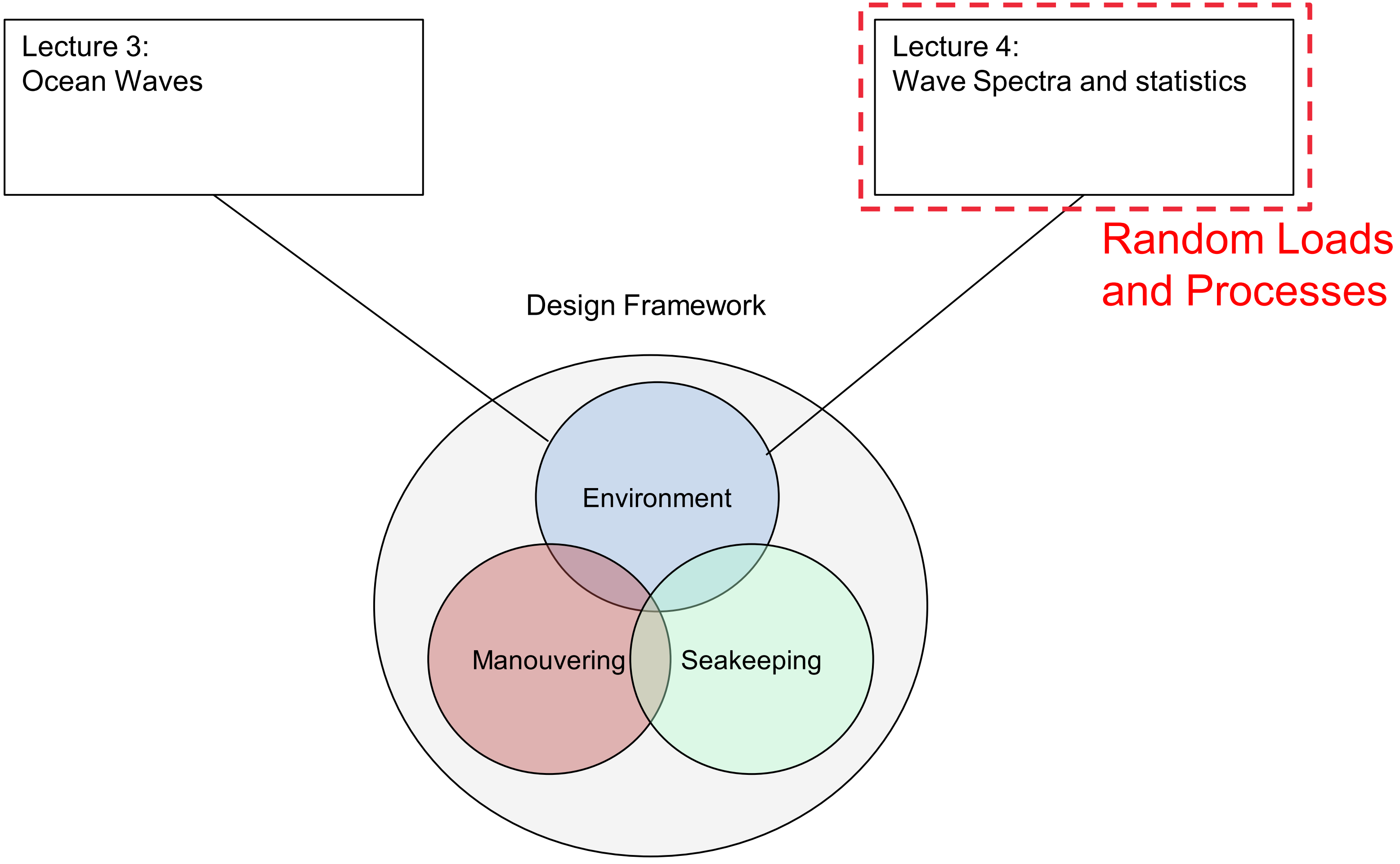
Aalto University
School of Engineering

MEC-E2004 Ship Dynamics (L)

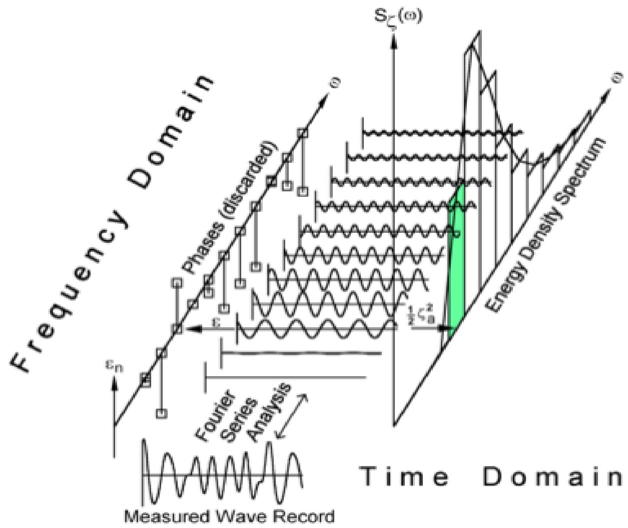
Lecture 4 –Irregular Seas

Where is this lecture on the course?

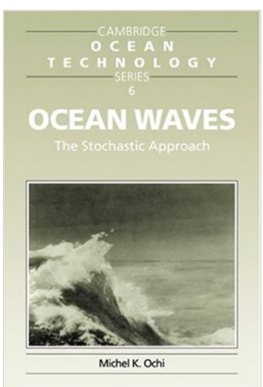


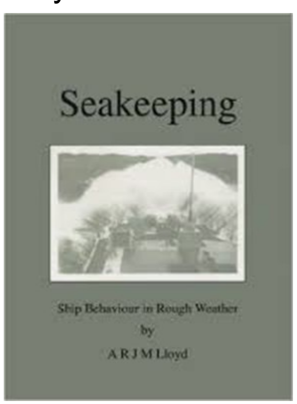
Contents

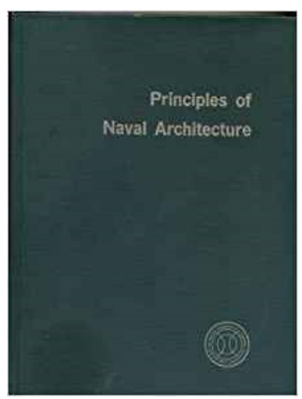
- **Aim :** To understand the wave spectrum and how it may be used to calculate short term ship responses in irregular seas ; Some brief introduction to Long term responses.

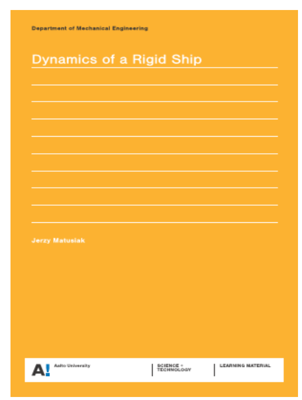


- <u>Literature</u>
  - ➢ Ochi, M., “Ocean Waves - The Stochastic Approach”, Cambridge Series, Ocean Technology, 6, Chapter 1
  - ➢ Lloyd, A.R.J.M, ”Seakeeping – Ship Behaviour in Rough Weather”, John Wiley & Sons, Chapters 3-4
  - ➢ Lewis, ”Principles of Naval Architecture – Vol. III”, SNAME, 1989
  - ➢ Matusiak, J., ”Dynamics of Rigid Ship”, Aalto University
  - ➢ Simon Haykin and Barry van Veen (2007), Signals and Systems, 2nd Edition, Wiley.









Motivation

- Ships operate in varying wave conditions. We should be able to evaluate Loads and motions under different wave heights and lengths

- Even if the ship is rigid it experiences varying pressures around hull . We have to know the influence of this varying pressure on motions, hydrodynamics pressures, shear forces and bending moments

- Hydrodynamic idealisations are possible in both frequency and time domains.
  - ➢ Frequency domain is useful for screening the worst conditions for our ship
  - ➢ Time domain to perform non-linear simulations at a given sea state

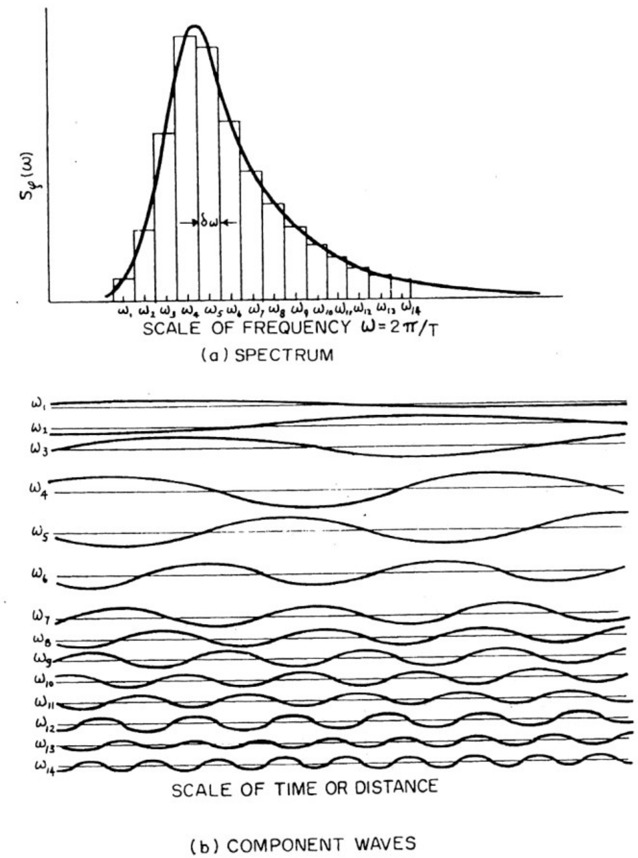


Fig. 8 Typical variance spectrum of waves, showing approximation by a finite sum of components

Assignment 2

Grades 1-3:

- ✓ Select a book-chapter related to ocean waves
- ✓ Define the water depths for your ship's route and seasonal variations of wave conditions
- ✓ Based on potential flow theory, sketch what kind of waves you can encounter during typical journey (deep water, shallow water)
- ✓ Identify and select the most suitable wave spectra for your ship - Justify the selection.
- ✓ Discuss the aspects (e.g. likelihood) to consider in case of extreme events from viewpoint of operational area

- Grades 4-5:
  - ✓ Read 1-2 scientific journal articles related to ship dynamics
  - ✓ Reflect these in relation to knowledge from books and lecture slides

- Report and discuss the work.

Example

Mediterranean or Baltic Sea

- 9 months in open water
- 3 months in ice

Route: …

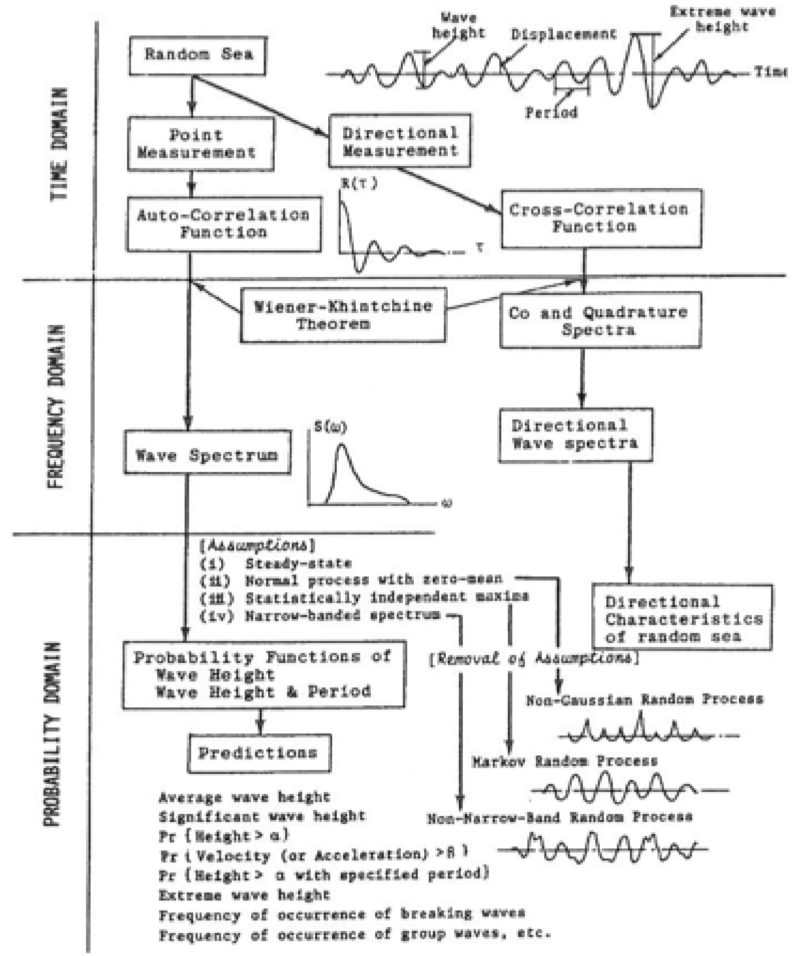
Water depth: …

Waves and Probability – the basics

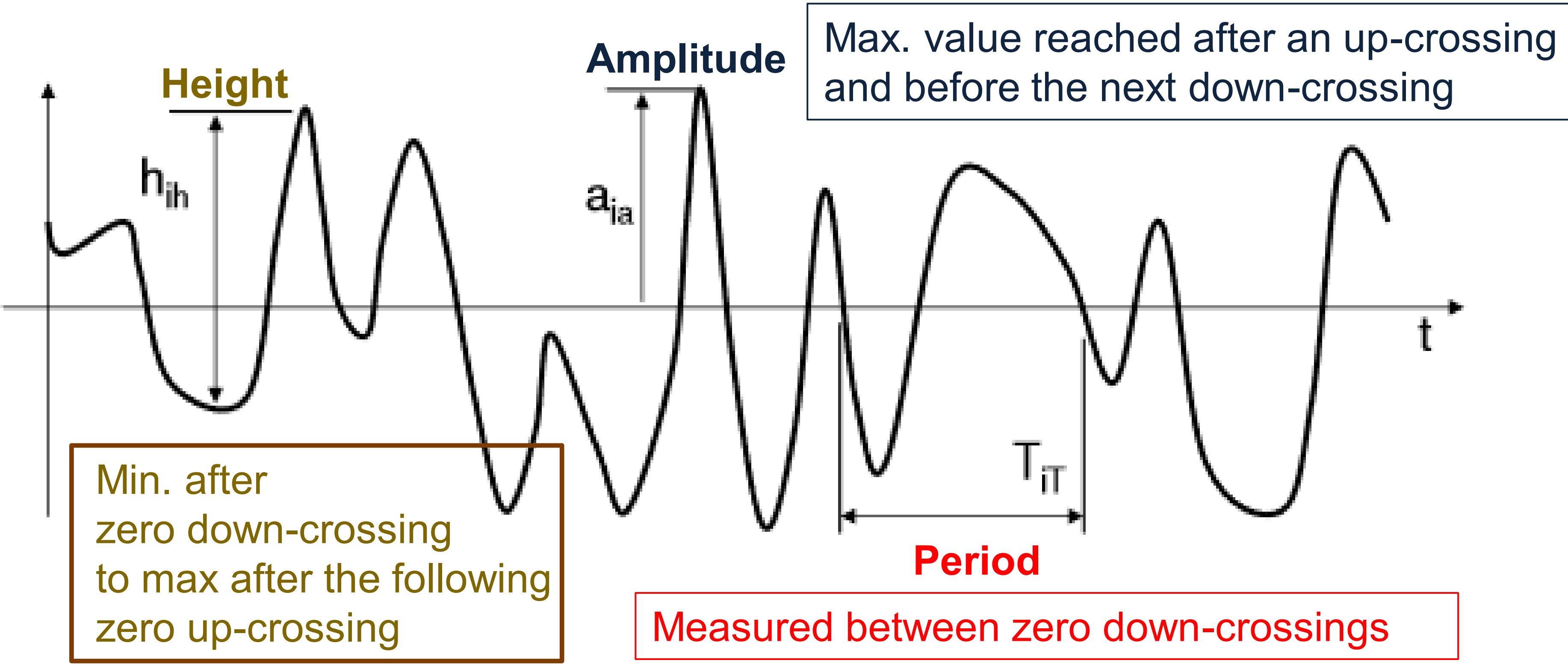
- When we measure the wave elevation of the random sea at a specific point we should move from time domain to probability domain through
  - ➢ Auto-correlation function, Fourier transformation
  - ➢ Wave spectrum

- Assumptions that are necessary to obtain the probabilities are:
  - ➢ Steady state process (probabilities will not be changing much from one transition to the next – stable probabilities)
  - ➢ Normal process (Gaussian / Bell type / Standard distribution) with zero mean
  - ➢ Statistically independent maxima (occurrence of one event does not affect the other)
  - ➢ Narrow-banded statistical process (spectrum energy with focus on single frequency or small number of frequencies)

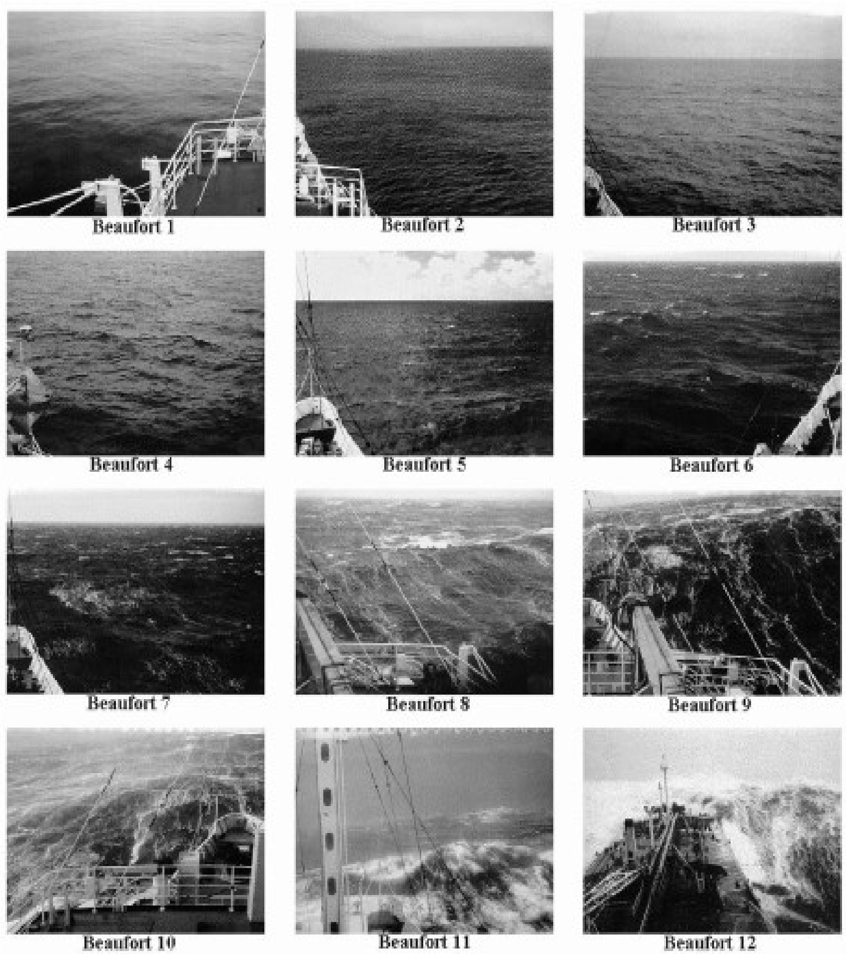
- If we remove these assumptions also the way to assess probabilities, e.g. for extreme loads change



The Irregular Wave



Irregular Waves - classification

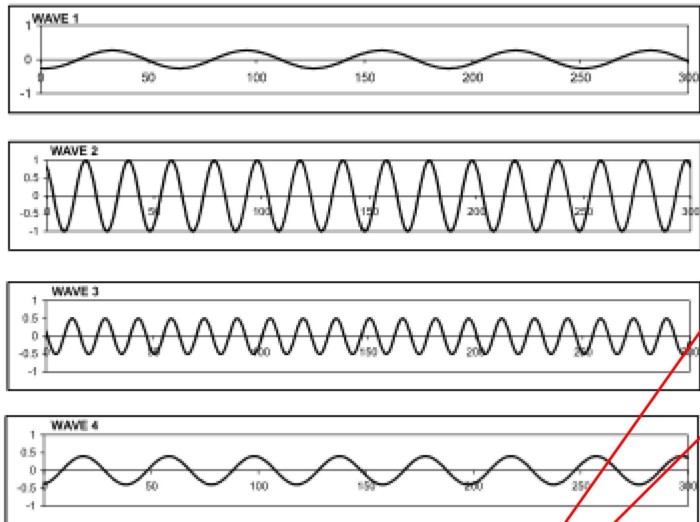


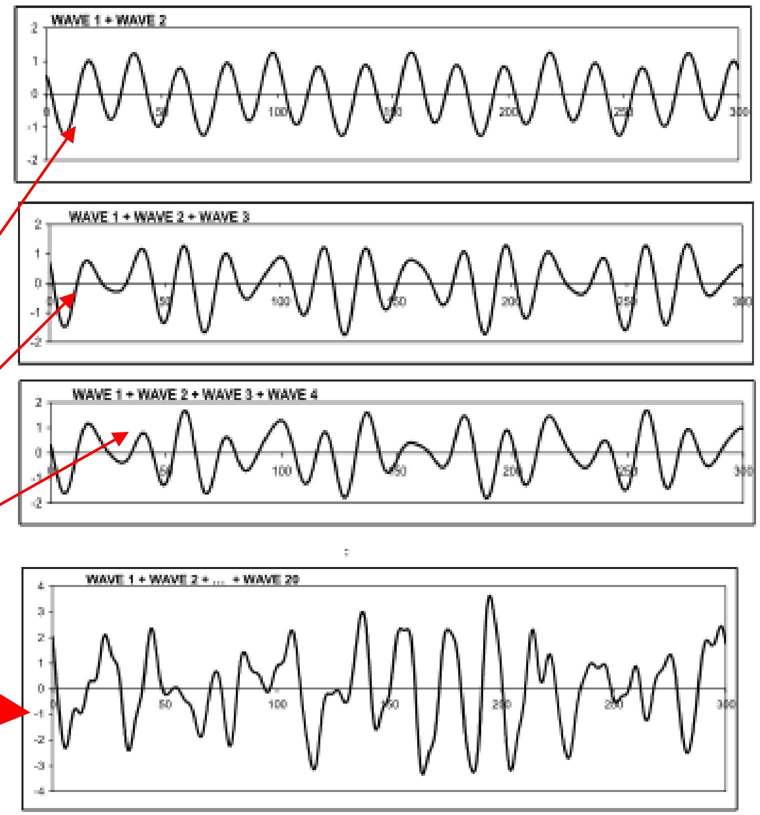
Determination of the wave spectra is carried out by observations of seaway and prevailing wind.

Description of wind	Beaufort number	Wind speed (knots)	SWH $h_{1/3}$ (m)
Light air	1	2 -3	1.00
Light breeze	2	4 - 7	1.40
Gentle breeze	3	8 - 11	1.65
Moderate breeze	4	12 - 16	2.25
Fresh breeze	5	17 - 21	3.10
Strong breeze	6	22 - 27	4.15
Moderate gale	7	28 - 33	5.40
Fresh gale	8	34 - 40	7.10
Strong gale	9	41 - 48	10.10
Whole gale	10	49 - 56	12.45
Storm	11	57 - 65	15.90
Hurricane	12	more than 65	

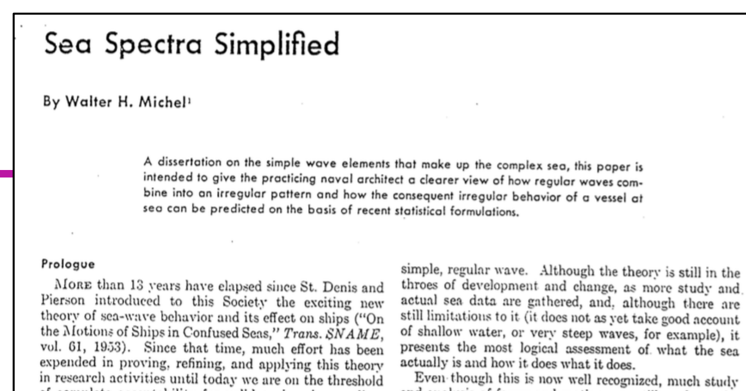
This table may be useful in obtaining wave spectra when wind speed is known.

The irregular wave formation





Combination of waves leads to irregular wave



Sea Spectra Simplified

By Walter H. Michel[1]

A dissertation on the simple wave elements that make up the complex sea, this paper is intended to give the practicing naval architect a clearer view of how regular waves combine into an irregular pattern and how the consequent irregular behavior of a vessel at sea can be predicted on the basis of recent statistical formulations.

Prologue

More than 13 years have elapsed since St. Denis and Pierson introduced to this Society the exciting new theory of sea-wave behavior and its effect on ships ("On the Motions of Ships in Confused Seas," *Trans. SNAME*, vol. 61, 1953). Since that time, much effort has been expended in proving, refining, and applying this theory in research activities until today we are on the threshold

simple, regular wave. Although the theory is still in the throes of development and change, as more study and actual sea data are gathered, and, although there are still limitations to it (it does not as yet take good account of shallow water, or very steep waves, for example), it presents the most logical assessment of what the sea actually is and how it does what it does.

Even though this is now well recognized, much study

Irregular wave formation - mathematics

- Consider a regular wave described by

$$\zeta(t) = a\cos(\omega t + \alpha)$$

- An irregular wave would result form the superposition of a large number of regular waves. So,

$$\zeta(t) = \sum_{i=1}^{M} a_i \cos(\omega_i t + \alpha_i)$$

- Consequently the surface wave elevation can be expressed as

$$\zeta(x,t) = \sum_{i} a_i \cos(k_i x - \omega_i t + \beta_i)$$

when waves propagate along x- axis (i.e. unidirectional seaway).

ω_i = frequency of the *ith* regular wave

a_i = amplitude

β_i = the randomly chosen phase angle

k_i = wave number

The irregular wave formation - mathematics

If the mean is zero (i.e. $\langle \zeta(t) \rangle = 0$) then the mean square value becomes :

wave spectrum

$$\langle \zeta^2(t) \rangle = \frac{1}{2} \sum_{i=1}^{M} a_i^2 = \int_0^{\infty} \Phi_{\zeta\zeta}(\omega) d\omega$$

- Practically the phase angles are selected from a random distribution ranging from 0 to 2π (i.e. 360 degrees)

- The mean square value of the irregular seaway after integration can be proved to be :

$$m_0 = \frac{1}{2} \sum_i a_i^2 = \int_0^{\infty} \Phi_{\zeta\zeta}(\omega) d\omega \approx \sum_i \Phi_{\zeta\zeta}(\omega_i) \Delta\omega_i \quad (1)$$

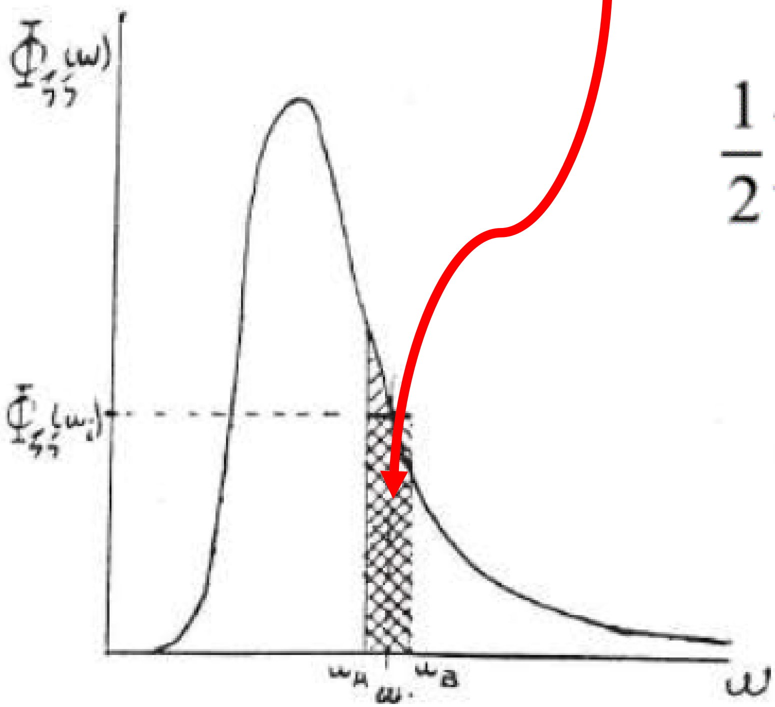
$\sum_i \Phi_{\zeta\zeta}(\omega_i) \Delta\omega_i$ is a crude way of evaluating the area under the wave spectrum

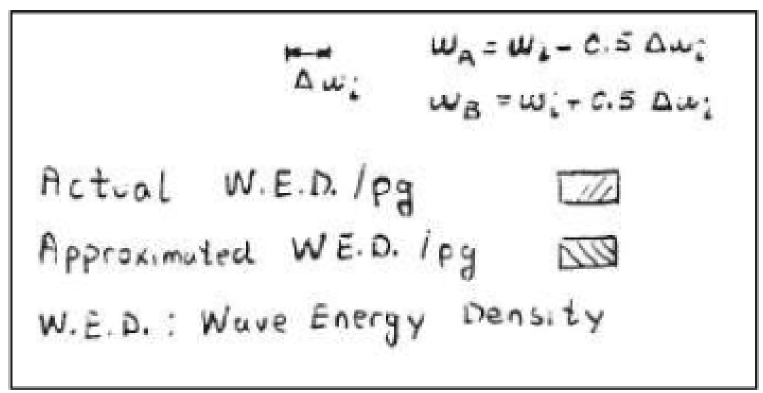
The irregular wave formation - mathematics

- If we are familiar with the form of a **wave spectrum** then we can determine form (1) the component waves as

$$a_i = \sqrt{2\,\Phi_{\zeta\zeta}(\omega_i)\,\Delta\omega_i}$$

$$\frac{1}{2}\sum_i a_i^2 \approx \sum_i \Phi_{\zeta\zeta}(\omega_i)\,\Delta\omega_i$$





Directionality of Spectra

Continuous

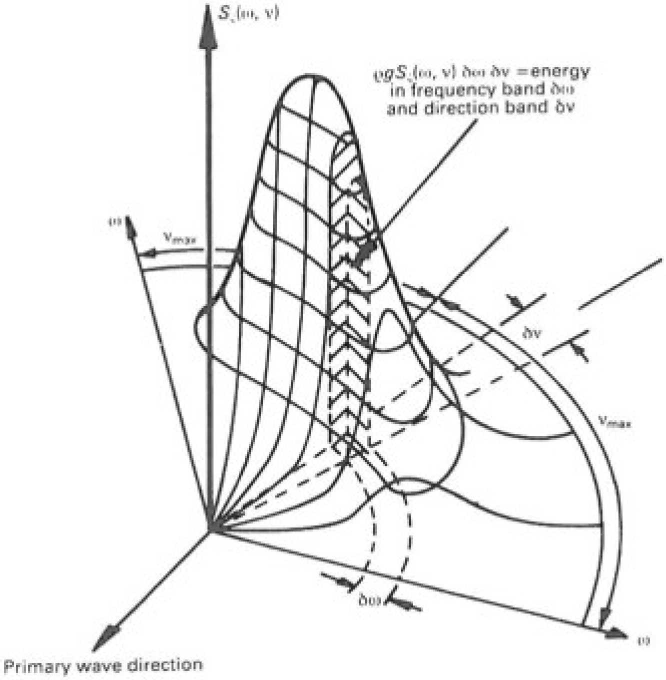


Fig. 4.13 — Typical directional wave spectrum.

Discrete spreading

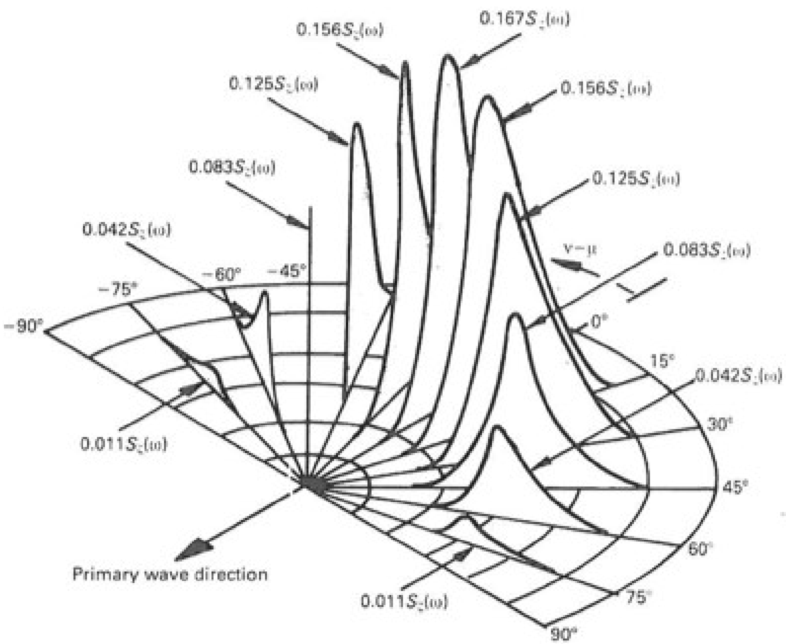
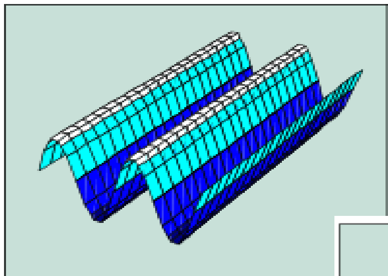


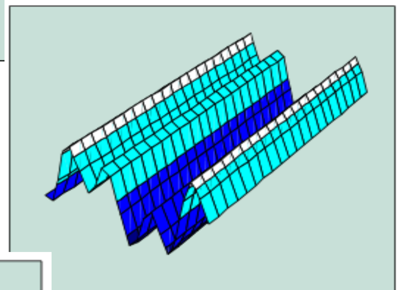
Fig. 4.15 — Representation of directional spectrum at discrete heading intervals of 15°; cosine squared spreading over ± 90°.

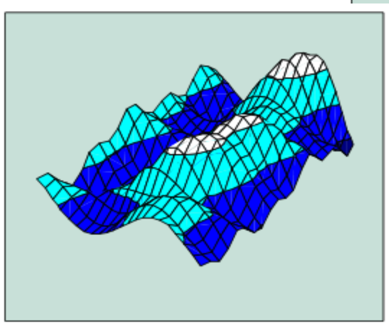
From 2D to 3D wave description – spreading

Long crested regular wave



Long crested irregular wave (M = 4)





Short crested (or confused seas) irregular wave (M=4)

In short crested or confused seas spreading function is used to express the waves in different directions
The spreading function is :

Wave spectrum

$$\Phi_{\zeta\zeta}(\omega,\mu) = \cos^n \mu \; \Phi_{\zeta\zeta}(\omega)$$

$$\text{for} \quad -\pi/2 \le \mu \le \pi/2 \quad \text{and} \quad n = 2 \text{ or } 4$$

For confused seas ITTC recommends spreading function

$$f(\mu) = \frac{2}{\pi}\cos^2\mu, \text{ where } -\pi/2 < \mu < \pi/2. \quad \textit{and } n = 2$$

Spectrum idealisation – mathematical background

- **<u>Time domain :</u>** Your model/system is evaluated according to the progression of it's state with time.

- **<u>Frequency domain :</u>** Your model/system is analysed according to its response for different frequencies.

- In a linear system you can use Fourier Transform to "transport" your model from time domain to frequency domain. Conversely your system can be transformed form frequency to time domain via an inverse Fourier transform (also known as convolution integral)

- The Fourier Transform decomposes any function into a sum of sinusoidal basis functions. Each of these basis functions is a complex exponential of a different frequency. The Fourier Transform therefore gives us a unique way of viewing any function as the sum of simple sinusoids. It applies to both periodic and non periodic functions

Spectrum idealisation – mathematical background

The Fourier Transform of a function g(t) is defined by:

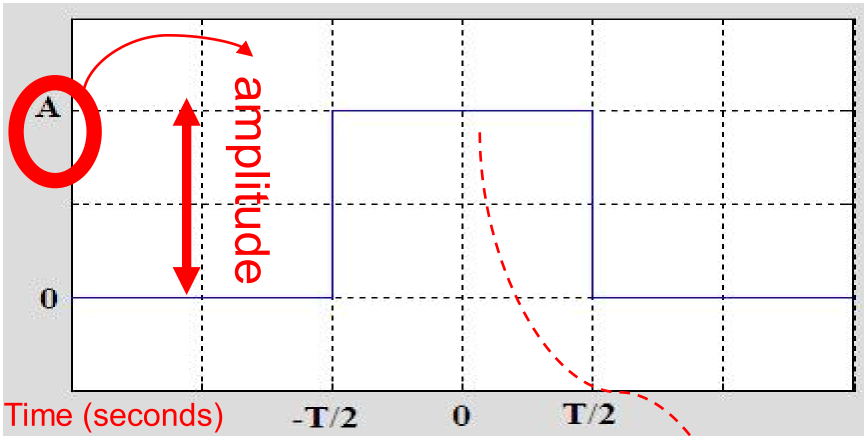
$$\mathcal{F}\{g(t)\} = G(f) = \int_{-\infty}^{\infty} g(t) e^{-2\pi i f t} dt \quad (1)$$

The result is a function of f, or frequency. As a result, G(f) gives how much power g(t) contains at the frequency f. **G(f) is often called the spectrum of g.** In addition, g can be obtained from G via the inverse Fourier Transform (convolution integral) as :

$$\mathcal{F}^{-1}\{G(f)\} = \int_{-\infty}^{\infty} G(f) e^{2\pi i f t} df = g(t) \quad (2)$$

Spectrum idealisation – mathematical background

The box function (also known as square pulse or square wave)

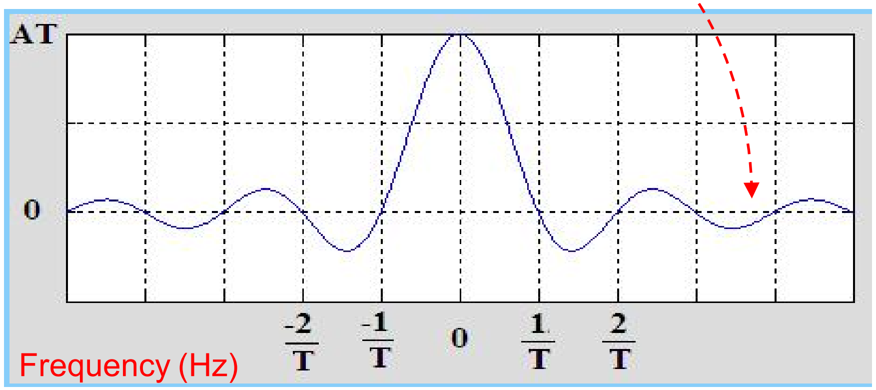


$$\mathcal{F}\{g(t)\} = G(f) = \int_{-\infty}^{\infty} g(t)e^{-2\pi ift}dt$$

$$= \int_{-T/2}^{T/2} Ae^{-2\pi ift}dt = \frac{A}{-2\pi if}\left[e^{-2\pi ift}\Big|_{-T/2}^{T/2}\right]$$

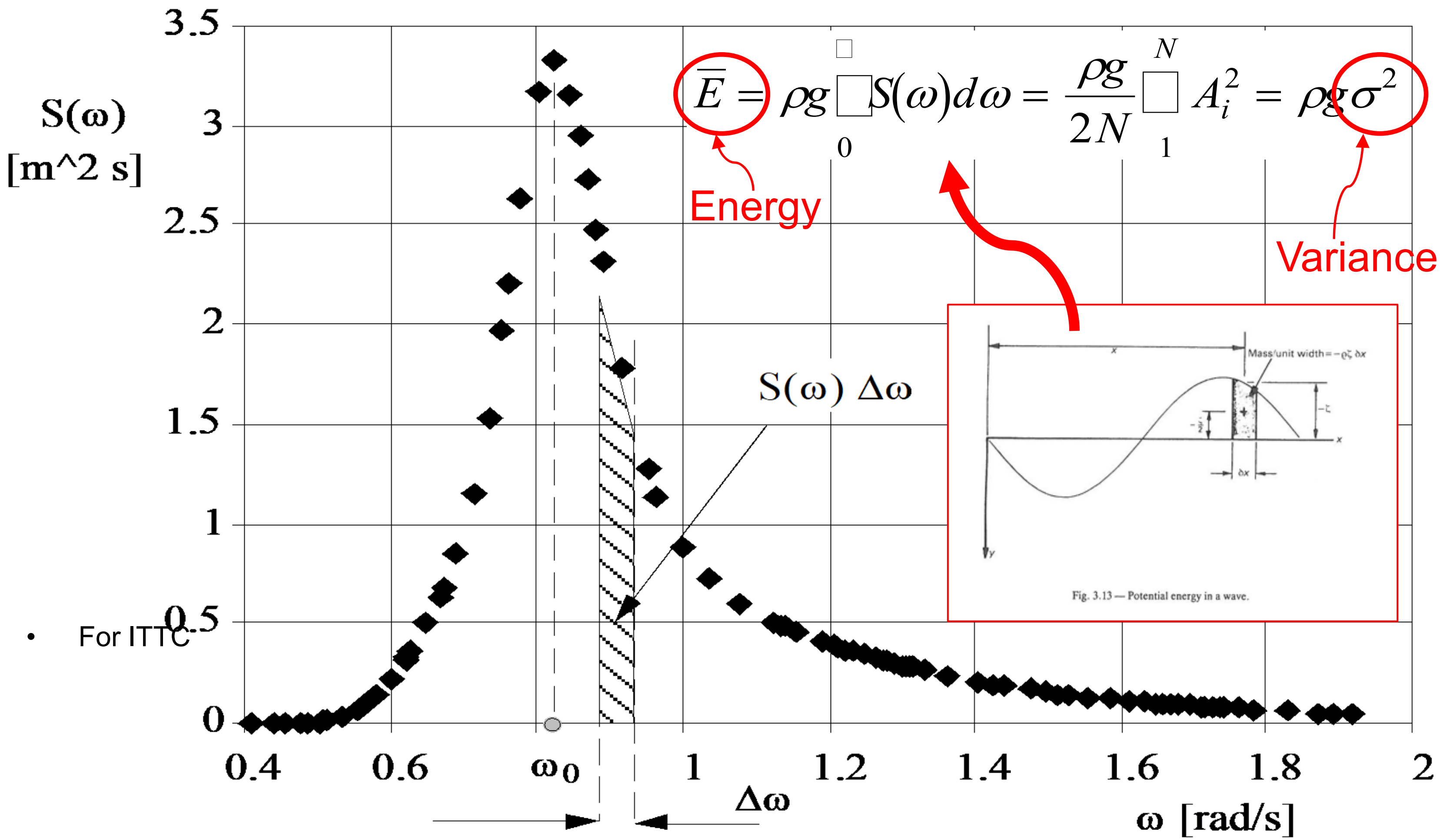
$$= \frac{A}{-2\pi if}\left[e^{-\pi ifT} - e^{\pi ifT}\right] = \frac{AT}{\pi fT}\left[\frac{e^{\pi ifT} - e^{-\pi ifT}}{2i}\right]$$

$$= \frac{AT}{\pi fT}\sin(\pi fT) = AT[\mathrm{sinc}(fT)]$$



The sinc function is the Fourier Transform of the box function.

Power spectral density of wave amplitude
- 100 frequency components



- For ITTC

Extreme Value Response

- The k^{th} moment (analogous to mechanics)

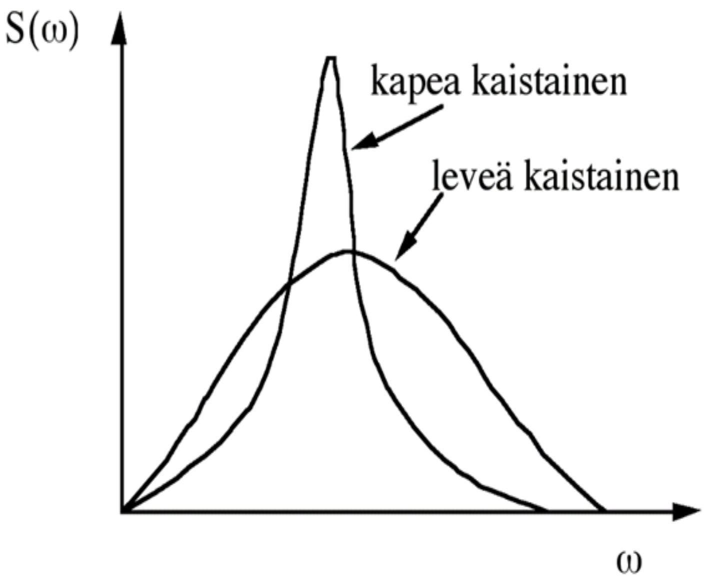
$$m_k = \int_0^{\infty} \omega^k S(\omega) d\omega$$

- The average angular velocity

$$\overline{\omega}_1 = \frac{m_1}{m_0} = \frac{\int_0^{\infty} \omega S(\omega) d\omega}{\int_0^{\infty} S(\omega) d\omega}$$

- The k^{th} moment with respect to average angular velocity

$$\mu_k = \int_0^{\infty} \left(\omega - \overline{\omega}\right)^k S(\omega) d\omega$$



- The bandwith parameter (0 for narrow band and 1 for broad band)

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}$$

$$0 \le \varepsilon \le 1$$

Extreme Value Response

- Let *X(t)* be stationary Gaussian process with zero mean and spectral area m_0 while the objective is to define the most probable extreme value at certain time

$$\bar{z} = \sqrt{\ln n}\sqrt{2m_0} \qquad \bar{N}_{0+} = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}$$

- The expected value for zero-crossings for certain time is calculated by

$$n = \frac{T}{2\pi}(60)^2\sqrt{\frac{m_2}{m_0}}$$

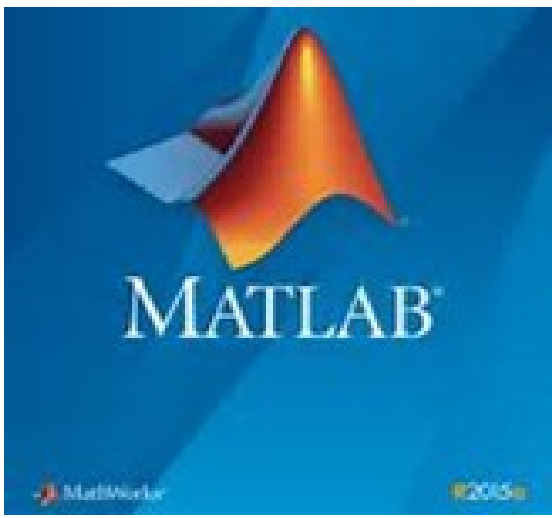
- and the extreme value

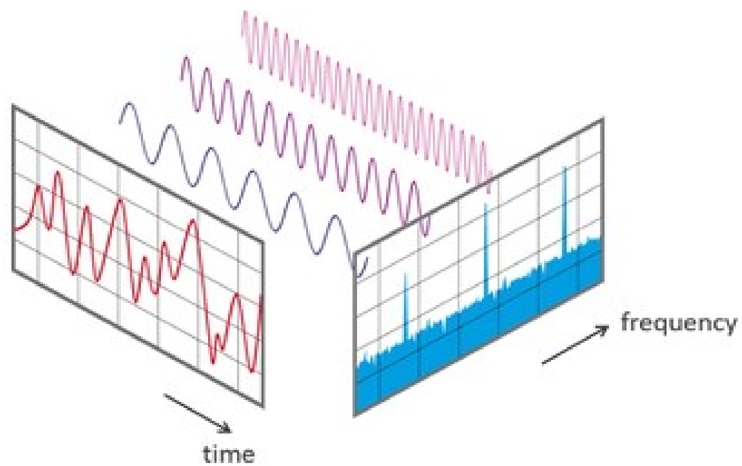
$$\bar{z} = \sqrt{2\ln\left(\frac{T}{2\pi}(60)^2\sqrt{\frac{m_2}{m_0}}\right)}\sqrt{m_0}$$

Spectrum idealisation practical

- A fast Fourier transform (FFT) is an algorithm that samples a signal over a period of time (or space) and divides it into its frequency components. These components are single sinusoidal oscillations at distinct frequencies each with their own amplitude and phase.

- FFT rapidly computes such transformations by factorizing the FT matrix into a product of sparse (mostly zero) factors. As a result, it manages to reduce the complexity of computing the DFT





Spectrum idealisation practical
A note on PSD

- Power Spectral Density (PSD) (or power spectrum) is a measure of a signal's power intensity in the frequency domain.
- In practice, the PSD is computed from the FFT spectrum of a signal. The PSD provides a useful way to characterize the amplitude versus frequency content of a random signal.
- So a PSD will gives the power of your signal, in each frequency band
- In MATLAB signal processing toolbox information on PSD is under : https://uk.mathworks.com/help/signal/ug/power-spectral-density-estimates-using-fft.html?s_tid=gn_loc_drop

Spectrum idealisation practical

From Time to Frequency domain

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fft

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R2016b

Fast Fourier transform

collapse all in page

Syntax

```
Y = fft(X)
Y = fft(X,n)
Y = fft(X,n,dim)
```

example
example
example

Description

`Y = fft(X)` computes the discrete Fourier transform (DFT) of X using a fast Fourier transform (FFT) algorithm. example

- If X is a vector, then `fft(X)` returns the Fourier transform of the vector.
- If X is a matrix, then `fft(X)` treats the columns of X as vectors and returns the Fourier transform of each column.
- If X is a multidimensional array, then `fft(X)` treats the values along the first array dimension whose size does not equal 1 as vectors and returns the Fourier transform of each vector.

`Y = fft(X,n)` returns the n-point DFT. If no value is specified, Y is the same size as X. example

- If X is a vector and the length of X is less than n, then X is padded with trailing zeros to length n.
- If X is a vector and the length of X is greater than n, then X is truncated to length n.
- If X is a matrix, then each column is treated as in the vector case.
- If X is a multidimensional array, then the first array dimension whose size does not equal 1 is treated as in the vector case.

`Y = fft(X,n,dim)` returns the Fourier transform along the dimension `dim`. For example, if X is a matrix, then `fft(X,n,2)` returns the n-point Fourier transform of each row. example

Spectrum idealisation practical

From Time to Frequency domain

```
Fs = 1000;            % Sampling frequency
T = 1/Fs;             % Sampling period
L = 1000;             % Length of signal
t = (0:L-1)*T;        % Time vector
```

Form a signal containing a 50 Hz sinusoid of amplitude 0.7 and a 120 Hz sinusoid of amplitude 1.

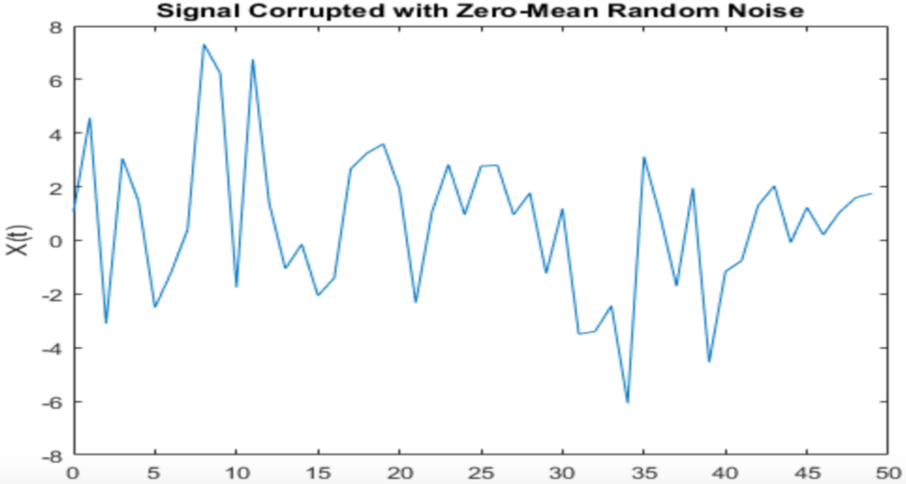
```
S = 0.7*sin(2*pi*50*t) + sin(2*pi*120*t);
```

Corrupt the signal with zero-mean white noise with a variance of 4.

```
X = S + 2*randn(size(t));
```

Plot the noisy signal in the time domain. It is difficult to identify the frequency components by looking at the signal `X(t)`.

```
plot(1000*t(1:50),X(1:50))
title('Signal Corrupted with Zero-Mean Random Noise')
xlabel('t (milliseconds)')
ylabel('X(t)')
```



Spectrum idealisation practical

From Time to Frequency domain

Compute the Fourier transform of the signal.

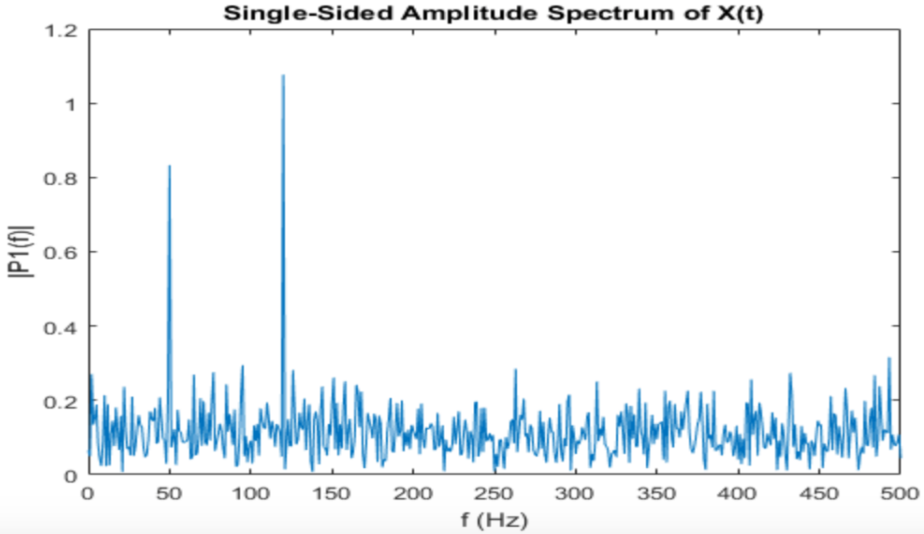
```
Y = fft(X);
```

Compute the two-sided spectrum P2. Then compute the single-sided spectrum P1 based on P2 and the even-valued signal length L.

```
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);
```

Define the frequency domain f and plot the single-sided amplitude spectrum P1. The amplitudes are not exactly at 0.7 and 1, as expected, because of the added noise. On average, longer signals produce better frequency approximations.

```
f = Fs*(0:(L/2))/L;
plot(f,P1)
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
```

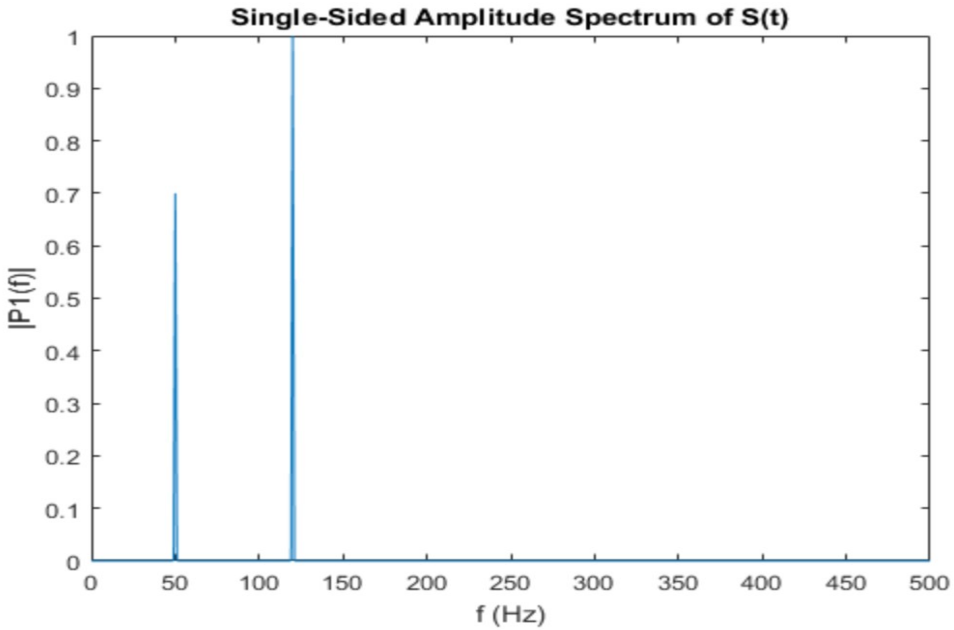


Spectrum idealisation practical

From Time to Frequency domain

Now, take the Fourier transform of the original, uncorrupted signal and retrieve the exact amplitudes, 0.7 and 1.0.

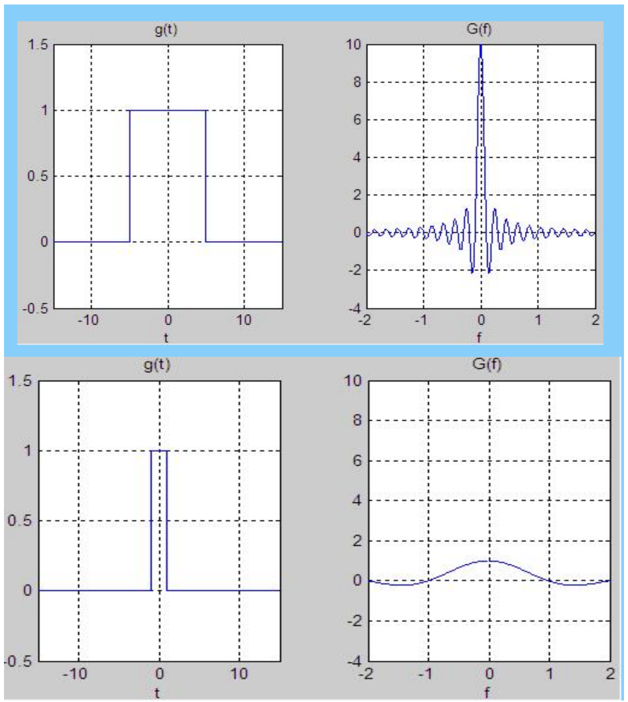
```
Y = fft(S);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);

plot(f,P1)
title('Single-Sided Amplitude Spectrum of S(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
```



Spectrum idealization practical

Exercise (at your own time)

To comprehend more MATLAB computations consider square pulses defined for T = 10 and T = 1. Then Produce the FT of these functions for Amplitude A = 1



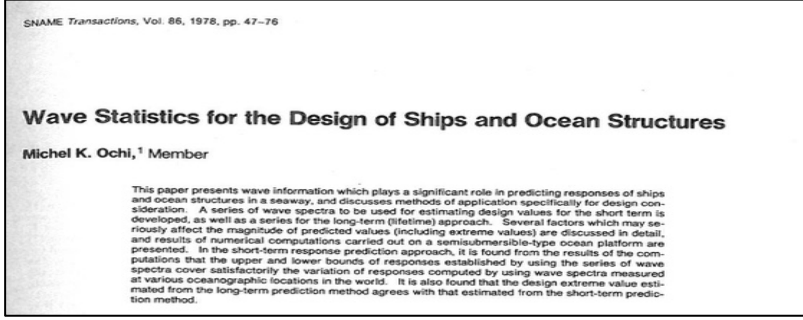
The Box Function with T=10, and its FT

A wider square pulse produces a narrower, more constrained spectrum

The Box Function with T=1, and its FT

- *A thinner square pulse produces a wider spectrum*
- *The box function is shorter in time, so it has less energy. This is reflected in the time domain spectrum.*

Types of wave spectra


SNAME *Transactions*, Vol. 86, 1978, pp. 47–76

Wave Statistics for the Design of Ships and Ocean Structures

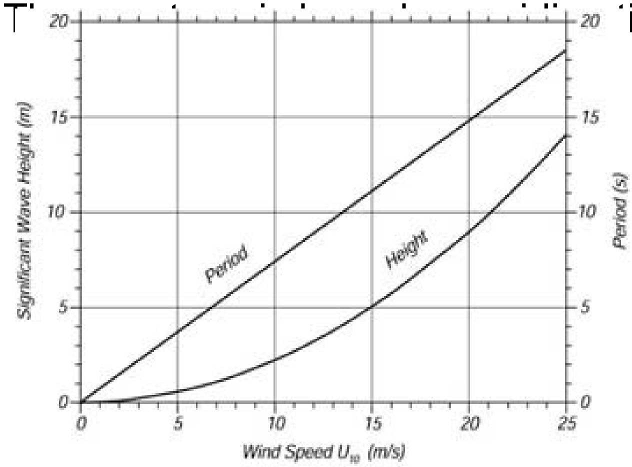
Michel K. Ochi,[1] Member

This paper presents wave information which plays a significant role in predicting responses of ships and ocean structures in a seaway, and discusses methods of application specifically for design consideration. A series of wave spectra to be used for estimating design values for the short term is developed, as well as a series for the long-term (lifetime) approach. Several factors which may seriously affect the magnitude of predicted values (including extreme values) are discussed in detail, and results of numerical computations carried out on a semisubmersible-type ocean platform are presented. In the short-term response prediction approach, it is found from the results of the computations that the upper and lower bounds of responses established by using the series of wave spectra cover satisfactorily the variation of responses computed by using wave spectra measured at various oceanographic locations in the world. It is also found that the design extreme value estimated from the long-term prediction method agrees with that estimated from the short-term prediction method.

- There are a number of wave spectrum descriptions that depend on correlation of observation data and assumptions

- After the wind has blow for some time the seas are considered as fully developed

- The basis of the most well accepted spectra is based on the work by by **Pierson – Moskowitz.** T… ional fully developed seas and is defined as :



$$\Phi_{\zeta\zeta}(\omega) = \frac{A}{\omega^5}\exp\left(-\frac{B}{\omega^4}\right)$$

(rad/s) frequency of the waves

where $A = 8.1\times10^{-3} g^2$ and $B = 0.74 (g/V)^4$,

(m^2/s) gravity acceleration

Wind speed (m/s) @ 19.5 m above calm water level

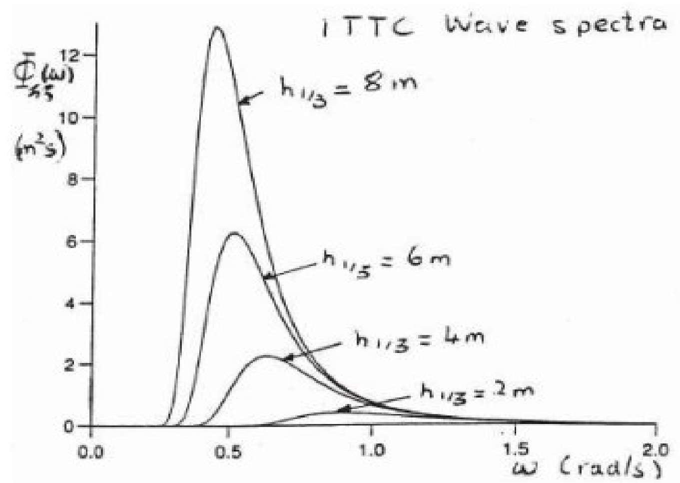
- In the original work by Pierson and Moskowitz both *A* and *B* were related to the wind speed 19.5 m above the mean sea surface. By assigning different values to A and B two main wave spectra that are currently in use are developed. **These are known as the ISSC and ITTC spectra**.

The ITTC and ISSC wave spectra

The **one parameter ITTC** spectrum is defined by

$$A = 8.1 \times 10^{-3} g^2 \quad \text{and} \quad B = \frac{3.11}{h_{1/3}^2} \qquad (2)$$

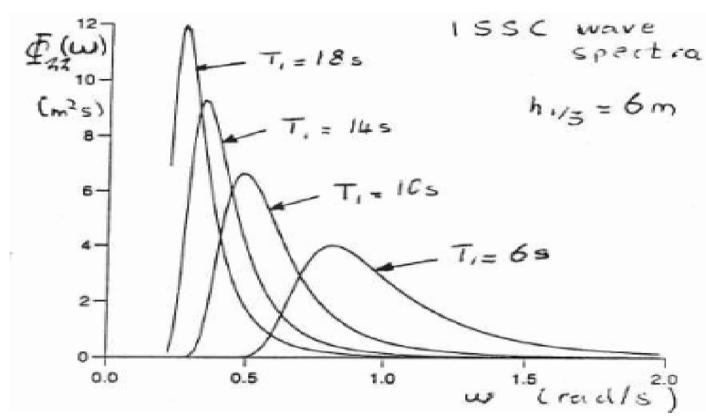
Significant wave height



The **two parameter** ISSC spectrum is defined by

$$A = \frac{173 h_{1/3}^2}{T_1^4} \quad \text{and} \quad B = \frac{691}{T_1^4} \qquad (3)$$

Characteristic wave period



NB : h(1/3) is *the mean of the one third largest waves in the sea ;* when computed from actual wave measurements, the new definition is about 5% higher

Properties of wave spectra

- The mean square value is evaluated as : $\frac{d}{d\omega}\left[\exp\left(-\frac{B}{\omega^4}\right)\right] = \frac{4B}{\omega^5}\exp\left(-\frac{B}{\omega^4}\right)$.

$$m_0 = \int_0^\infty \Phi_{\zeta\zeta}(\omega)\,d\omega = \int_0^\infty \frac{A}{\omega^5}\exp\left(-\frac{B}{\omega^4}\right)d\omega = \frac{A}{4B}\exp\left(-\frac{B}{\omega^4}\right)\Big|_0^\infty = \frac{A}{4B}$$

- Using equations (2), (3) : for ITTC/ISSC spectra $m_0 = \frac{1}{15.97}h_{1/3}^2$ $m_0 = \frac{1}{15.977}h_{1/3}^2$
- The frequency at which the Pierson Moskowitz spectrum is max is :

$$\frac{d\,\Phi_{\zeta\zeta}(\omega)}{d\omega} = 0 = A\left[-\frac{5}{\omega^6}\exp\left(-\frac{B}{\omega^4}\right) + \frac{1}{\omega^5}\frac{4B}{\omega^5}\exp\left(-\frac{B}{\omega^4}\right)\right] = \frac{A}{\omega^6}\exp\left(-\frac{B}{\omega^4}\right)\left[-5+\frac{4B}{\omega^4}\right].$$

$$\omega_m = (0.8B)^{1/4} \quad \text{and} \quad T_m = 2\pi(0.8B)^{-1/4}.$$

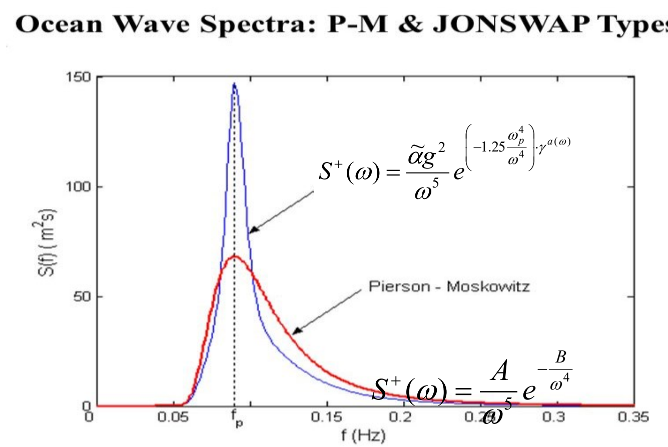
Average wave period

- For ITTC $\omega_m = 1.256(h_{1/3})^{-1/2}$ $T_m = 5.003(h_{1/3})^{1/2}$. $\overline{T} = 3.554\sqrt{h_{1/3}} = 0.71T_m$
- For ISSC $\omega_m = \frac{4.849}{T_1}$ $T_m = 1.296\,T_1$. $\overline{T} = 0.92T_1 = 0.71T_m$

The Jonswap wave spectrum

Jonswap : Joint North Sea Wave project

The Jonswap wave spectrum enhances the wave spectrum in way of the wave peak as compare with Pierson Moscowitz wave spectrum



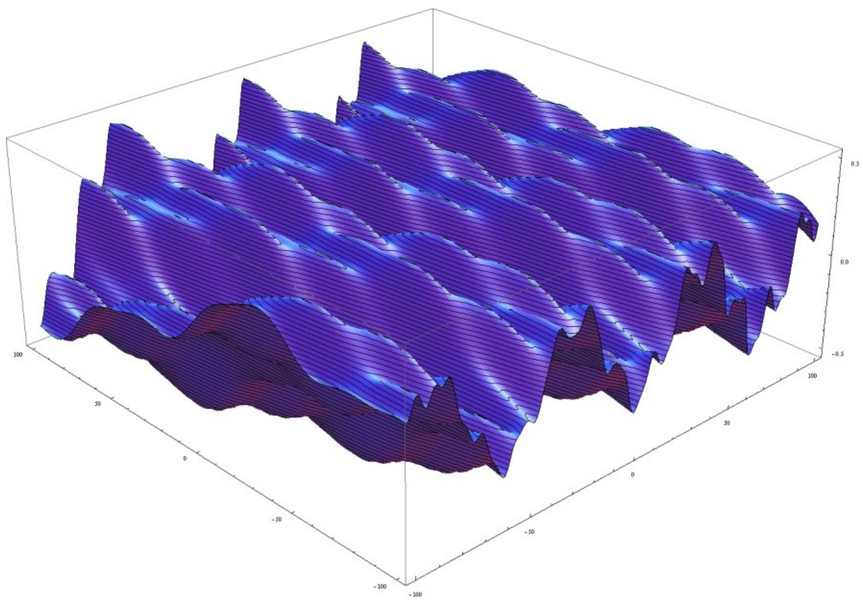
$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\beta \frac{\omega_p^4}{\omega^4}\right] \gamma^a$$

- $a = \exp\left[-\frac{(\omega - \omega_p)^2}{2 w_p^2 \sigma^2}\right]$
- $\sigma = \begin{cases} 0.07 & \text{if } \omega \leq \omega_p \\ 0.09 & \text{if } \omega > \omega_p \end{cases}$
- $\beta = \frac{5}{4}$
- α is a constant that relates to the wind speed and fetch length, see below. Typical values in the northern north sea are in the range of 0.0081 to 0.01
- ω is the wave frequency
- ω_p is the peak wave-frequency

Wave Surface Elevation: Realization

$$X(t;x,y)=\sum_{j=1}^{n}\sum_{k=1}^{m}\sqrt{S_X^+(\omega_j,\theta_k)\Delta\omega_j\Delta\theta_k}\left[A_{jk}\cos(\omega_j t-\frac{\omega_j^2}{g}(x\cos\theta_k+y\sin\theta_k))+B_{jk}\sin(\omega_j t-\frac{\omega_j^2}{g}(x\cos\theta_k+y\sin\theta_k))\right]$$

With Pierson- Moskowich Wave spectrum 3 waves in 2 directions (6 total)



Proposal of a New Standard for Wave Realizations in Time-Domain Simulations

M. Razola, M. Huss, A. Rosén, K. Garme

Abstract

With the increasing computer performance, time-domain simulations of ship responses in waves are becoming feasible tools in research as well as in design. When simulating rare and complex hydrodynamic phenomena such as parametric rolling and slamming, efficient and accurate representation of the wave environment is crucial. The most common approach for numerical wave realization is to represent the wave surface as a Fourier series of a finite number of harmonic wave components based on a standardized target spectrum. In time-domain simulations the computational cost is generally proportional to the number of wave components, and it is hence desirable to use the minimum number of wave components that gives a wave process with sufficient statistical quality. This paper evaluates four approaches to discretization of the target spectrum regarding computational cost and statistical quality. The presented results highlight the need for careful consideration when performing numerical wave realization. Based on the findings a new standard for irregular wave realization is proposed where the target spectrum is discretized in the period domain. It is shown to yield excellent wave sequence quality with as few as 100 wave components. Establishment of a unified wave realization standard would have large benefits, for example in simulation code benchmarking and in development of criteria such as the direct stability assessments on level 3 in the IMO second generation intact stability criteria.

Wave Making

- Simulations
  - Spectrum is needed to for time domain simulations
  - Principles of constucting several load histories as given above

- Wave basin
  - Controlled flaps
  - Towing tank: single flap, other end the beach to absorb the waves
  - Wide seakeeping basins have flaps at two adjacent sides to produce the oblique seas, beaches in other two sides to absorb the waves

Statistics on Sea States

- For certain *operational area*, certain sea states occur with certain probability
- Probability for certain *sea states* with *T* and *H* is known from the measurements, (scatter diagram), $\mathbf{p_1(H,T)}$
- Fourier analysis can be used to extract different wave components from the irregular wave time history
- Sea state can be described with *wave spectrum,* which includes *energy contribution of certain wave components*
- From wave spectrum *average, extreme elevation* etc., amplitude etc. can be calculated), $\mathbf{p_2(H_{max}) \Rightarrow ptot = p_1 p_2}$

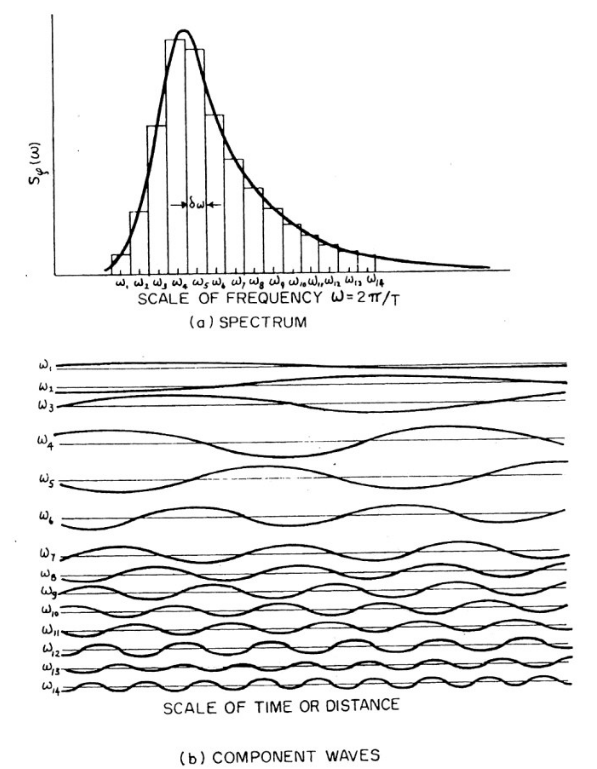


Fig. 8 Typical variance spectrum of waves, showing approximation by a finite sum of components

Table 5—Observed Percentage Frequency of Occurrence of Wave Heights and Periods (Hogben and Lumb data)
Northern North Atlantic

Wave height, m	Wave Period T_1, sec: 2.5	6.5	8.5	10.5	12.5	14.5	16.5	18.5	20.5	Over 21	Total
0-1	13.7204	3.4934	0.8559	0.3301	0.1127	0.0438	0.0249	0.0172	0.0723	0.3584	19.0291
1-2	11.4889	15.5036	6.4817	1.8618	0.5807	0.1883	0.0671	0.0254	0.0203	0.0763	36.2941
2-3	1.5944	7.8562	8.0854	3.7270	1.1790	0.3713	0.1002	0.0321	0.0091	0.0082	22.9629
3-4	0.3244	2.2487	4.0393	2.9762	1.3536	0.4477	0.1307	0.0428	0.0050	0.0040	11.5724
4-5	0.1027	0.7838	1.6998	1.5882	0.9084	0.3574	0.1443	0.0433	0.0072	0.0049	5.6400
5-6	0.0263	0.1456	0.3749	0.4038	0.2493	0.1200	0.0382	0.0067	0.0027	0.0027	1.3702
6-7	0.0277	0.1477	0.3614	0.4472	0.2804	0.1301	0.0504	0.0113	0.0011	0.0032	1.4605
7-8	0.0084	0.0714	0.1882	0.2199	0.1634	0.0785	0.0353	0.0069	0.0018	0.0034	0.7772
8-9	0.0037	0.0325	0.0856	0.1252	0.1119	0.0558	0.0303	0.0045	0.0027	0.0033	0.4555
9-10	0.0034	0.0204	0.0674	0.1173	0.0983	0.0550	0.0303	0.0173	0.0079	0.0047	0.4220
10-11		0.0005	0.0012	0.0023	0.0031	0.0012		0.0005			0.0088
11+		0.0005	0.0007	0.0019	0.0035	0.0002			0.0005		0.0073
Totals	27.3003	30.3043	22.2415	11.8009	5.0143	1.8493	0.6517	0.2080	0.1306	0.4691	100.000

Statistics on Sea States

- Often idealized wave spectrum that neglect time and place are used, e.g.
  - Pierson-Moskowitz for fully developed sea
  - JONSWAP for developing sea

- Often the sea is considered as *long-crested* (conservative assumption) meaning that the waves are assumed to come from the same direction. Realistic seas are however often *short-crested* meaning that the waves come from different directions

- The sea states are described in global wave statistics

Table 5—Observed Percentage Frequency of Occurrence of Wave Heights and Periods (Hogben and Lumb data)
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6-7	0.0277	0.1477	0.3614	0.4472	0.2804	0.1301	0.0504	0.0113	0.0011	0.0032	1.4605
7-8	0.0084	0.0714	0.1882	0.2199	0.1634	0.0785	0.0353	0.0069	0.0018	0.0034	0.7772
8-9	0.0037	0.0325	0.0856	0.1252	0.1119	0.0558	0.0303	0.0045	0.0027	0.0033	0.4555
9-10	0.0034	0.0204	0.0674	0.1173	0.0983	0.0550	0.0303	0.0173	0.0079	0.0047	0.4220
10-11		0.0005	0.0012	0.0023	0.0031	0.0012		0.0005			0.0088
11+		0.0005	0.0007	0.0019	0.0035	0.0002			0.0005		0.0073
Totals	27.3003	30.3043	22.2415	11.8009	5.0143	1.8493	0.6517	0.2080	0.1306	0.4691	100.000

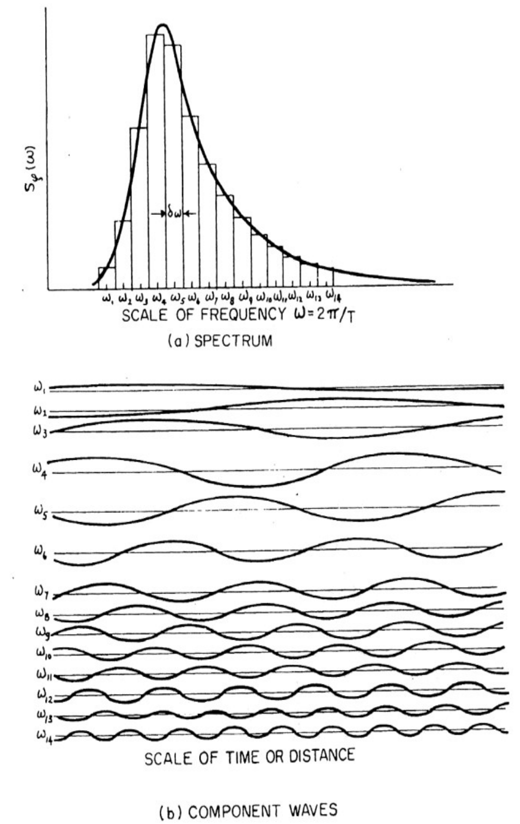
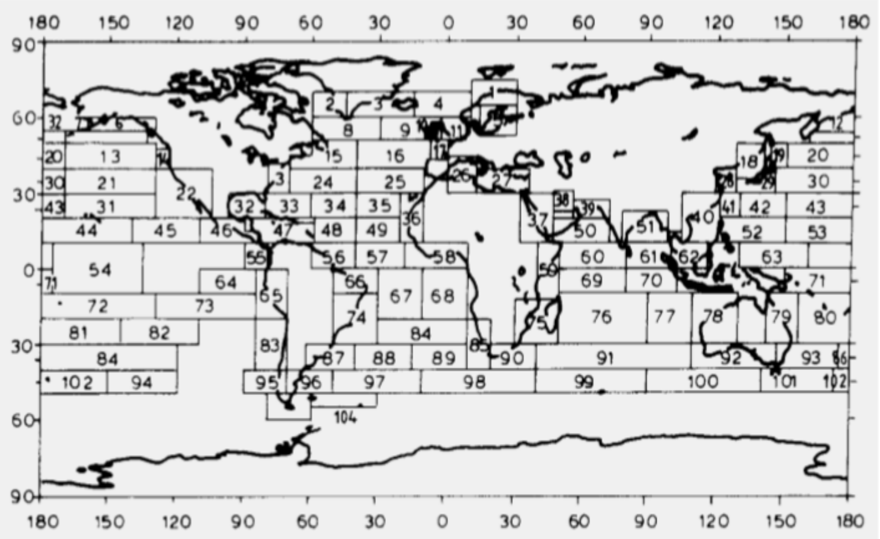


Fig. 8 Typical variance spectrum of waves, showing approximation by a finite sum of components

Sea States for ship structures (Long Term)

- For unlimited operation the North-Atlantic (Area 25 of BSRA statistics)
- For restricted service at the discretion of the Class Society Service Factor Analysis can be employed
- Some Key References :
  - ➢ IACS URS 11A, Rec. 34 ;
  - ➢ Lloyd's Register Rules (Part 4 Ship Structures) and

Hogben, N., Dacunha, N.M. and Olliver, G.F. (1986). Global wave statistics, British Maritime Technology.



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Service Factor Assessment of a Great Lakes Bulk Carrier Incorporating the Effects of Hydroelasticity

Spyridon E. Hirdaris,[1] Norbert Bakkers,[2] Nigel White,[2] and Pandeli Temarel[3]

This paper presents a summary of an investigation into the effects of hull flexibility when deriving an equivalent service factor for a single passage of a Great Lakes Bulk Carrier from the Canadian Great Lakes to China. The long term wave induced bending moment predicted using traditional three-dimensional rigid body hydrodynamic methods is augmented due to the effects of springing and whipping by including allowances based on two-dimensional hydroelasticity predictions across a range of headings and sea states. The analysis results are correlated with full scale measurements that are available for this ship. By combining the long term "rigid body" wave-bending moment with the effects of hydroelasticity, a suitable service factor is derived for a Great Lakes Bulk Carrier traveling from the Canadian Great Lakes to China via the Suez Canal.

Keywords: Great Lakes; hydrodynamics; longitudinal strength

Table 5.2 — Wave height and period statistics. (After Hogben, Dacunha and Olliver (1986).) Reproduced by permission of British Maritime Technology Ltd.)

DECEMBER TO FEBRUARY

AREA 9

NORTH WEST

PERCENTAGE OF OBS = 11.28%

Significant wave height (m) by zero crossing period (s)

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	2
13-14	-	-	-	-	-	-	-	1	1	-	-	2
12-13	-	-	-	-	-	-	1	1	1	-	-	3
11-12	-	-	-	-	-	-	1	1	1	1	-	5
10-11	-	-	-	-	-	1	2	2	2	1	-	8
9-10	-	-	-	-	-	2	4	4	2	1	-	13
8-9	-	-	-	-	1	3	4	6	4	1	-	22
7-8	-	-	-	-	2	8	11	10	5	2	-	36
6-7	-	-	-	-	4	12	19	14	7	2	-	58
5-6	-	-	-	1	8	24	30	20	8	2	-	92
4-5	-	-	-	2	17	42	43	24	8	2	-	139
3-4	-	-	-	6	28	65	52	23	6	1	-	181
2-3	-	-	1	16	62	78	45	14	3	-	-	220
1-2	-	-	4	32	65	48	17	4	1	-	-	171
0-1	-	1	6	15	12	6	1	-	-	-	-	38
TOTAL	-	1	11	73	206	287	231	123	48	14	4	1000

NORTH

PERCENTAGE OF OBS = 6.28%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	1
13-14	-	-	-	-	-	-	-	-	-	-	-	1
12-13	-	-	-	-	-	-	-	-	-	-	-	1
11-12	-	-	-	-	-	-	1	1	-	-	-	2
10-11	-	-	-	-	-	-	1	1	1	-	-	4
9-10	-	-	-	-	-	1	2	2	1	1	-	7
8-9	-	-	-	-	1	3	3	3	2	1	-	12
7-8	-	-	-	-	1	4	7	8	3	1	-	23
6-7	-	-	-	1	3	10	13	8	3	2	1	42
5-6	-	-	-	1	8	20	22	15	6	2	1	76
4-5	-	-	-	4	20	38	36	20	7	2	-	128
3-4	-	-	1	11	43	64	48	22	7	2	-	197
2-3	-	-	3	28	75	80	44	15	4	1	-	250
1-2	-	-	10	48	76	50	18	4	1	-	-	208
0-1	-	2	10	19	13	4	1	-	-	-	-	48
TOTAL	-	2	23	113	241	273	188	97	37	11	4	1000

NORTH EAST

PERCENTAGE OF OBS = 4.58%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	-
13-14	-	-	-	-	-	-	-	-	-	-	-	-
12-13	-	-	-	-	-	-	-	-	-	-	-	-
11-12	-	-	-	-	-	-	-	-	-	-	-	1
10-11	-	-	-	-	-	-	-	-	-	-	-	2
9-10	-	-	-	-	-	1	1	1	1	-	-	3
8-9	-	-	-	-	1	1	2	2	1	-	-	7
7-8	-	-	-	-	1	4	4	3	2	1	-	15
6-7	-	-	-	1	4	8	9	6	3	1	-	32
5-6	-	-	-	2	10	17	17	10	4	1	-	63
4-5	-	-	1	6	22	35	29	15	6	2	-	115
3-4	-	-	2	16	46	58	40	18	8	1	-	187
2-3	-	-	5	36	78	75	40	14	4	1	-	253
1-2	-	1	16	62	83	52	19	5	1	-	-	240
0-1	-	4	20	31	20	6	1	-	-	-	-	83
TOTAL	-	5	44	154	265	258	163	74	26	8	3	1000

WEST

PERCENTAGE OF OBS = 22.04%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	1	1	-	-	4
13-14	-	-	-	-	-	-	1	1	1	-	-	3
12-13	-	-	-	-	-	-	1	1	1	1	-	4
11-12	-	-	-	-	-	1	2	2	2	1	-	7
10-11	-	-	-	-	-	1	3	4	3	1	-	12
9-10	-	-	-	-	-	2	3	8	4	2	-	20
8-9	-	-	-	-	1	6	9	10	6	2	1	33
7-8	-	-	-	-	1	7	16	15	8	2	1	50
6-7	-	-	-	-	3	14	28	21	9	3	1	78
5-6	-	-	-	-	8	26	39	27	10	2	-	110
4-5	-	-	-	1	13	43	55	28	9	2	-	149
3-4	-	-	-	3	28	64	57	24	6	1	-	181
2-3	-	-	-	8	45	72	44	13	2	-	-	186
1-2	-	-	1	18	51	44	16	3	-	-	-	133
0-1	-	-	3	12	12	4	1	-	-	-	-	31
TOTAL	-	-	5	42	158	281	270	158	62	18	5	1000

ALL DIRECTIONS

PERCENTAGE OF OBS = 100.00%
(INCLUDING 1.09% DIRECTION UNKNOWN)

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	2
13-14	-	-	-	-	-	-	-	-	-	-	-	1
12-13	-	-	-	-	-	-	-	1	1	-	-	2
11-12	-	-	-	-	-	-	1	1	1	1	-	4
10-11	-	-	-	-	-	-	1	2	2	1	-	7
9-10	-	-	-	-	-	1	2	4	3	1	1	13
8-9	-	-	-	-	-	2	6	7	5	2	1	23
7-8	-	-	-	-	1	3	12	13	8	3	1	42
6-7	-	-	-	-	2	12	23	21	10	3	1	72
5-6	-	-	-	-	6	25	40	30	13	3	1	118
4-5	-	-	-	1	15	48	58	35	12	3	1	172
3-4	-	-	-	4	32	73	65	29	8	1	-	212
2-3	-	-	-	11	52	75	45	14	3	-	-	199
1-2	-	-	2	20	45	34	11	2	-	-	-	114
0-1	-	-	3	8	6	2	-	-	-	-	-	19
TOTAL	-	-	5	44	159	277	265	158	65	20	6	1000

EAST

PERCENTAGE OF OBS = 6.16%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	-
13-14	-	-	-	-	-	-	-	-	-	-	-	-
12-13	-	-	-	-	-	-	-	-	-	-	-	1
11-12	-	-	-	-	-	-	-	-	-	-	-	1
10-11	-	-	-	-	-	-	1	1	-	-	-	2
9-10	-	-	-	-	-	1	1	1	1	-	-	4
8-9	-	-	-	-	1	2	2	2	1	1	-	8
7-8	-	-	-	-	1	3	4	4	2	1	-	15
6-7	-	-	-	1	3	8	9	6	3	1	-	32
5-6	-	-	-	2	9	17	17	11	5	2	-	63
4-5	-	-	-	5	21	34	29	16	6	2	-	114
3-4	-	-	1	15	45	58	41	18	6	2	-	187
2-3	-	-	3	38	79	77	41	15	4	1	-	258
1-2	-	1	16	64	85	53	20	5	1	-	-	244
0-1	-	3	17	28	17	5	1	-	-	-	-	70
TOTAL	-	4	39	148	261	259	168	78	29	9	3	1000

SOUTH WEST

PERCENTAGE OF OBS = 19.76%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	2
13-14	-	-	-	-	-	-	-	-	-	-	-	1
12-13	-	-	-	-	-	-	-	1	1	-	-	2
11-12	-	-	-	-	-	-	1	1	1	-	-	4
10-11	-	-	-	-	-	1	2	2	1	1	-	6
9-10	-	-	-	-	-	1	3	3	2	1	-	11
8-9	-	-	-	-	1	3	6	6	3	1	-	20
7-8	-	-	-	-	3	6	10	9	5	2	1	34
6-7	-	-	-	-	3	12	18	14	7	2	1	58
5-6	-	-	-	1	8	24	30	20	8	2	1	95
4-5	-	-	-	2	16	43	44	25	9	2	-	143
3-4	-	-	-	7	37	67	54	24	7	1	-	198
2-3	-	-	1	17	63	78	45	14	3	1	-	221
1-2	-	-	6	33	64	46	16	3	1	-	-	169
0-1	-	1	6	15	12	4	1	-	-	-	-	37
TOTAL	-	1	12	73	207	285	230	123	48	14	5	1000

SOUTH

PERCENTAGE OF OBS = 19.41%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	-
13-14	-	-	-	-	-	-	-	-	-	-	-	-
12-13	-	-	-	-	-	-	-	-	-	-	-	1
11-12	-	-	-	-	-	-	-	-	-	-	-	1
10-11	-	-	-	-	-	-	-	1	1	-	-	2
9-10	-	-	-	-	-	-	1	1	1	1	-	4
8-9	-	-	-	-	-	1	2	3	2	1	1	9
7-8	-	-	-	-	1	3	5	5	4	2	1	19
6-7	-	-	-	-	2	7	12	10	6	2	1	41
5-6	-	-	-	1	6	18	25	19	9	3	1	81
4-5	-	-	-	3	18	42	45	27	11	3	1	149
3-4	-	-	1	10	46	78	61	29	9	2	-	235
2-3	-	-	3	28	81	80	50	17	4	1	-	273
1-2	-	-	8	42	61	38	13	3	-	-	-	166
0-1	-	1	4	7	4	1	-	-	-	-	-	17
TOTAL	-	1	16	81	219	276	214	115	47	15	8	1000

SOUTH EAST

PERCENTAGE OF OBS = 9.40%

Height	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
>14	-	-	-	-	-	-	-	-	-	-	-	-
13-14	-	-	-	-	-	-	-	-	-	-	-	-
12-13	-	-	-	-	-	-	-	-	-	-	-	1
11-12	-	-	-	-	-	-	-	-	-	-	-	1
10-11	-	-	-	-	-	-	1	1	1	-	-	3
9-10	-	-	-	-	-	1	1	1	1	-	-	5
8-9	-	-	-	-	1	2	2	2	1	1	-	9
7-8	-	-	-	-	1	3	5	4	2	1	-	17
6-7	-	-	-	-	3	7	8	7	4	2	1	33
5-6	-	-	-	1	7	16	18	12	5	2	1	62
4-5	-	-	-	4	19	34	31	18	7	2	1	115
3-4	-	-	1	13	44	62	48	21	7	2	-	198
2-3	-	-	4	35	84	84	48	16	4	1	-	275
1-2	-	1	14	61	83	52	19	5	1	-	-	236
0-1	-	2	11	18	11	3	1	-	-	-	-	45
TOTAL	-	3	31	133	232	265	179	88	34	11	4	1000

TABULATED PROBABILITIES ARE IN PARTS PER THOUSAND OF THE POPULATION IN EACH TABLE

Summary

- Wave spectrum is needed to derive ship responses
- Stochastic loads can be assessed using spectral methods
- When you know the spectrum, you can define the maximum response (probability theory for stochastic processes)