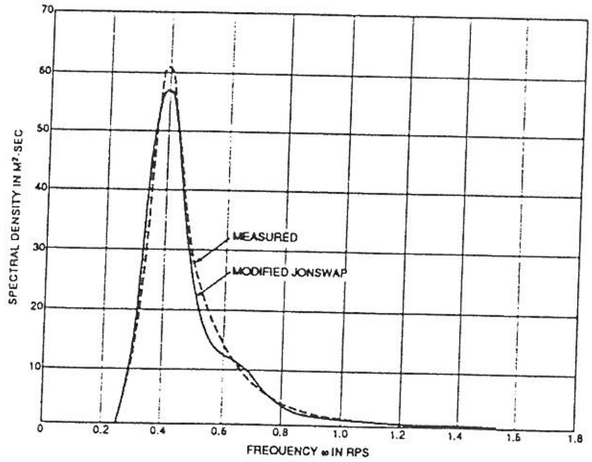

Figure 11:

Comparison between measured and modified JONSWAP spectra, Hurricane GLORIA (Significant wave height 14.3 m)

Design Application

There is no doubt that estimation of severe environmental conditions during hurricanes provides information vital for the design and safe operation of ships and offshore structures, hereafter called marine systems. In particular, consideration of simultaneous loadings associated with winds and waves is essential for marine system design. For evaluating simultaneous loadings of winds and waves, we may consider the following two different situations shown in Figure 12 which is a summary of Figures 3 and 4. One is the severest wind speed in a hurricane and the associated sea severity given by Eq.(1) (straight line in the figure), the other is the severest sea expected in a tropical cyclone and the associated wind speed which is given by Eq.(2).

As a practical application, suppose a hurricane wind speed of 100 knots (51.4 m/sec) is chosen as the design wind speed for a marine system in a seaway, then it is necessary to consider (i) a sea of significant wave height of 12.1 meters along with a wind speed of 100 knots, and (ii) a sea of significant wave height of 16.0 meters along with a wind speed of 50 knots. In both cases, evaluation of simultaneous loadings excited by wind and waves is highly desirable. If a wind speed of 50 knots (25.7 m/sec) or less is considered sufficient for the design, then we may consider only the severest sea expected in a tropical cyclone and the associated wind speed given by Eq.(2).

For evaluating wind loads, consideration of turbulent wind spectra carrying a significantly large amount of energy at low frequencies is recommended. For evaluating wave-induced loads during hurricanes, the concept of a family of wave spectra developed based on the results obtained in the previous section may be applied. That is, one of the features of wave spectra observed during hurricane-generated severe seas is that the modal frequency where the spectrum peaks occurs is in a small frequency range as

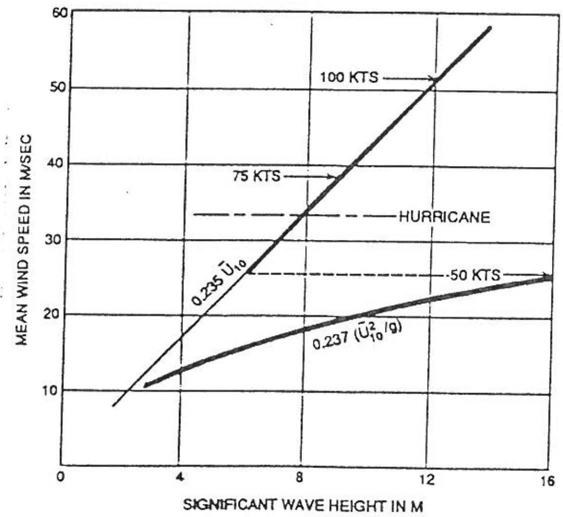

Figure 12:

Combination of mean wind speed and significant wave height for design consideration shown in Figure 6. In particular, the frequency range is extremely limited for severe seas of significant wave heights greater than 10 meters. Since the location of the modal frequency in severe seas appears to be indepndent of significant wave height, we may choose the three modal frequencies 0.063, 0.073 and 0.083 Hz (0.40, 0.46 and 0.52 rps, respectively) for design consideration. The results of analysis indicate that the probabilities of occurrence of these modal frequencies are 0.75, 0.17 and 0.08, respectively. By using these values of modal frequencies, a family of wave spectra consisting of three members can be generated by Eqs.(8) or (8′) for a specified significant wave height.

As an example, Figure 13 shows two sets of wave spectra which can be considered for a design wind speed of 100 knots. One is a family having a significant wave height of 12.1 meters for which a simultaneous loading associated with a wind speed of 100 knots (51.4 m/sec) should be considered; the other is a family having a significant wave height of 16.0 meters for which a wind-induced loading associated with wind speed of 50 knots (25.7 m/sec) should be concurrently considered.

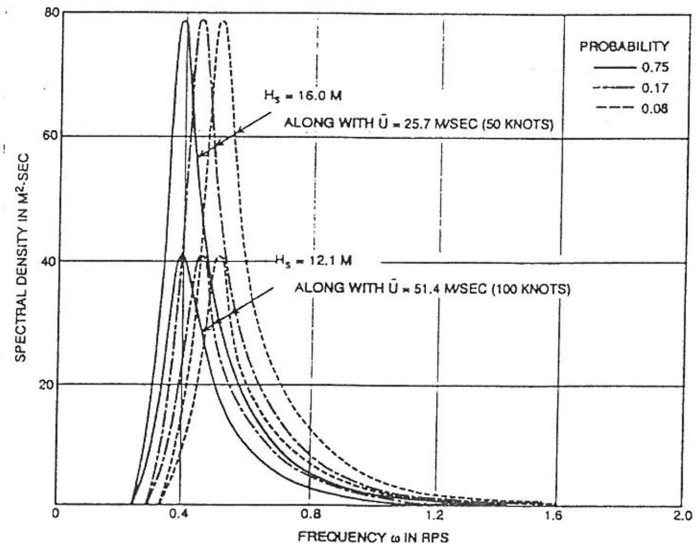

Figure 13: Family of wave spectra for design mean wind speed of 100 knots

Conclusions

This paper addresses the relationship between hurricane (or tropical cyclone) wind speed and sea seveity as well as the shape of wave spectra during hurricanes. It was found from analysis of measured data obtained by NOAA buoys that there are two different situations in the relationship between sea severity and mean wind speed. One is the growing stage of hurricanes in which the wind speed is increasing at an extremely high rate but the sea severity is comparatively mild; the functional relationship between wind speed and sea severity is given by Eq.(1). The other is the sea condition resulting from continuous winds of mild severity blowing for one week or longer then followed by a tropical storm in which the sea condition is very severe but the magnitude of wind speed is much less than that of a hurricane; the functional relationship between wind speed and sea severity is given by Eq.(2).

For the design and safe operation of marine systems, therefore, it is highly desirable to consider simultaneous loadings associated with winds and waves under these two circumstances.

From analysis of 400 wave spectra obtained from measured data during hurricanes, a wave spectral formulation specifically applicable for hurricane-generated seas is derived in the form of the JONSWAP formulation but as a function of significant wave height and modal frequency. Comparisons between wave spectra obtained in Hurricanes ELOISE, KATE and GLORIA and computed spectra by the formulation show good agreement.

Acknowledgements

The author would like to express his deep appreciation to Mr. Emmett Foster for his excellent analysis on the shape of wave spectra during hurricanes. He is also grateful to Ms. Laura Dickinson for typing the manuscript.

References

Antani, J.K., "Mathematical Presentation of Hurricane Associated Wave Spectra", University of Florida, *Report UFL/COEL*-81/007, 1981.

Bretschneider, C.L. and Tamaye, E.E., "Hurricane Wind and Wave Forecasting Techniques", *Proc. 5th Coastal Eng. Conf.*, 1976, pp. 202-237.

Cardone, V.J., Pierson W.J. and Ward, E.G., "Hindcasting the Directional Spectra of Hurricane-Generated Seas", *J. Petroleum Tech.* Vol. 28, 1976, pp. 385-395.

Foster, M.F., "JONSWAP Spectral Formulation Applied to Hurricane-Generated Seas", University of Florida, *Report UFL/COEL*-82/004, 1982.

Hasselmann, K. et al., *Measurements of Wind-Wave Growth and Swell Decay During the Joint North Sea Wave Project (JONSWAP)*, Deutsches Hydrograph. Inst., 1973.

NOAA Data Report, "Buoy Observations during Hurricane ELOISE", National Oceanographic Data Center, 1975.

Ochi, M.K. and Hubble, N.E., "On Six-Parameter Wave Spectra", *Proc. 15th International Coastal Eng. Conference*, Vol. 1, 1976, pp. 301-328.

Pierson, W.J., Neumann, G. and James, R.W., *Practical Methods for Observing and Forecasting Ocean Waves*. Hydrographic Office, U.S. Navy, Publication #603, 1955.

Pierson, W.J. and Moskowitz, L., "A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S.A. Kitaigorodskii", *Journal Geoph. Res.*, Vol. 69, 1964, pp. 5181-5190.

Ross, D. and Cardone, V., "A Comparison of Parametric and Spectral Hurricane Wave Prediction Products", *Turbulent Fluxes through Sea Surface, Wave Dynamics and Prediction*, 1978.

Young, I.R., "Parametric Hurricane Wave Prediction Model", *J. Waterway, Port, Coastal & Ocean Eng.*, Vol. 114, No. 5, 1988, pp. 637-652.

Young, I.R. and Sobey, R.J., "The Numerical Prediction of Tropical Cyclone Wind-Waves", *Res. Bulletin No. CS20*, University of North Queensland, 1981.