AN INTRODUCTION TO SEAKEEPING ANALYSIS

WORKSHOP

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Contents

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OCEAN WAVES

1. OBJECTIVES

- Identify the important characteristics of ocean waves.
- Explain how a wave spectrum is generated.
- Describe how a wave spectrum is influenced by different factors.
- Calculate the statistical properties of a spectrum
- Distinguish between wave frequency and encounter frequency for a moving vessel.
- Convert a wave spectrum to an encounter spectrum.

2. INTRODUCTION

Ocean waves are surface gravity waves, which may be individually idealised as trochoids or sinusoids. Wave characteristics are a function of water depth, but for our purposes we shall consider only deep water i.e. depth> 0.5 wavelength. Deep water waves are dispersive which allows a number of simplifications.

3. DEFINITIONS

If all the waves travel in one direction only, the wave system is called one-dimensional or *long-crested*. If the waves come from different directions the wave system is called two-dimensional or *short-crested*. We shall be dealing with (simpler) long-crested seas most of the time.

3.1 Wave velocities

*3.1.1 phase velocity or celerity C_p:*
This is the velocity at which the wave shape travels and is the most important for the naval architect.

3.1.2 group velocity C_g:
This is the velocity at which a group or packet of waves travel, and is half the phase velocity for deep water waves. It is the rate at which energy is transmitted by the wave.

3.1.3 orbital velocities:
The particles of water in a wave do not move with the wave (except for slight surface drift), but rotate in an orbit of radius equal to the wave amplitude at the surface:
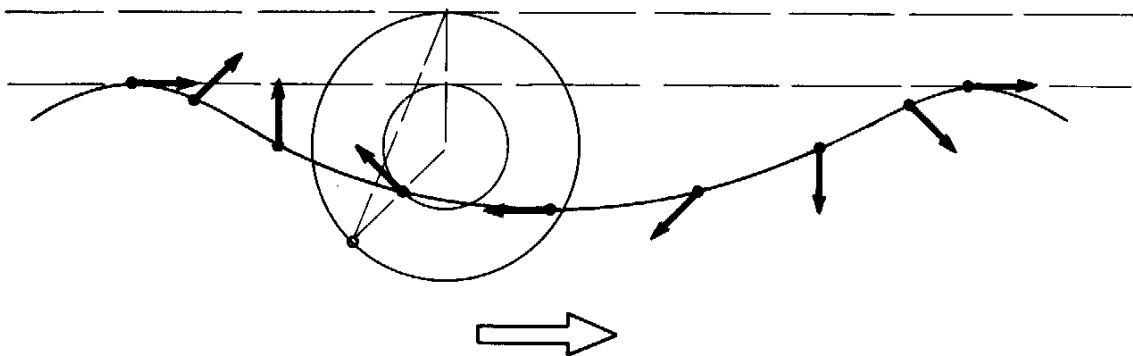
The orbit radius decreases with depth exponentially. Note that orbital velocities move with the phase velocity at the crest and against it at the trough.

In these lectures the term 'velocity' refers to the wave phase velocity unless specifically stated otherwise. It is related to wavelength (in deep water) by:

$$\lambda = \frac{2\pi C_p{}^2}{g}$$

where λ = wavelength (m)
C_p = wave phase velocity (m/s)

The only other wave formulae to be remembered are:

$$T = \frac{2\pi}{\omega}$$

and

$$\lambda = C_p T$$

where T = wave period (s)
ω = wave frequency (rad/s)

These three formulae can be rewritten in all sorts of combinations e.g.
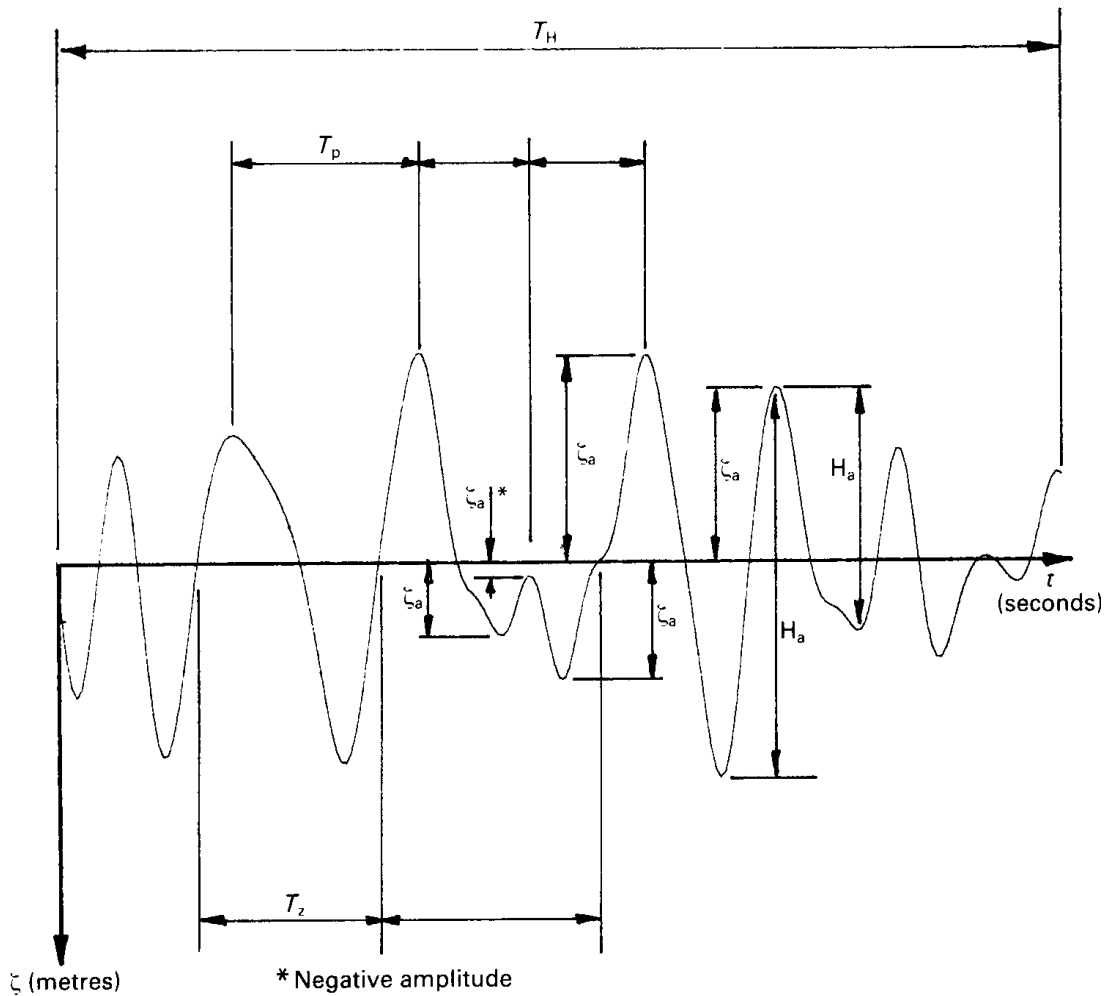
$$\lambda = \frac{2\pi g}{\omega^2}$$

The 3 wave formulae above are sometimes written in terms of the wave number k where

$$k = \frac{2\pi}{\lambda}$$

3.2 Irregular waves

Clearly , ocean waves are not regular shapes and frequencies but are made up of a number of random, irregular waves.

ζ (metres)　　　*Negative amplitude

wave amplitude ζ_a = vertical distance from mean water level to a peak or trough.
wave height H_a = vertical distance from a trough to a succeeding peak
wave period T_p = time between two successive peaks

wave period T_z = time between two successive upward or downward zero crossings.

Mean values of several readings are usually used, signified by a bar e.g. $\overline{T_z}$

3.3 Significant wave height
When investigating boat motions due to waves we are often most interested in the largest waves rather than the average, since they are the ones likely to cause problems. A simple way of describing waves in this manner is to calculate the average height of the highest waves which make up 1/3rd of the total number of waves recorded. This is the *significant wave height* $H_{1/3}$ (Sometimes the highest 1/10th waves are averaged; the answer is then given the symbol $H_{1/10}$). The significant wave height is surprisingly close to the wave height estimated by an experienced observer, generally about 5% greater.

Example: The following record of wave data has been obtained. Find the significant wave height.

Wave height (m)	0 0.5	0.5 – 1	1 – 1.5	1.5 - 2	2 – 2.5	2.5 - 3	3 – 3.5	3.5 - 4
No. of observations	5	10	20	40	55	40	25	5

Σ waves = 200 take highest one-third 200/3 = 67 highest waves

Mean height (m)	3.75	3.25	2.75	Sum
No.	5	25	37	67
product	18.75	81.25	101.75	201.75

So $H_{1/3} = \dfrac{201.75}{67} = 3.01\text{m}$

## 4 Energy Spectra
4.1 The concept
Ocean waves are made up of a number of apparently random irregular waves. However, we can still use sine wave mathematics to describe ocean waves by considering the random sea to be the sum of a number of sine waves of varying frequency and amplitude.
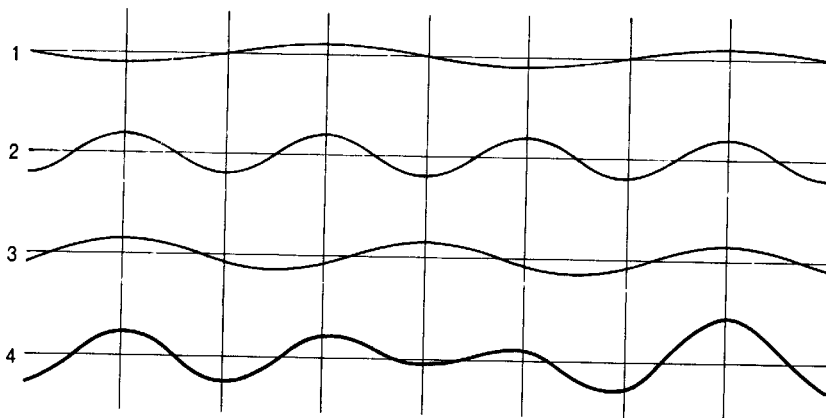
The energy contained in a sinusoidal wave is
$0.5\,\rho\,g\,\zeta_a^2$ joules per m^2 of sea surface
so the total energy per m^2 for n waves is

$$E_{TOT} = 0.5\,rg\left(Z_{a1}^2 + Z_{a2}^2 + Z_{a3}^2 + \text{........}Z_{an}^2\right)$$

Thus any given seaway can be described by the plotting the energy contained at each frequency present in that particular seaway. Such a plot is called an *energy density spectrum.*
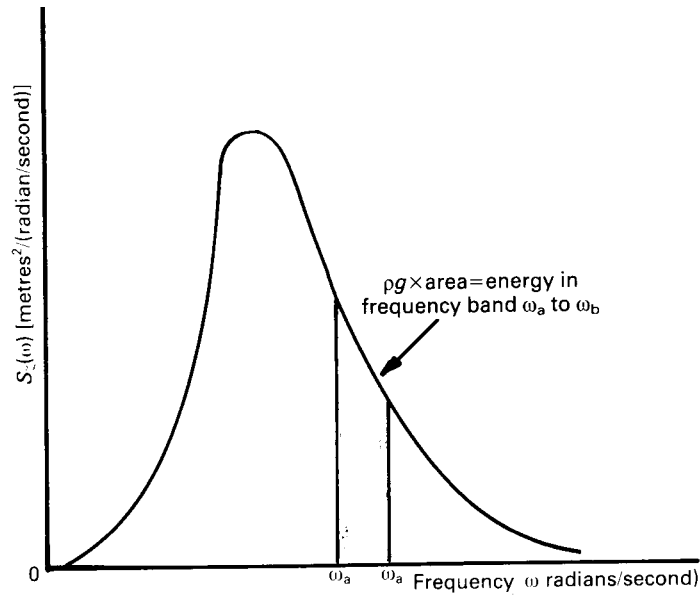
The spectrum is plotted such that the area under a part of the curve δw wide represents the energy per m^2 of sea surface for waves in that frequency band. Thus the total area under the curve is proportional to the total energy/m^2 for that particular sea state. To achieve this, the vertical ordinate has units proportional to energy per unit frequency and is called the spectral density or energy density S(ω).

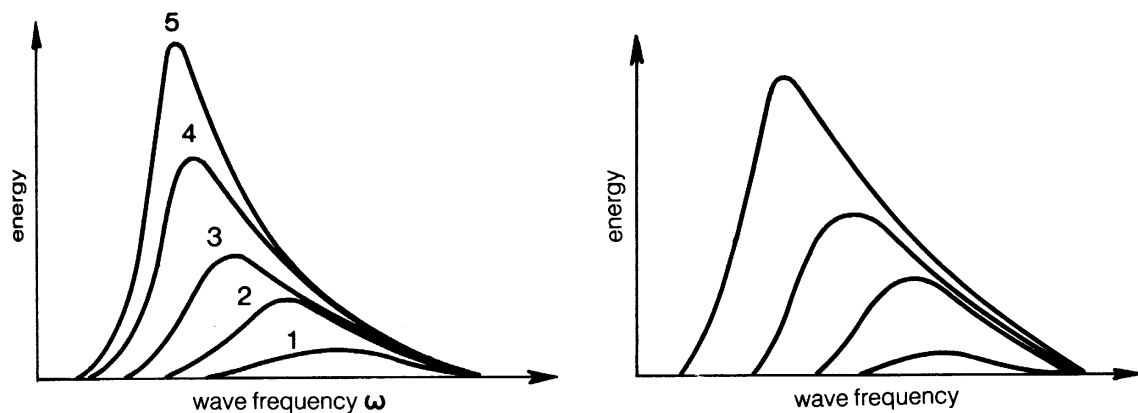$$total\ energy = rg\int_0^\infty S(w)dw \text{ joules per m}^2$$

where

S(ω) = spectral density (m^2 s/rad)
ω = wave frequency (rad/s)

4.2 Effect of sea conditions on spectrum shape
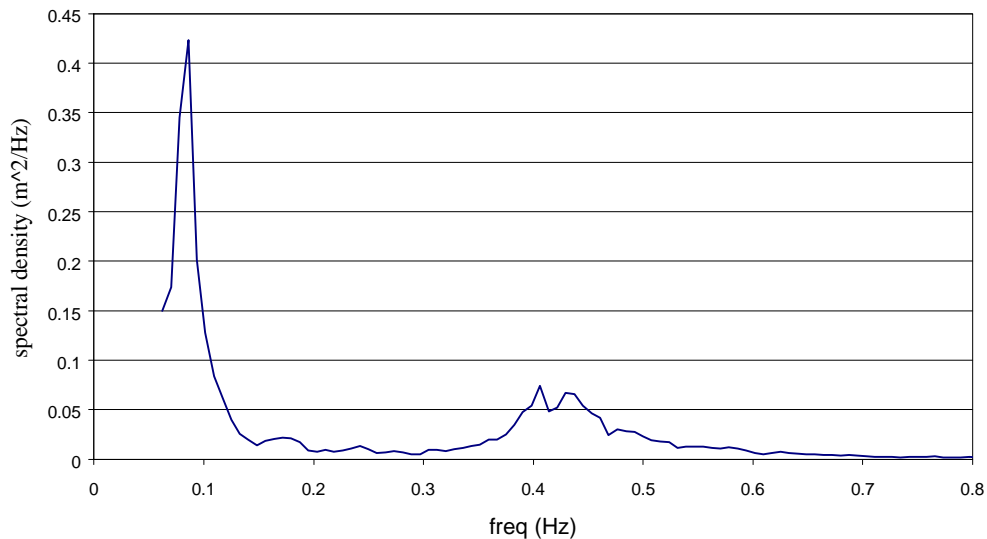The effect of increasing wind duration and fetch on the spectrum shape is as follows:

increasing duration (hrs)   increasing fetch

The presence of swell and the influence of the sea breeze are also distinctive in the spectrum as shown above.

4.3 Statistical properties of a spectrum

If a sufficiently large sample of waves are used to determine the spectrum , the area under the spectrum will represent the variance of the wave energy, symbol m_0 . Several wave characteristics can then be determined by taking moments about the vertical axis of the spectrum m_1, m_2 etc. (just like moments of a waterplane about one end) e.g.

$$\overline{T_z} = 2\boldsymbol{p} \sqrt{\frac{m_0}{m_2}} \ \text{sec}$$

$$\overline{T_p} = 2\boldsymbol{p} \sqrt{\frac{m_2}{m_4}} \ \text{sec}$$

Recall from earlier that

wave period T_p = time between successive peaks, called "T peak"

wave period T_z = time between two successive upward or downward zero crossings, called "T zed)"

The relationship between T_p and T_z is a measure of the width or broadness of the spectrum, defined from the broadness parameter:

$$\boldsymbol{e} = \sqrt{1 - \frac{\overline{T_p^2}}{\overline{T_z^2}}}$$

where ε, the bandwidth parameter, lies between 0 and 1

Lecture 1   Ocean Waves   6
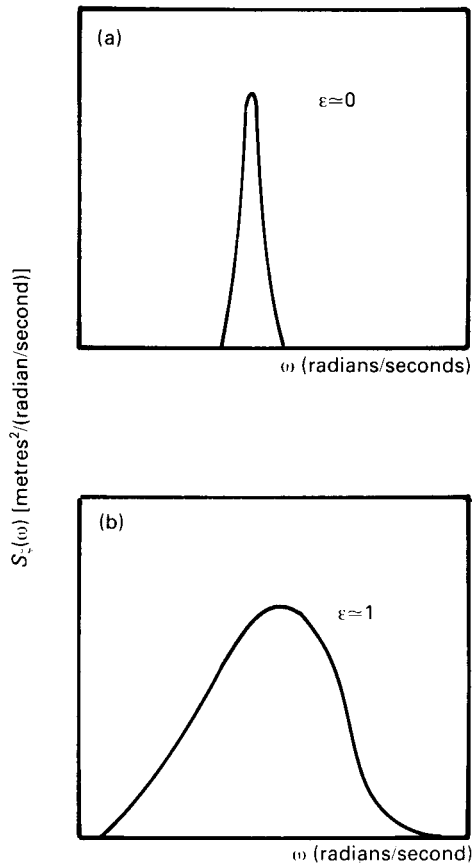
a) narrow band spectrum ($\varepsilon = 0$)   b) wide band spectrum ($\varepsilon = 1$)

$$H\frac{1}{3} = 4.0\sqrt{\left(1-\frac{e^2}{2}\right)}\sqrt{m0} \text{ metres}$$ the "corrected" value

$$H\frac{1}{3} = 4.0\sqrt{m0} \text{ metres for } e = 0$$ the "uncorrected" value

$$H\frac{1}{3} = 2.83\sqrt{m0} \text{ metres for } e = 1$$ not usually found in ocean waves

4.4 Multi-directional wave spectra

So far we have ignored the direction of wave propagation and simply measured the wave energy (or amplitude) passing the point of measurement. In reality the waves are multi-directional (i.e. short-crested) and the spectral density will be a function of both wave frequency AND direction.
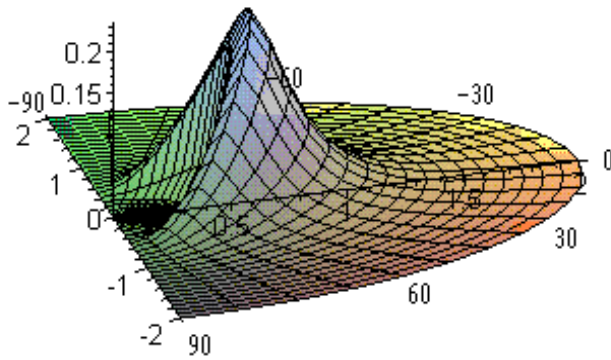
The spectral density at any one point will be

$$S(w) = \int S(w, m) dm$$

where μ = direction of wave component relative to dominant direction

The area under the wave spectrum thus becomes

$$m_0 = \int_0^\infty \int_{-\frac{p}{2}}^{\frac{p}{2}} S(w) f(m) dm \, dw$$

where $f(m)$ is called the spreading function.

Since the directionality of the spectrum cannot alter the total energy, the integral of the spreading function must be equal to 1.0. The most commonly assumed spreading function is

$$f(m) = \frac{2}{p} \cos^n m$$

where n = 2 is typical.

Note that the Seakeeper software does not currently offer directional spectra capability.

4.5 Standard spectra:
It is usually too expensive to actually measure the wave spectrum for the locality of interest, so a number of formulae have been developed which define the spectral curve as a function of various wave-influencing parameters. The most commonly used is the ITTC or Bretschneider "two parameter" spectrum. This assumes the sea is fully developed in open deep water,

$$S_{BV}(w) = \frac{A}{W^5} \exp\left(\frac{-B}{W^4}\right) \text{ metres}^2 /(\text{rad}/\sec)$$

where

$S_{BV}(w) = s$pectral ordinate

ω = wave frequency (rad/s)

$$A = 172.75 \dfrac{\overline{H1}^{2}}{T^{4}} \; \text{metres}^{2}/\sec^{4}$$

$$B = \dfrac{691}{T^{4}} \; \sec^{-4}$$

H_1 is a characteristic height, usually $H_{1/3}$ for a narrow band spectrum (even though Bretschneider is a broad band spectrum).

T is usually a characteristic period, usually $\dfrac{\overline{T_z}}{0.92}$

In coastal waters where the fetch may be limited the JONSWAP (Joint North Sea Wave Project) spectrum may be used:
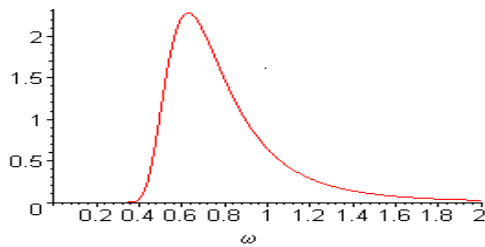
$$S_{JV}(w) = 0.658 C \, S_{BV}(w)$$

where S_B is the Bretschneider ordinate, S_J is the JONSWAP ordinate and C is

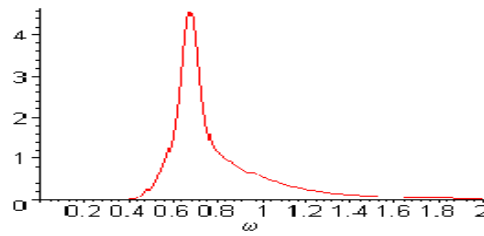$$C = 3.3 \uparrow \exp\left[\dfrac{-1}{2s^{2}}\left(\dfrac{wT_0}{2p} - 1 \right)^{2} \right]$$

where

$$s = 0.07 \; \text{for } w \le \dfrac{2p}{T_0}$$

$$s = 0.09 \; \text{for } w > \dfrac{2p}{T_0}$$

Bretschneider   Jonswap

Occasionally a much simplified ITTC spectrum called the Pierson-Moskowitz spectrum is used, which has windspeed as its only variable:

$$S(w) = \frac{8.1 \times 10^{-3} g^2}{w^5} \exp\left[-0.74\left(\frac{g}{wV_w}\right)^4\right] \text{ m}^2 \text{ sec/rad}$$

where V_W is the windspeed in metres/sec

Other standard spectra are available in the Seakeeper software.

It will be evident later that a wave *slope* spectrum is sometimes required. This is easily obtained from the wave amplitude spectrum by noting the maximum slope of a sine wave is

$$\text{slope} = \frac{2pz_a}{l}$$

Now $l = \frac{2pg}{w^2}$ So you just multiply each amplitude spectral ordinate by $\frac{w^4}{g^2}$ to get the slope spectrum

4.6 Wave spectrum example

Determine the energy spectrum of 5 different waves having the following characteristics:

ω (rad/s)	0.2	0.4	0.6	0.8	1.0
ζ (m)	0.1	0.5	0.8	0.6	0.3

 (Note: A useful spectrum model needs at least 100 waves, not just 4)
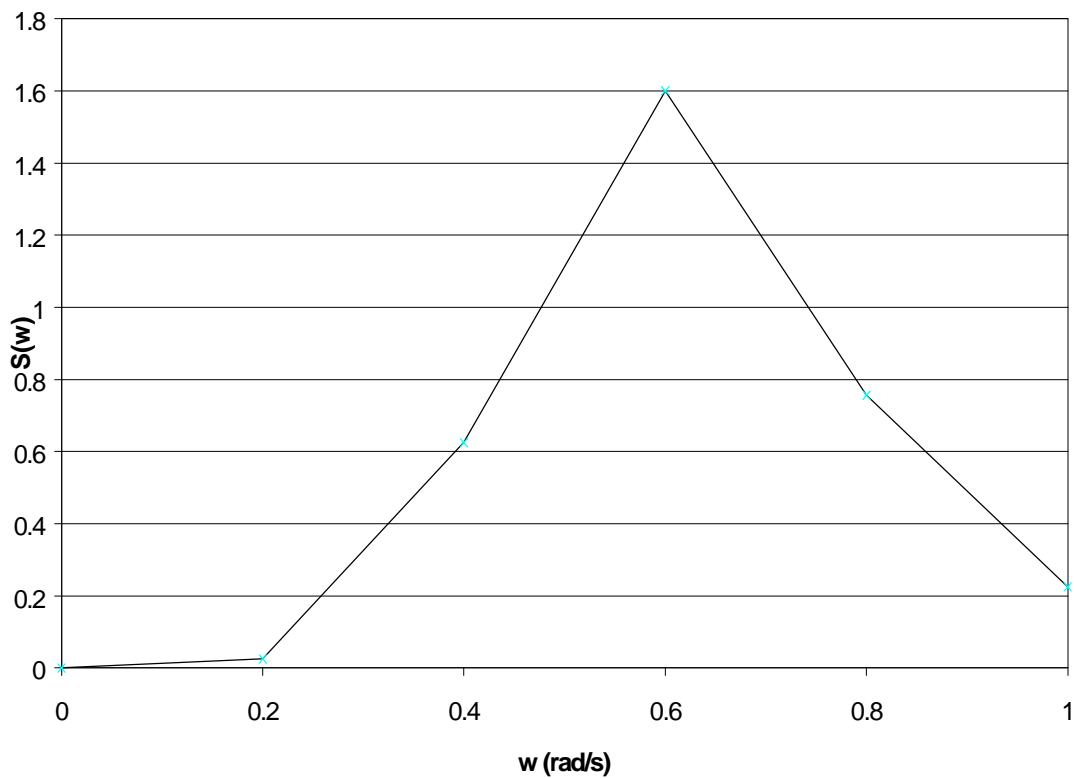Answer:
energy in a wave $= 0.5 \, \rho \, g \, z$

$$total\ energy = rg \int_0^\infty S(w)dw$$

So $S(\omega) = 0.5 \, \zeta_a^2$ per frequency band width.
In this example the band width is 0.2 rad/s for all waves, so:

ω (rad/s)	0.2	0.4	0.6	0.8	1.0
ζ (m)	0.1	0.5	0.8	0.55	0.3
ζ^2	0.01	0.25	0.64	0.3	0.09
$S(\omega)$	0.025	0.125	0.32	0.15	0.045

m0 (m^2)	0.624
m2 (m rad/s)^2	0.255
m4 (m^2 rad^2/s^4)	0.129
Tz (s)	9.83
Tp (s)	8.83
Epsilon	0.441
Hs uncor (m)	3.16
Hs cor (m)	3.00
To (s)	10.47

5 ENCOUNTER FREQUENCY

As ships move through the water the rate at which they encounter waves is dependent on their speed and direction. The convention for defining the heading is shown in the following diagram.

U - boat speed

c
wave
celerity

μ Heading angle
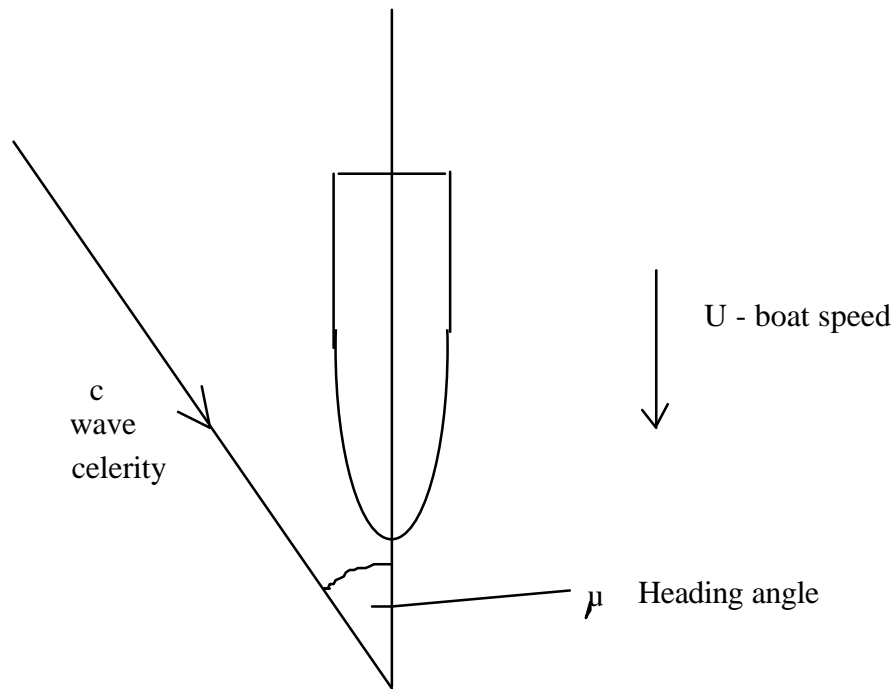
$\mu = 0°$	is a *following sea*
$\mu = 180°$	is a *head sea*
$\mu = 90°$ or $270°$	is a *beam sea*
$\mu = 0\text{-}90°$ or $270\text{-}360°$	is a *stern quartering sea*
$\mu = 90\text{-}270°$	is a *bow quartering sea*

Consider waves of frequency ω, wave length λ and travelling at a speed c. The velocity of the wave relative to the ship, travelling at speed U, is then

$$C_p - U \cos \mu$$

The time between encountering wave crests, the encounter period T_e , is

$$T_e = \frac{\lambda}{C_p - U \cos\mu}.$$

The encounter frequency ω_e is then

$$\omega_e = \frac{2\pi}{T_e} = \frac{2\pi (C_p - U \cos \mu)}{\lambda}$$

Now

$$C_p = \frac{\omega\lambda}{2\pi}$$
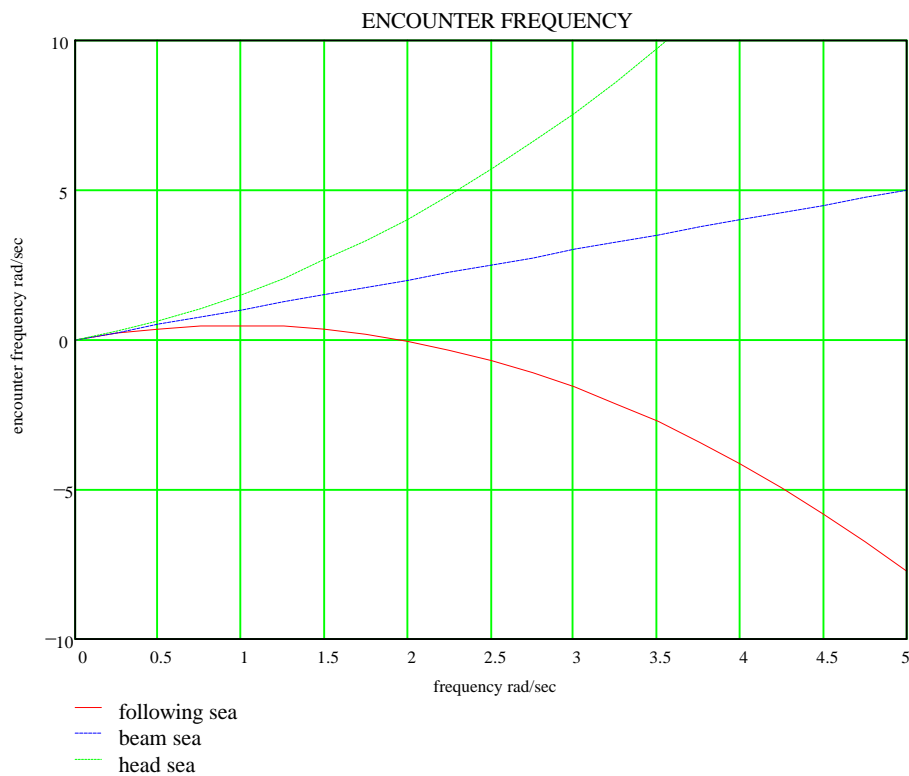
and for deep water waves

$$\lambda = \frac{gT^2}{2\pi}$$

$$\frac{\omega^2}{g} = \frac{2\pi}{\lambda}$$

then

$$\omega_e = \omega - \frac{\omega^2}{g} U \cos\mu \qquad \text{rad/sec}$$

The graph below illustrates three cases for a vessel travelling at 5m/s (approx 10 Knots)

ENCOUNTER FREQUENCY

- following sea
- beam sea
- head sea

For a head sea the encounter frequency is higher than the wave frequency.

For a beam sea the encounter frequency equals the wave frequency.

In a following sea the encounter frequency is initially positive, meaning that the waves overtake the vessel , passes through zero and then goes negative which means that the vessel overtakes the waves.

6 ENCOUNTER SPECTRA

From the notes on ocean waves we know that the area under a wave energy spectrum is proportional to the total energy in that wave field. If the spectrum were measured from a moving platform, the frequencies measured would change from wave frequency to encounter frequency, thus altering the horizontal axis of the spectrum. Clearly the total energy is not changed simply by measuring from a moving point. So to maintain the same area under the spectrum the vertical ordinates must be suitably adjusted. The algebraic condition to be met is:

$$S(w_e)dw_e = S(w)dw$$

where: $S(w_e)$ = vertical ordinate of encounter spectrum.
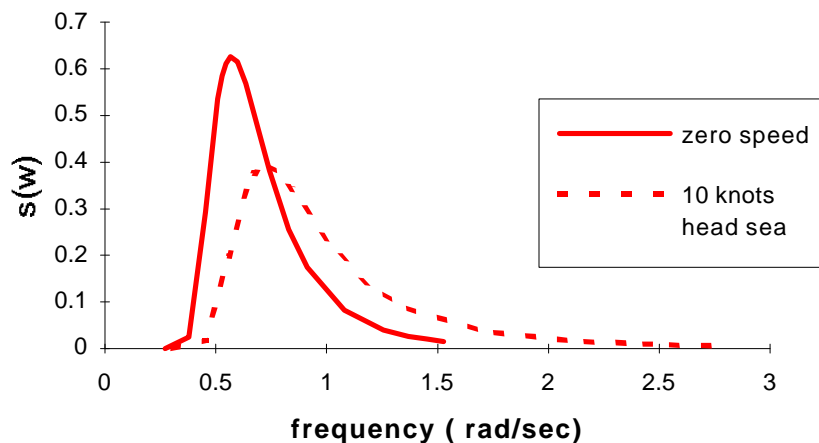
Hence the new vertical ordinates $S(w_e)$ are found from the differential of the encounter frequency formula:

$$S(w_e) = \frac{S(w)}{1 - \frac{2wU}{g}\cos m}$$

where: U   =   ship speed (m/s)
       μ   =   encounter angle from stern

The converted spectrum is called the *encounter* spectrum. It will look similar to the original wave energy spectrum but (for head seas) with the peak reduced and shifted to the right.

Bretschneider spectrum modal period 11secs, sig wave heght 2m at 0 knots and 10 knots head sea

Motions Of Ships

1. OBJECTIVES

- Determine the natural period of roll, pitch and heave for a ship in calm water.

- Explain the terms added mass, added inertia coefficient and damping ratio.

- Describe the response of a simple shape in waves
- Describe the influence of damping on vessel response
- Identify methods of determining the Response Amplitude Operators for a vessel.
- Outline the principles of strip theory.
- Use spectral techniques to estimate vessel response in irregular waves.

2 MOTIONS OF SHIPS IN CALM WATER
2.1 Definitions
The directions of motions are defined below.
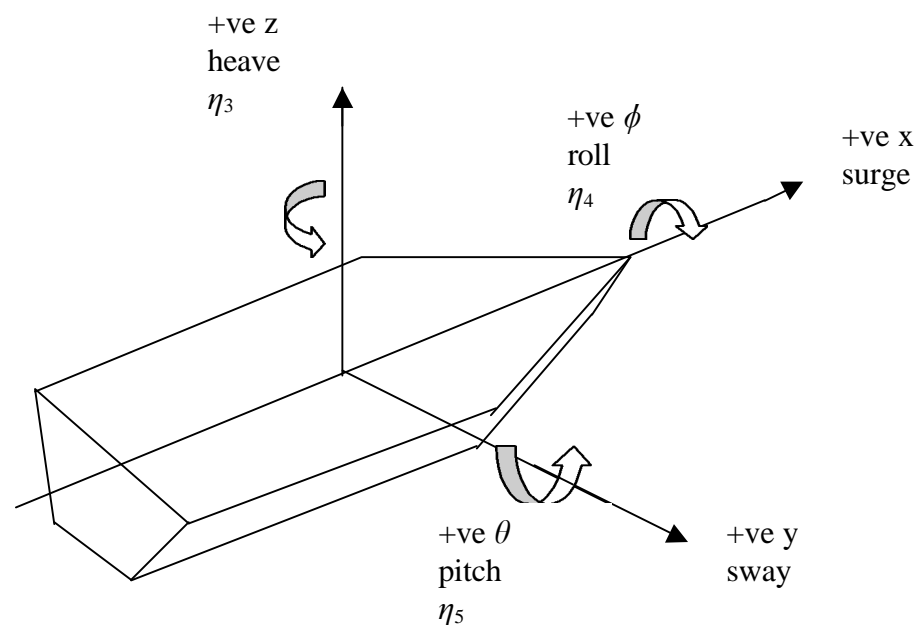
There are only three which are inherently oscillatory - pitch, heave, roll - so we shall concentrate on these. The other motions do not normally have any restoring force or moment. Motion equations are usually 2nd order 1st degree differential equations, the solution of which may be found in text books. We are mainly concerned with the physical significance of these solutions.

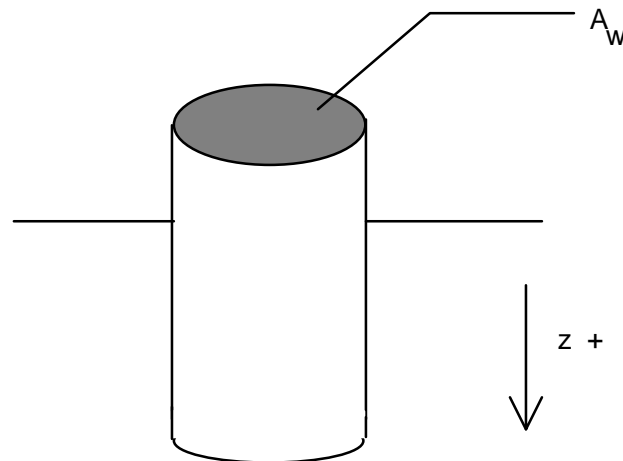## 2.2 Estimating Motion Periods

2.2.1. *Heave*

Q: What is the natural undamped heave period in calm water for a circular cylinder pushed down a distance z then released?

Draw a diagram - it usually helps;

for undamped calm water the equation describing the motion is:

acceleration force + restoring force = 0
(we can justify ignoring the damping later)

$$a\ddot{z} + cz = 0 \quad \text{where } \ddot{z} = \frac{d_2 z}{dt^2} = \textit{heave acceleration}$$

$a\ddot{z}$ represents a force, so 'a' must be in units of mass. In this case it is the mass of the cylinder PLUS the mass of surrounding water affected by the motion. The mass of this water is called the ADDED MASS. Unfortunately it is often given the symbol 'a', but I shall call it 'a_m' , so the constant 'a' can be rewritten as:

$a = (\Delta + a_m)$

where Δ = cylinder mass (Kg)
        a_m = added mass in heave (Kg)

(Note for later that the added mass varies with motion frequency)

'c' is the term associated with the restoring force. If this were an equation describing, say, a weight on the end of a spring, the restoring force would come from the stiffness of the spring. However, this is not a spring; it is a buoy in the water. So where does the restoring force come from? It is the additional buoyancy force due to submergence of the cylinder a distance z from equilibrium:

$cz = \rho\, g\, A_w\, z$ where: A_w = waterplane area (m²)

so the constant $c = \rho\, g\, A_w$

and the equation of motion is:

$$(\Delta + a_m)\ddot{z} + (r\, g\, A_w)\, z = 0$$

which is Simple Harmonic Motion (SHM) The natural frequency ω of an SHM equation is found from

$$\ddot{z} + w^2\, z = 0$$

so for heave, $\quad w_z = \sqrt{\dfrac{rgA_w}{\Delta + a_m}} \quad$ rad / s

Now period $T = \dfrac{2p}{w}$

so $\quad T_z = 2p\sqrt{\dfrac{\Delta + a_m}{rgA_w}} \quad$ seconds

Some confusion on symbols:
Natural period is sometimes written as T_o or just T. I have used T_z above to distinguish natural heave period of the ship from natural period of its other motions, which will probably be completely different values……

2.2.2 Roll
The equation for roll is essentially the same as for heave except that we are now dealing with angular not linear movement. This means that each term in the equation represents a moment or couple rather than a force. So for undamped roll:

angular acceleration moment + restoring moment = 0

$$a\,\ddot{f} \;+\; c\,f \;=\; 0$$

where: f = roll angle (rad)
$\quad\ddot{f}$ = roll angular acceleration (rad/s)

the 'a' term will be inertia (couple = inertia x angular acceleration). It is the polar mass moment of inertia of the ship about the roll axis (x-x) *plus* the added inertia of the affected water (c/f added mass for heave).

The added inertia is treated slightly differently from added mass in that the complete 'a' term is written as:

$$I_{m_{xx}}(1 + s_x) \quad \text{where } s_x = \text{added inertia coefficient}$$

so σ_x represents the ratio of added inertia to ship inertia. The polar mass moment of inertia Im_{xx} is often written in terms of the radius of gyration (or 'gyradius') k_{xx} such that:

$$I_{m_{xx}} = \Delta\, k_{xx}^2$$

Back to the roll equation; the term $c\phi$ represents the restoring moment, which must be the righting moment from stability calculations.

Now Righting moment at small angles $= \Delta g GM\boldsymbol{f}$ $\boldsymbol{f}$ in radians

so the term 'c' $= \Delta$ g GM, so the roll equation can be written:

$$I_{m_{xx}}\left(1+\boldsymbol{s}_x\right)\ddot{\boldsymbol{f}} + \Delta g\, \text{GM}\boldsymbol{f} = 0$$

By similar methods to heave, the roll period is therefore:

$$T_\phi = 2\pi\,\sqrt{\frac{\text{Im}_{xx}\,(1+\sigma_x)}{\Delta\, g\, GM}}$$

2.3 Damping

The following analysis is discussed as roll motion but may also be applied to pitch or heave if the damping is fairly light. The equation for damped roll in calm water is:

$$a\ddot{\boldsymbol{f}} + b\dot{\boldsymbol{f}} + c\boldsymbol{f} = 0$$

The solution can be shown to be:

$$\boldsymbol{f} = \boldsymbol{f}_0 \exp\left(-\boldsymbol{n}t\right)\cos\left(\boldsymbol{w}t\right)$$

where: ν = a decay constant $= \dfrac{b}{2a}$

        $\boldsymbol{f}_0$ = max. roll angle

The motion of a ship in still water, when given an initial heel angle then released will therefore look like:

Damped roll in calm water
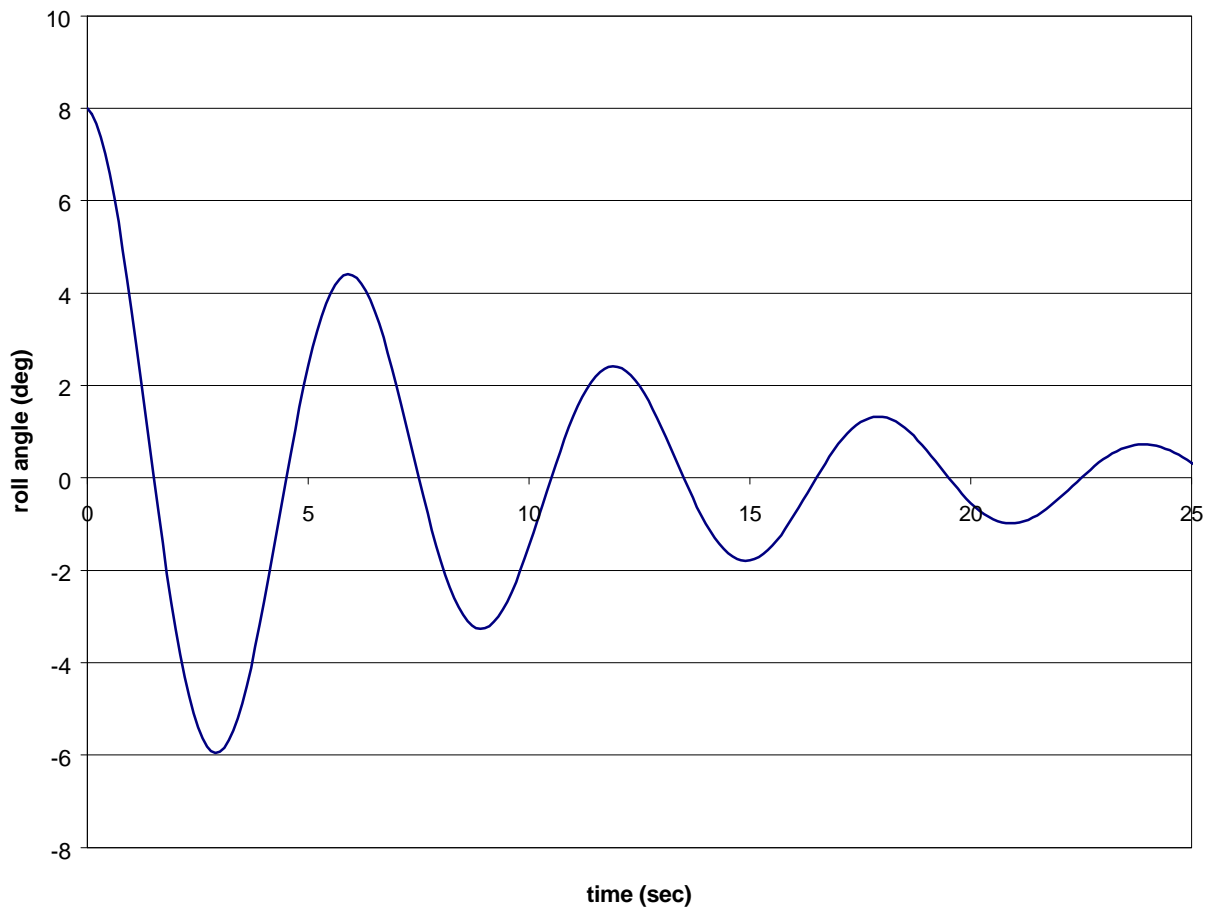
At t = 0, $\boldsymbol{f} = \boldsymbol{f}_0$

If we consider the solution at time t = T then:

$$\boldsymbol{f} = \boldsymbol{f}_2 = \boldsymbol{f}_0 \exp(-\boldsymbol{n}T)$$

so: $$\frac{\boldsymbol{f}_2}{\boldsymbol{f}_0} = \exp(-\boldsymbol{n}T)$$

hence: $$\log_e\left(\frac{\boldsymbol{f}_0}{\boldsymbol{f}_2}\right) = \frac{b}{2a}T$$

Now $$T = 2\boldsymbol{p}\sqrt{\frac{a}{c}}$$

so: $$\log_e\left(\frac{\boldsymbol{f}_0}{\boldsymbol{f}_2}\right) = \frac{b}{\sqrt{ac}}\boldsymbol{p}$$

$\dfrac{b}{\sqrt{ac}}$ is called the *damping coefficient,* but just to make life interesting, it is also written as

$\dfrac{b}{2\sqrt{ac}}$ which is called the *damping ratio* (or sometimes the damping coefficient!!) Both are given the same symbol, ,β and are dimensionless. Seakeeper uses the second definition, with the "2" in it, and calls it damping ratio. It is a dimensionless quantity.

Typical values of β are:
        0.05 for roll
        0.2 for pitch
        0.3 for heave

and so

$$\log_e\left(\frac{f_0}{f_2}\right) = 2bp$$

2.4 Example

Tests on a 100m barge show the following maximum roll angles:

Port (deg)	10.4		7.7		5.9	
Stbd (deg)		8.9		6.7		5.2

        Estimate the damping ratio β.

3. MOTIONS OF SHIPS IN WAVES

3.1 Heave Of A Simple Shape in Waves

3.1.1 The basic equation

The basic equation will be similar to that for calm water, except the right hand side will be the wave force:
$$a\ddot{z} + b\dot{z} + cz = F_0\cos\left(w_e t + s\right)$$
where: F_0 is the maximum wave force, and σ is the phase difference between the wave force and the wave motion.

3.1.2 Solution to the equation:
Standard maths texts show the solution to be:
$$z = z_a\cos(\omega_e t - \tau)$$

where: z_a is the maximum heave amplitude, and τ is the phase lag between the cylinder motion and wave force.

It can be shown by several pages of algebra and a small amount of magic that:

$$z_a = F_0 \left\{ \left(c - [m + a_m] w_e^2 \right)^2 + b^2 w_e^2 \right\}^{-\frac{1}{2}} \quad \text{and}$$

$$e = \tan^{-1} \frac{b w_e}{\left(c - [m + a_m] w_e^2 \right)}$$

3.1.3 Making sense of the solution:

It is more helpful to rewrite the equation solution in terms of three parameters:

tuning factor $l = \dfrac{w_e}{w_o}$ i.e. ratio of forcing frequency to natural frequency,

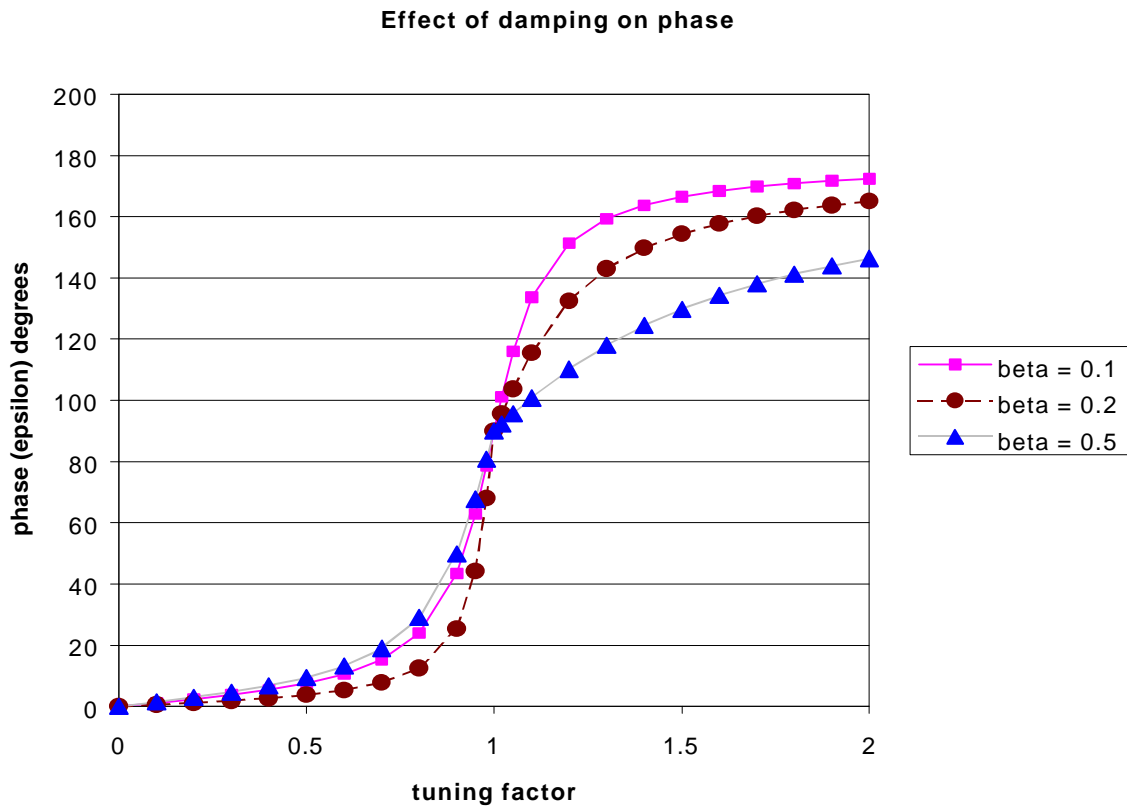damping factor $b = \dfrac{b}{2\sqrt{ac}}$, from earlier calm water motions notes, and

Response Amplitude operator $\quad RAO = \left[\left(1 - \Lambda^2 \right)^2 + 4 b^2 \Lambda^2 \right]^{-\frac{1}{2}}$ which is the ratio of cylinder heave to wave amplitude.

The results look like:

Effect of damping on RAO
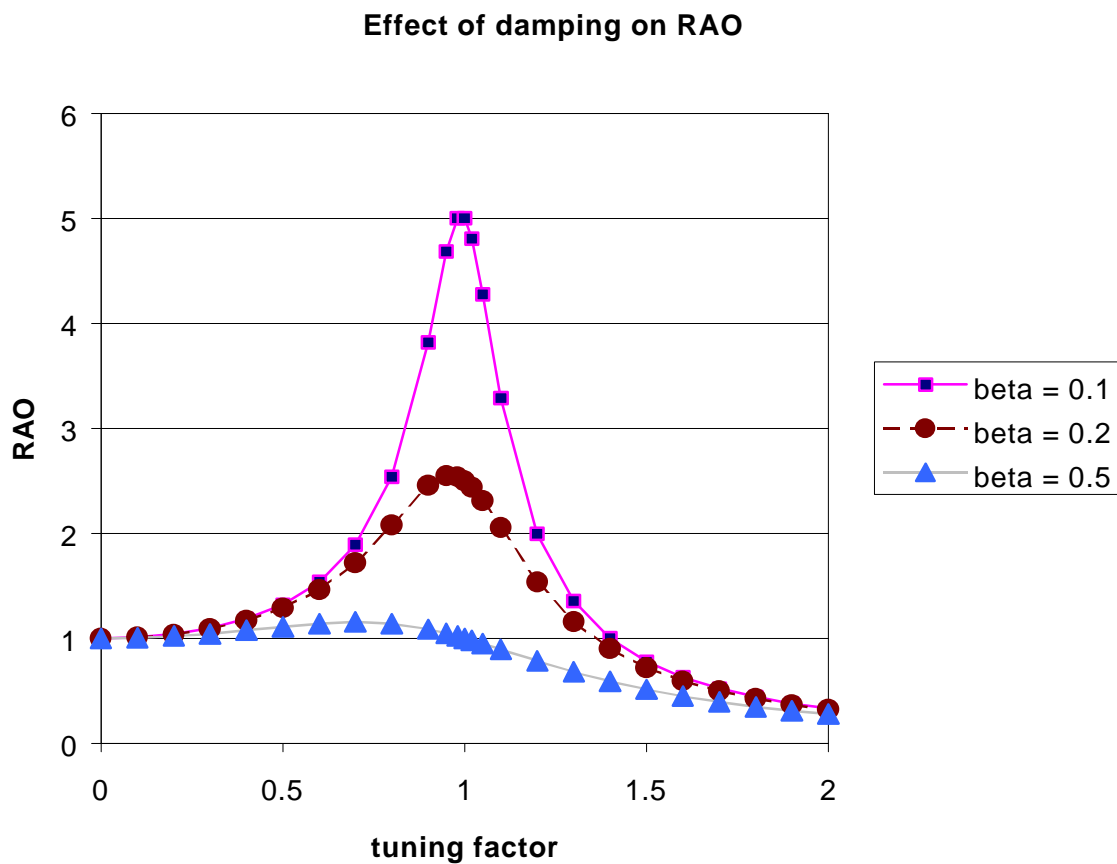
The formulae for the phase angles become:

$$\boldsymbol{e} = \tan^{-1} \frac{2\boldsymbol{b}\Lambda}{1 - \Lambda^2}$$ between heave force and heave motion

Effect of damping on phase

$$\boldsymbol{s} = \tan^{-1} \frac{2\boldsymbol{b}\Lambda}{1 - \left(\dfrac{a_m}{m + a_m} \right)\Lambda^2}$$ between wave force and wave motion

$\tau = \varepsilon - \sigma$ between heave motion and wave motion

If there were no damping then all phase angles would be either 0º or 180º.
If the mass of the buoy m were zero then:

$$\sigma = \varepsilon$$
and $$\tau = 0$$

At resonance, Λ = 1, so
ε = 90

4. COUPLED MOTIONS AND STRIP THEORY

So far we have considered each motion in isolation. In practice all motions occur at the same time, and are coupled, i.e. motion of one sort will generate motion of another sort. Some motions are more strongly coupled than others e.g. pitch and heave are strongly coupled whereas yaw and heave are weakly coupled. The full coupled equations of motion for a vessel would contain over 100 terms and would be practically impossible to solve. The approach taken is to consider only strongly coupled motions then use strip theory.

4.1 Strip theory:
- Divide the ship into sections or strips
- Calculate the added mass, damping and restoring force at each strip
- Integrate the added mass and damping over the length of the vessel
- Put these values into the equations of motion and solve them.

For heave and pitch (the most common motions), the equations look like:

$$a\ddot{z} + b\dot{z} + cz + d\ddot{q} + e\dot{q} + hq = F_0 \cos(w_e t + s) \text{ for heave, and}$$

$$A\ddot{q} + B\dot{q} + Cq + D\ddot{z} + E\dot{z} + Hq = M_0 \cos(w_e t + a) \text{ for pitch}$$

the terms *d, e, h, D, E,* and *H* are the cross-coupling coefficients. F_0 and M_0 are the maximum wave force and moment respectively.

A note on nomenclature:
The general notation of a,b,c, etc. for the coefficients is often defined more precisely by adding a matrix numbering system (p59 of Seakeeper manual) , see first page of these notes for definitions. This changes the notation e.g.

a becomes A_{33}, meaning the added mass coefficient for heave due to heave
b becomes B_{33}, meaning the damping coefficient for heave due to heave
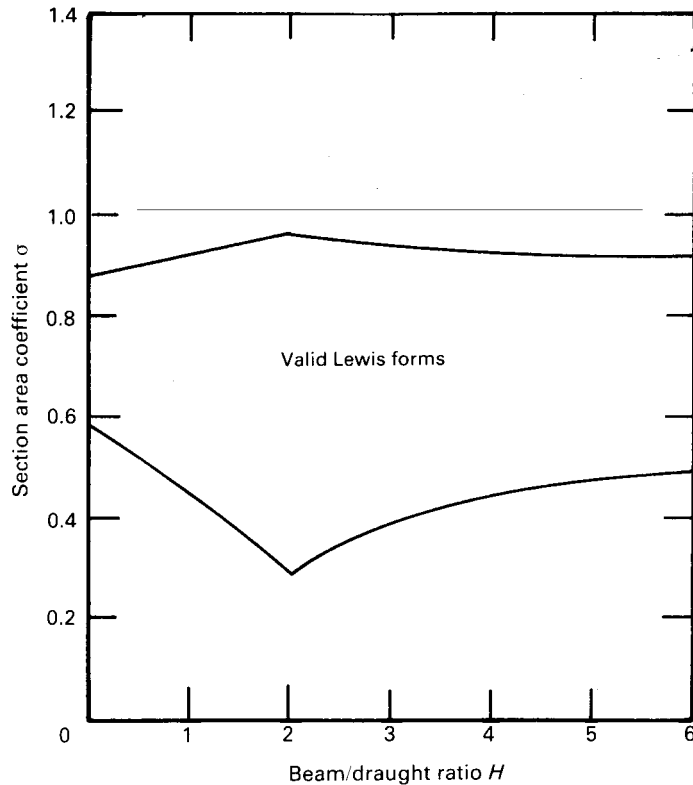*h becomes C_{35} , meaning   ?*

and just to make life really interesting, all motions are often given the symbol η, with a number subscript as the identifier e.g.
η_3 = heave motion

These coefficients are determined by conformally mapping each ship section to a circle, then using the known analytical solution for a circle (Ursell, 1949). The values are then put back into the equations of motion which are decoupled and solved, yielding RAOs and phase angles for pitch and heave.
The mapping will not replicate the ship section exactly; the goodness of fit depends mainly on the number of terms used in the mapping equation. However, the more terms, the slower the computation. Seakeeper uses a three-term mapping equation, known as a Lewis mapping. This is adequate for mapping most conventional hull shapes, though it will have difficulty with some bulbous bows and very high section area coefficients.

The y-axis is labelled "Section area coefficient σ" with values 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. The x-axis is labelled "Beam/draught ratio H" with values 0, 1, 2, 3, 4, 5, 6. The region between the two curves is labelled "Valid Lewis forms".

Some strip theories do not use conformal mapping, instead they use a boundary element or boundary integral method, also known as Frank close fit method. There is usually very little difference in results between the conformal mapping and Frank close fit methods.

Strip theory assumes that
- The ship is slender i.e. L>>B and L>>D
- There is no significant planing force. This implies low to moderate speeds for monohulls.
- The motions vary linearly with wave amplitude, which is usually valid for slender vessels operating in waves of small amplitude. However, extreme motions tend to be very non-linear.
- There is no flow between strips, i.e. the motion is two-dimensional. Whilst this is clearly incorrect, the results are surprisingly accurate.
- Viscous damping terms are negligible (a poor assumption for roll, but reasonable for pitch and heave under most conditions).
- The presence of the hull does not affect the incoming waves

4.2 Other theories:

- For low frequency response, e.g. for yaw, *slender body theory* may be used. For zero forward speed in head seas this yields reasonable predictions.

- A combined strip and slender body theory has been developed by Sclavanous (1985) which works well over a wide range of frequencies. (the "SWAN" code) but is computationally intensive and still a research level code rather than a general use code.

- Three-dimensional, zero speed problems in sinusoidal waves can be solved using *source-panel methods*, whereby the flow round the moving object is represented by placing sources of fluid around the panellised shape at appropriate locations and source strengths. This is rather like finite element analysis. These theories are often applied to motions problems for stationary offshore structures. (e.g. "AQUA" code)

Details of most methods can be found in Newman (1977)

5. PREDICTION OF MOTIONS IN IRREGULAR SEAS

5.1 Introduction

If we want to predict pitch, roll, deck wetness etc. for a ship operating in a particular sea area we must have information on:

- the waves likely to be experienced
- the response of the craft to waves.

This information can then be combined to generate a motion response spectrum, from which statistical likelihoods can be calculated for the seaworthiness characteristics of interest.

5.2 Response Amplitude Operators (RAOs)

The response of the ship to waves may be determined either from tank test experiments or from theoretical calculations. The end product is usually a plot of vessel response against encounter frequency, called an RAO curve. The RAO curve is usually presented non-dimensionally:
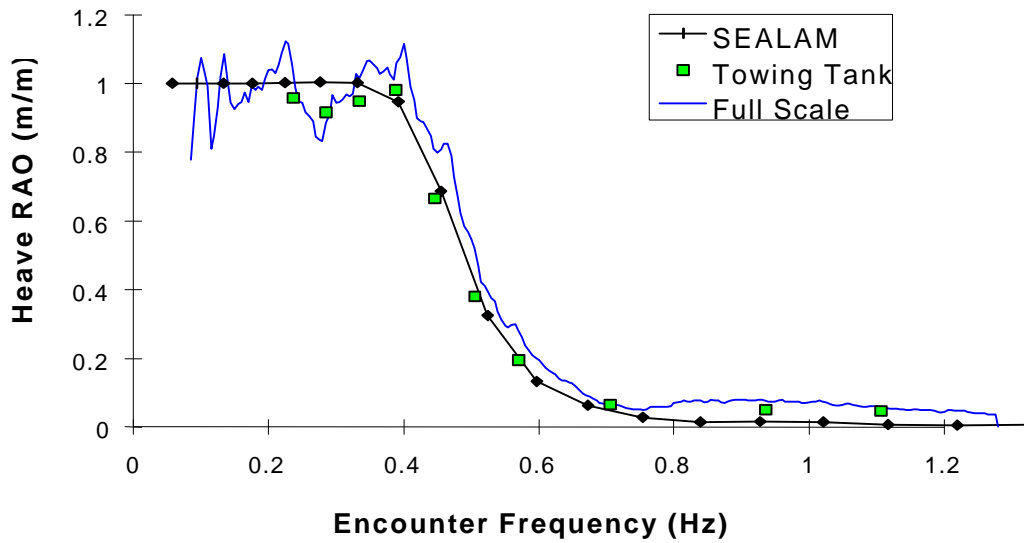
For linear motions, e.g. heave z $\qquad RAO_z = \dfrac{z_0}{x_0}$
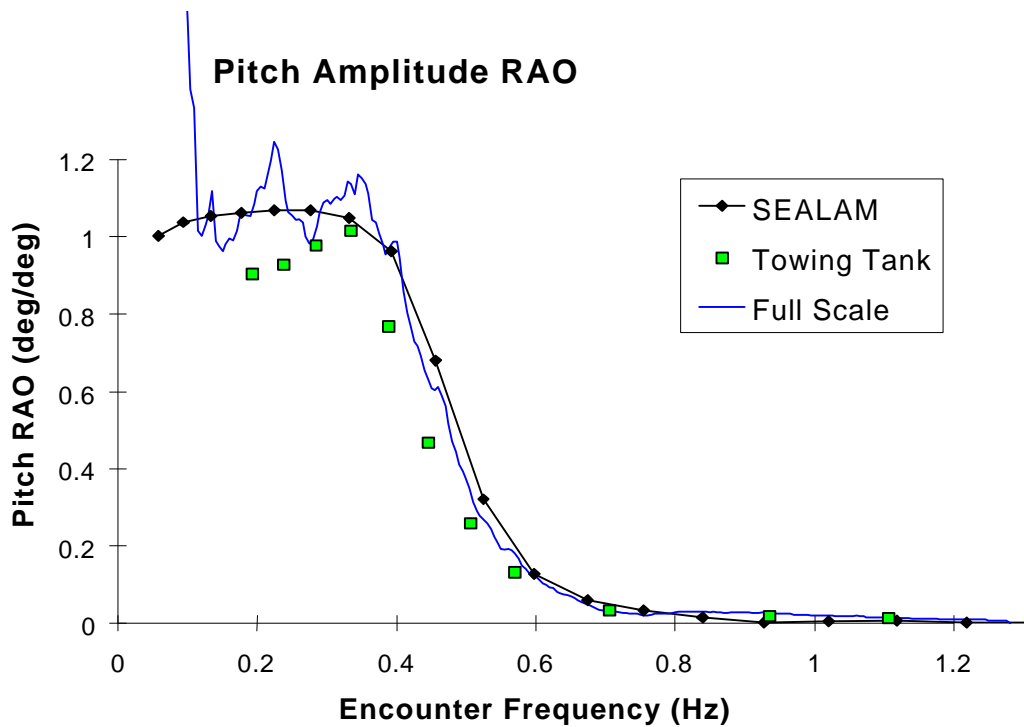
For angular motions e.g. pitch θ $\qquad RAO_q = \dfrac{q_0}{kz_0}$

Where k = wave number = $\dfrac{2p}{l}$ (λ is wavelength)

So kζ is the wave slope

Heave Amplitude RAO

Pitch Amplitude RAO

There are several techniques for obtaining RAO curves

Model Tests

The most common method is to run a model in regular waves of a particular frequency and amplitude, varying the frequency with each run. The entire range of wave frequencies likely to be encountered must be covered, and each frequency run at the different speeds of interest. Clearly, this takes a long time if a full set of data is to be obtained, but does not require very sophisticated equipment. An alternative approach is to generate the wave spectrum of interest and run the model through it.However, the run time in most tanks is short, so a full spectrum

of waves will probably not be encountered in a single run. Whatever method is used, care must be taken to ensure the model has correctly scaled moments of inertia. Most tanks can only run in head seas – tests in oblique waves require the use of a comparatively expensive wave basin (not available in Australia).

Theoretical Predictions

Methods such as strip theory are used (see earlier discussion).

Full Scale Trials

RAOs for the vessel may be obtained by full size trials. The motion response spectrum can be measured on board a ship during trials using accelerometers and/or rate sensors. If the wave spectrum experienced at the time is known, (measured using a wave buoy or on-board radar sensor) the RAOs can be worked out. This is useful for validating model experiments and theoretical predictions Care must be taken with data acquisition and processing in order to obtain meaningful results.

5.3 The Response Spectrum

The wave energy spectrum and the RAO curve are combined to produce a motion response spectrum with ordinates representing motion energy rather than wave energy. The area under the curve will then be a function of motion amplitude (energy $\propto$ amplitude^2). This motion response spectrum is obtained by considering a narrow strip of area $\delta\omega$ wide:

$$S_{wave}(w)dw = const \times z^2$$

We want a graph such that e.g. for heave z

$$S_z(w)dw = const \times z^2$$
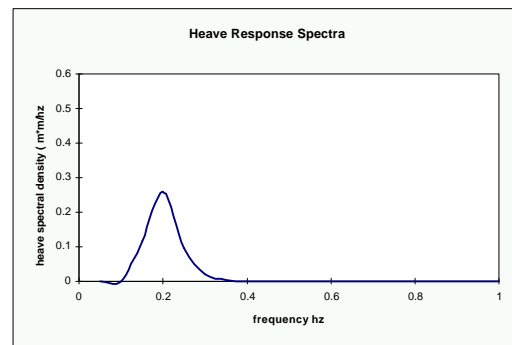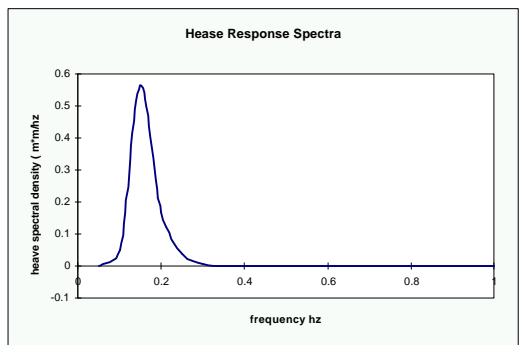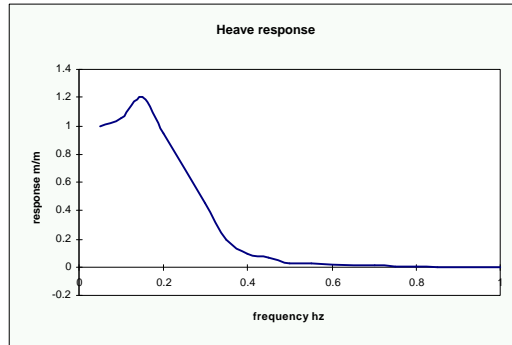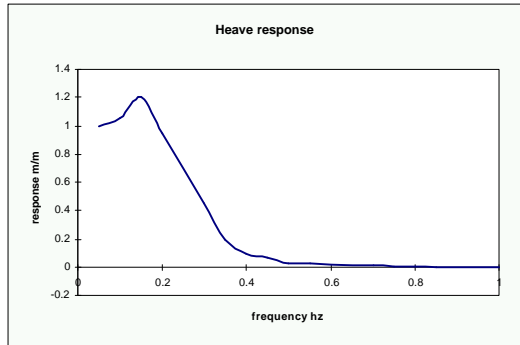
The ordinate S (w) is obtained simply by :

$$S_z(w) = S_z(w) \times RAO^2$$

since $RAO^2 = \dfrac{z^2}{z^2}$

This process can be carried out using either wave frequency or encounter frequency on the horizontal axis. Encounter frequency is usually used but it does not matter which, as long as it is the same for both wave spectrum and RAO.
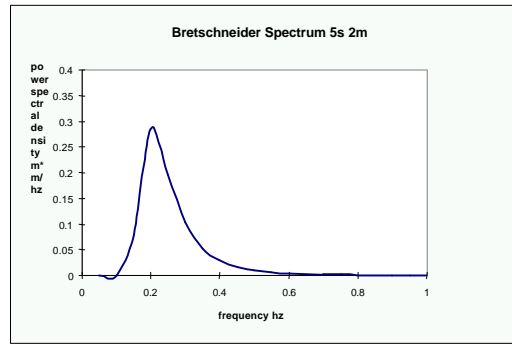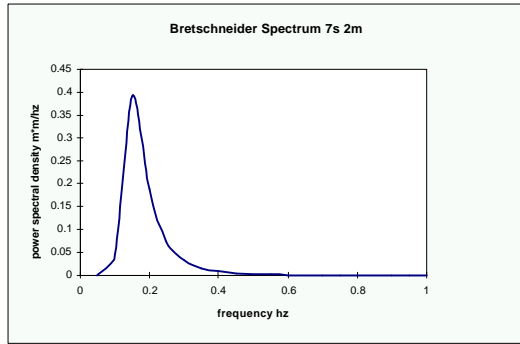
Note in the above example the right column has the same RAO as the left column, and the significant wave height of the two wave spectra are both the same. However, the response spectra (and hence the vessel motions and accelerations) are markedly different.
Why?

Introduction to Seakeeper Software

Overview

Three sets of data required for effective seakeeping analysis;
1.   Weather conditions expected
2.   Seakeeping performance of vessel
3.   Criteria for assessment of performance

Seakeeper helps with the middle one.

Can use standard spectra and statistical weather data for first

Third is the least well understood, there are a variety of considerations depending on vessel's role (Passenger vessel, freight, naval vessel, sailing vessel). Some of the most common criteria require predicting the probabilities of exceeding certain prescribed (arbitrary) values of roll, heave, pitch, acceleration which are determined in some way or another. Other criteria are MSI (motion sickness incidence) and another gaining favour, especially in military vessels is the concept of MII (Motion Induced Interruptions) or how often a person cannot do their job.

Basic Principals

1.   Use strip theory to predict vessel response
2.   Decide the sea states that the vessel is likely to find itself in
3.   Calculate the motions in these sea states
4.   Calculate motions criteria such as MSI etc
5.   Assess them against acceptable levels.

Seakeeper uses a theoretical method know as strip theory to calculate the vessel's motions in a seaway. This is a linear theory, which assumes that the vessel's response is proportional to wave height. Making this assumption means that the vessel's response depends only on the vessel's underwater shape, the vessel's speed, the direction of the waves relative to the vessel's track and the wavelength of the waves.

The vessel's response to regular waves is calculated for a number of different wavelengths. Once this is known, by using the principal of superposition, the vessel's response to any set of irregular waves may be calculated.

Getting started with Seakeeper

In this section you will learn how to open a design and perform a rudimentary seakeeping analysis on it. You will be introduced to the Seakeeper user interface and how to navigate around the program.

In subsequent sections you will be given more information on how to refine the seakeeping analysis to obtain the best quality results.

Load design

The first step of the analysis is to load a Maxsurf design. However, before you do so, you should check that all the trimming is correct and that all sections though the hull are correct. The rules which apply to Hydromax also apply to Seakeeper: All sections must have at most one opening (which is then closed off with a straight line). There must be no excess portions

of surfaces intersecting the contour. In addition, for Seakeeper there can be only one closed contour. In practice, to accurately model the main hull, it is usually necessary to remove underwater appendages.

These constraints may require you to make a copy of your original Maxsurf design which you then use for the Seakeeper analysis, possibly having removed surfaces which are not required in the Seakeeping analysis, e.g.: keels, rudders etc. See below for an example.
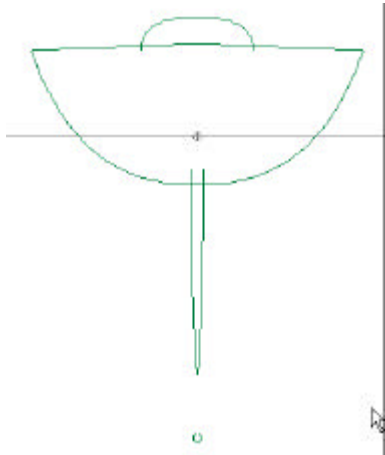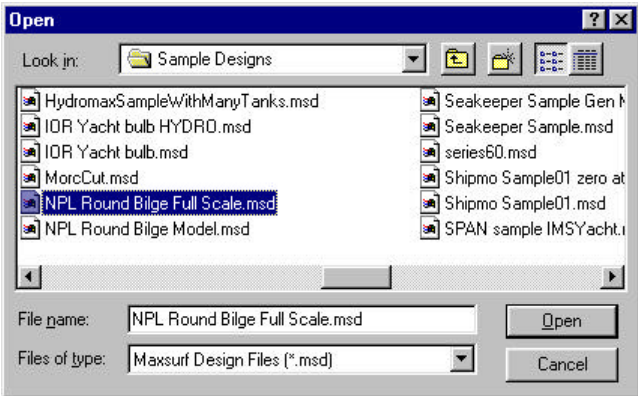

Original Maxsurf design, note untrimmed surfaces, keel and bulb.
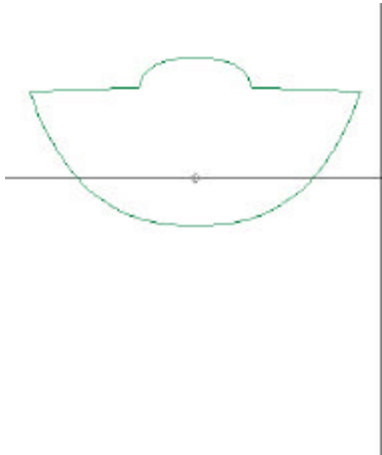
Design ready for Seakeeper, after trimming and removing keel and bulb.

A good example design file is:
C:\Program Files\Maxsurf\Sample Designs\NPL Round Bilge Full Scale.msd
This one is about 42m on the waterline and the default settings will work fine.

Initial analysis

It is usually helpful to perform a quick initial analysis of the vessel to get a feel for its response before proceeding with the detailed seakeeping analysis. This will confirm that the model has been read in correctly and that the vessel behaves as expected.

When you first start Seakeeper, it will have a set of default analysis options which are sensible for an initial analysis. These default values will be appropriate for most vessels.

However, if the vessel is particularly large or small it may be necessary to change the wave spectrum period and / or the vessel speed. An explanation of the various parameters and how these may be changed is given below.

First we will carry out a calculation with the default settings and then get a feel for the layout of the Seakeeper program.

To run the full analysis Choose Calculate Seakeeping Data from the bottom of the Analysis menu. This will perform all aspects of the analysis: measuring the hull and calculating the Lewis mappings of the hull's sections; calculating the vessel's RAOs and finally calculating the vessel's motions to the specified wave spectrum.

Then you should look at the Results or Graphs window, see section below, to check that the calculation has worked OK and you have some results.

Tour de Seakeeper

Design window

There are four design views: Perspective, Plan, Profile and Bodyplan. The design view is useful for verifying the measured sections and the calculated Lewis sections. The most useful views are the Perspective and Bodyplan views. The sections, design waterline and Lewis mappings are most easily turned on or off using the Contours toolbar:

Sections | DWL | Mapped Sections.

Alternatively you can use the Contours dialog from the Display menu.

Typical displays form the Perspective and Bodyplan views are shown below:
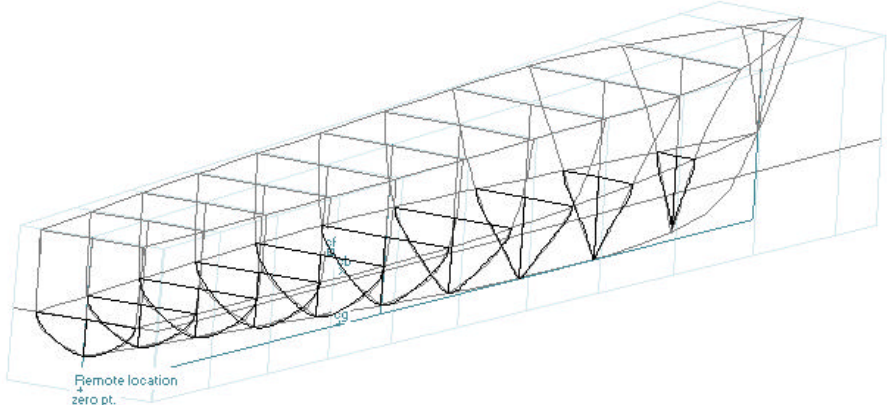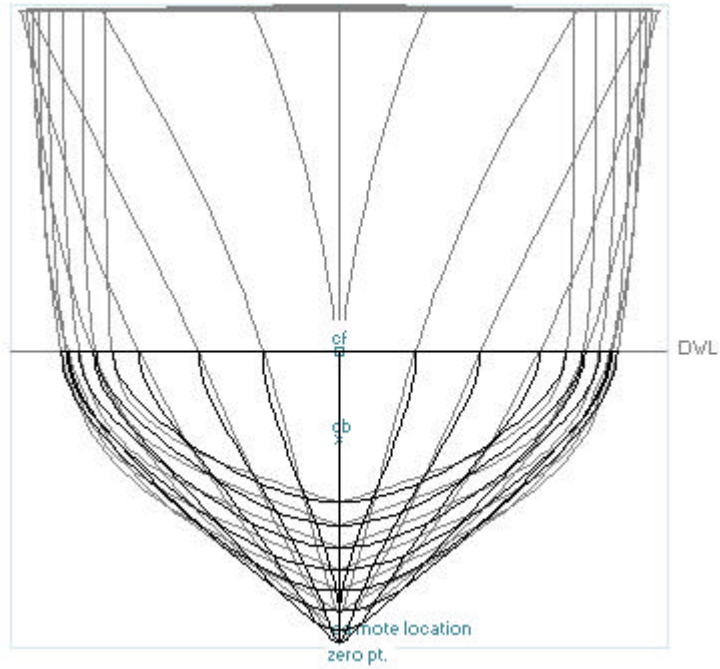
You should confirm visually that the sections have been formed correctly and that the mapped sections adequately represent the underwater portion of the hull. Because of the limitations of Lewis sections, there may be some discrepancies, particularly near the DWL and centreline.

Results window

The results view, presents all the data from the analysis in tabulated numerical format. These data may be copied from the Seakeeper tables and pasted into other applications such as MS Excel for post processing. A typical view of the results window is shown below.

There are seven separate tables in the Results window:

1	Summary	Summary of input parameters and integrated values from motion spectra.
2	CG RAOs	Response amplitude operators for heave, pitch and roll, including phase. Also added resistance operator.
3	CG spectra	Wave and encountered wave spectra and spectra of heave, pitch and roll response and added resistance for the specified wave spectrum.
4	Remote location spectra	Relative and absolute vertical motion, velocity and acceleration spectra at the remote location.
5	Global hydrodynamic coeff.	Integrated added mass, damping, stiffness and cross-coupling terms for the whole vessel
6	Sectional hydrodynamic coeff.	Added mass, damping, stiffness and cross-coupling terms for the individual 2D-sections
7	MSI	Motion sickness incidence at remote location

One of the key things to check is that the frequency range, over which the calculations are made, is sufficiently broad and has a sufficient number of points. When calculating accelerations, the high frequency end of the spectrum is particularly important because a factor of w_e^4 is applied. There two ways of checking that the frequency range is adequate and that there are sufficient frequency steps:

Firstly, in the summary table, the specified characteristic wave height of the wave spectrum is listed in the second row. This can be compared with the significant amplitude of the computed wave and encountered wave spectra, noting that the significant amplitude should be half the characteristic wave height. If the computed values are lower than those specified, this suggests that the frequency range is not broad enough and that the cut-off frequency should be extended. The procedure for doing this is explained later. Remember that for calculations of significant acceleration, the cut-off frequency should be extended even higher.

Secondly, you can quickly get a feel for how well the spectra and RAOs are defined by checking the data in the Graph window.

Graph window

The graph window displays all the results data apart from the summary data in Graphical format.

Bring the graph window to the front:
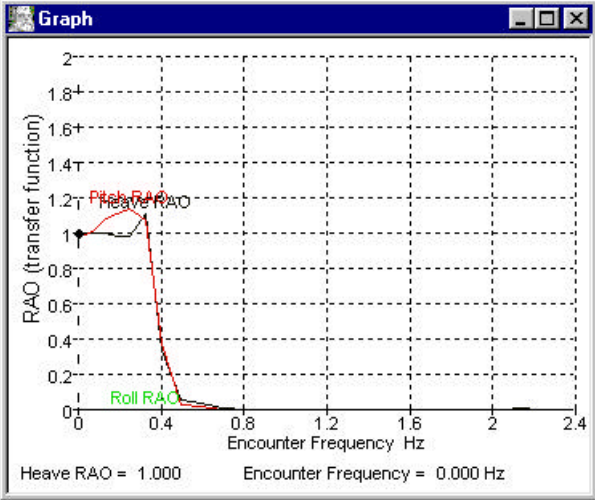
You may select which of the tables is graphed in the Windows menu:
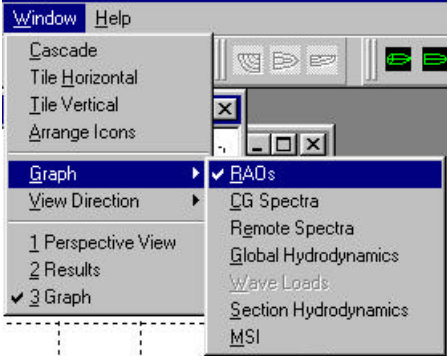
In addition to selecting the general type of graph from the Windows menu, you can also specify which data-sets should be displayed and the x-axis to use. Select the Graph Options dialog from the Display menu:
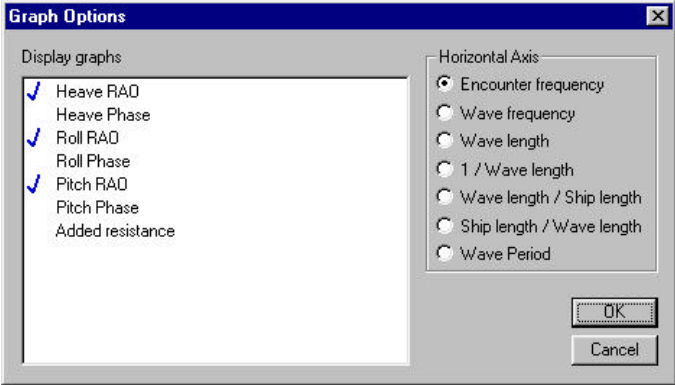
Place a tick next to the data-sets you wish to graph. On the right-hand-side, you can select the x-axis you wish to plot the data against. Note that you may only plot the spectra and MSI curves against wave or encounter frequency, depending on the type of spectrum. Also the frequency units for the spectra are always rad/s. These limitations are due to the fact that the spectra would have to be re-calculated if the x-axis were changed, to maintain constant areas under the spectrum curves.

For the section hydrodynamics curves, you must select the section or frequency you want to plot the data for. This is done by first selecting Section Hydrodynamics from the Graph sub-menu in the Window menu. Then selecting the Section Data dialog in the Display menu:
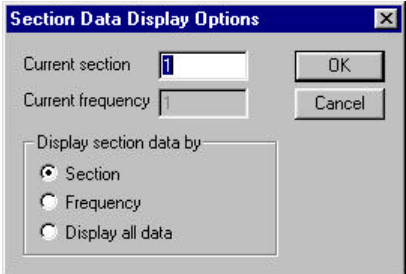

Select whether you want to plot the data for a specified section (the data will then be plotted against a frequency x-axis) or to plot for a specified wave frequency along the length of the hull. This is done by selecting the appropriate radio button.

Note that this dialog also affects how the data is displayed in the Results window table. If you select the Display all data option. The data will not be plotted (since it would be a mess) but all the data is displayed in the table and may be copied to a spreadsheet for post processing.

If you select either Display section data by Section or Frequency, you can select the particular section or frequency index you wish to view the data for. The following figure shows the added mass, damping and stiffness plotted along the length of the hull, against section position for a specified frequency.
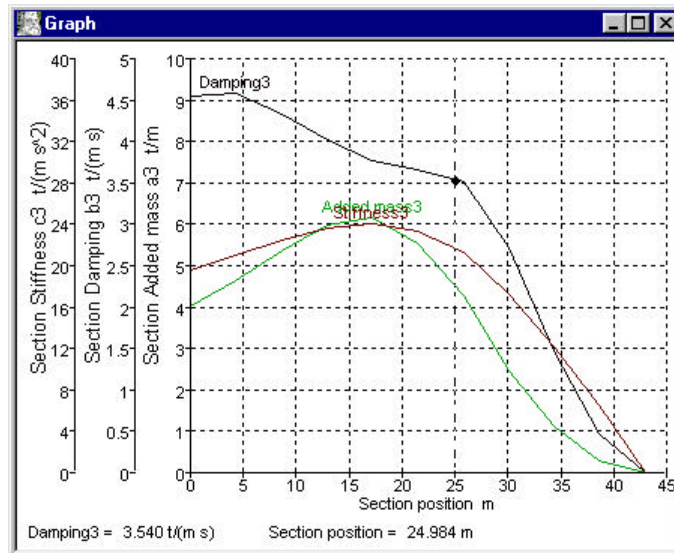
Alternatively, for a specified section, you can look at the variation of added mass, damping and stiffness with frequency.
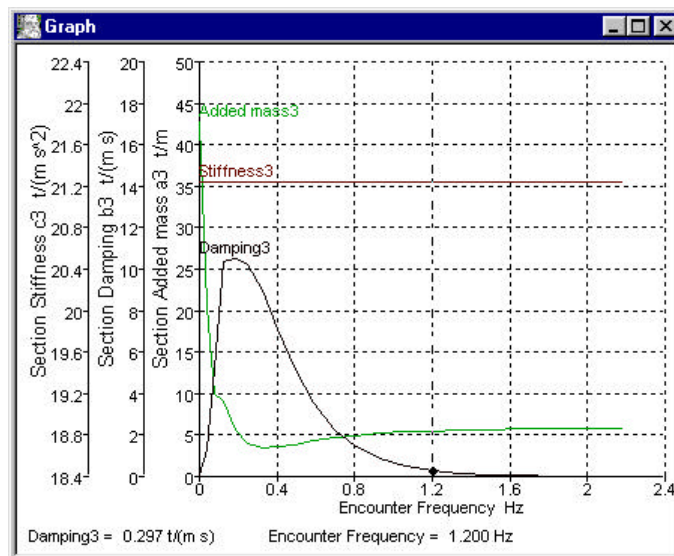
Menus

There are eight main menus in Seakeeper. Each one contains related commands:

File:	Opening and saving files, printing and page set up.
Edit:	Copy (Ctrl C) and Paste (Ctrl V), note it is often more convenient to use the keyboard short-cuts.
View:	Controls the zoom and pan in the design views, the colour and font used and which toolbars are displayed.
Analysis:	Set all the options for the analysis; perform the analysis..
Display:	Select which contours are displayed in the design view. Select which data-sets should be displayed in the graph and which section data to display.
Data:	Specify units and frame of reference.
Window:	Select required graph or view direction; quickly navigate between Seakeeper's windows.
Help:	Online help, version and system information.

Units

The data may be entered and displayed in a variety of units. Choose Data | Units to specify your preference:
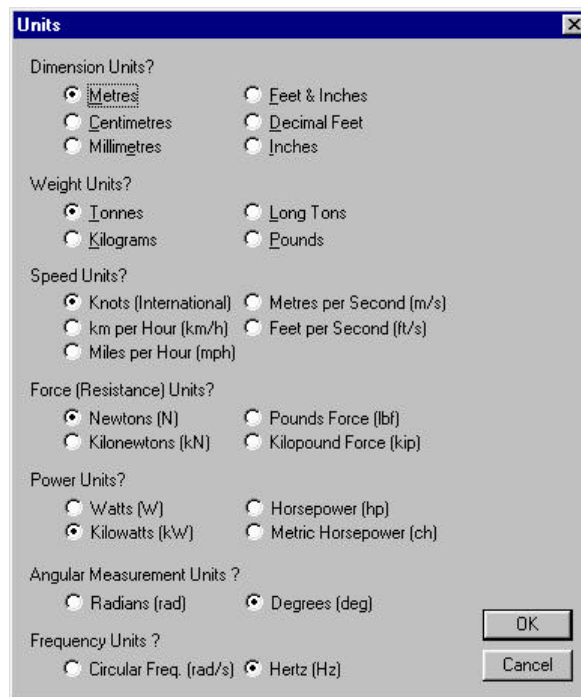
Note that the data for all spectra are for a frequency x-axis in rad/s.

Refining the analysis parameters

Once you have successfully completed a preliminary analysis, you should refine the analysis. This will generally involve increasing the number of stations used to calculate the hull's hydrodynamic characteristics and increasing the number of frequencies at which the response is calculated, you may also need to change the frequency range over which the calculations are performed.

Depending on the speed, vessel type and / or wave heading, it may also be appropriate to investigate the effects of changing the analysis method. MS Excel is a very useful tool at this stage, since it is very easy to copy and paste results from the Seakeeper RAO table and generate graphs to compare the influence of the analysis methods. You can also use this technique to investigate the sensitivity of the hulls response to other factors such as speed, wave heading, draught, gyradii etc.

Measure hull

The Measure Hull dialog allows you to select which surfaces should be included in the measurement of the hull sections and how many equally spaced, sections are placed between the fore and aft perpendiculars.
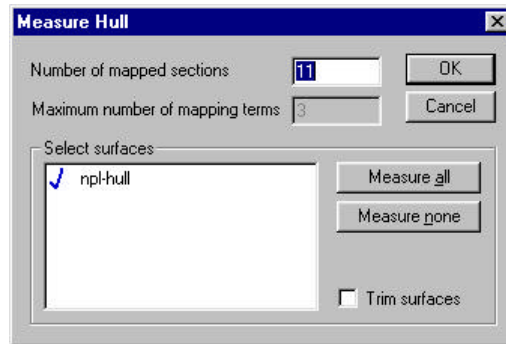
For final calculations, use perhaps 21 or 41 or more sections depending on the longitudinal variation of hull shape. You can examine the graph of section hydrodynamics and check that you have a smooth curve:

With the graph window topmost, select Graph | Section Hydrodynamics from the Window menu. Then in the Display menu, select the Section Data dialog.
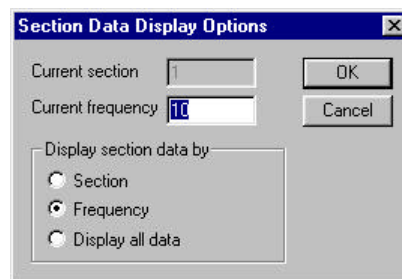
Choose to view by frequency and specify the frequency index you wish to view the results for. A low number will display a low frequency and the highest number will be the high cut-off frequency. (The highest number you can set is the number of frequency steps you have specified, see below; if you type in a number grater than this, Seakeeper will insert the maximum allowable number)

You should have sufficient sections so as to get a reasonably smooth curve for the section hydrodynamic properties, as shown below:

Added mass3 = 20.524 t/m   Section position = 30.000 m
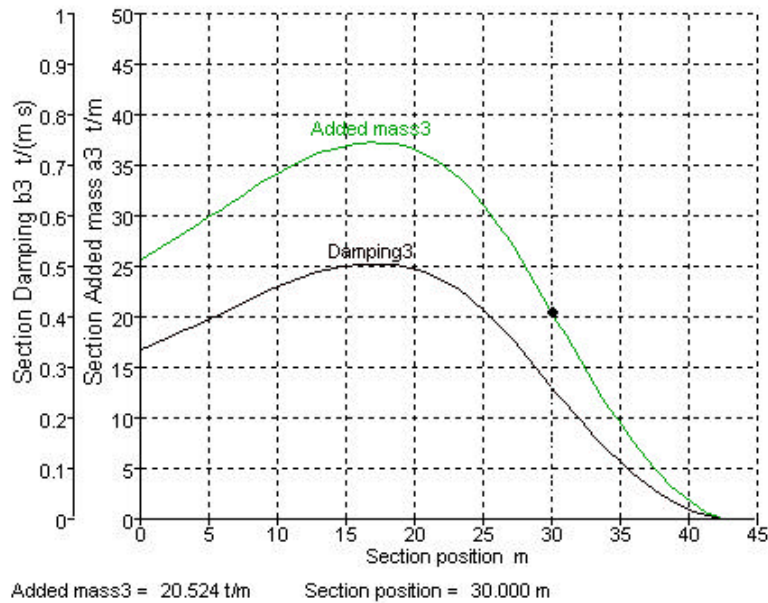
Frequency range

You may set the upper cut-off frequency for the analysis and the number of frequency steps, for Seakeeper to use. The greater the number of frequency steps, the better defined the RAOs will be and the integrated motion spectra will also be more accurate.

The upper integration limit should be sufficiently high to capture all the high-frequency spectral energy. This is particularly true for acceleration spectra which have a w_e^4 factor. This makes the high-frequency end of the spectrum very important, even if there is little wave energy and the vessel's motion RAOs are small. By default, if you set the spectrum type to JONSWAP, the default upper frequency cut-off will be 6 times the modal frequency, for all other spectra, the cut-off will be 10 times the modal frequency. However, you can override this in the Frequency Range dialog.
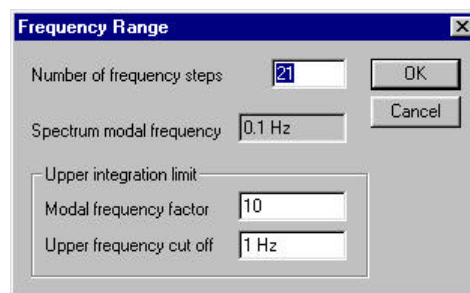
Analysis method

As with most theoretical methods, there are several variations on the basic theme. Seakeeper has several analysis options which may be set in the Analysis Method dialog:

Transom terms

The original formulation of the strip theory methods assumes that the vessel has zero beam at the bow and stern and that the section hydrodynamic properties also go to zero at the bow and stern.

For transom stern vessels, the vessels width does not go to zero at the stern. For this reason it is possible to add transom terms which aim to take account of this. The effect of transom terms is to damp the motions. Because they are at the stern of the vessel, they have a marked effect on the pitch response. The amount of additional damping due to the transom terms is proportional to the vessel's speed.

Transom terms were originally developed to account for relatively small transoms on container type vessels such as monohulls travelling at moderate Froude number, for this reason, when applied to high-speed monohulls and catamarans, the transom terms can over estimate the additional damping.

Users should compare the results with and without transom terms to gauge the size of their influence. For example:
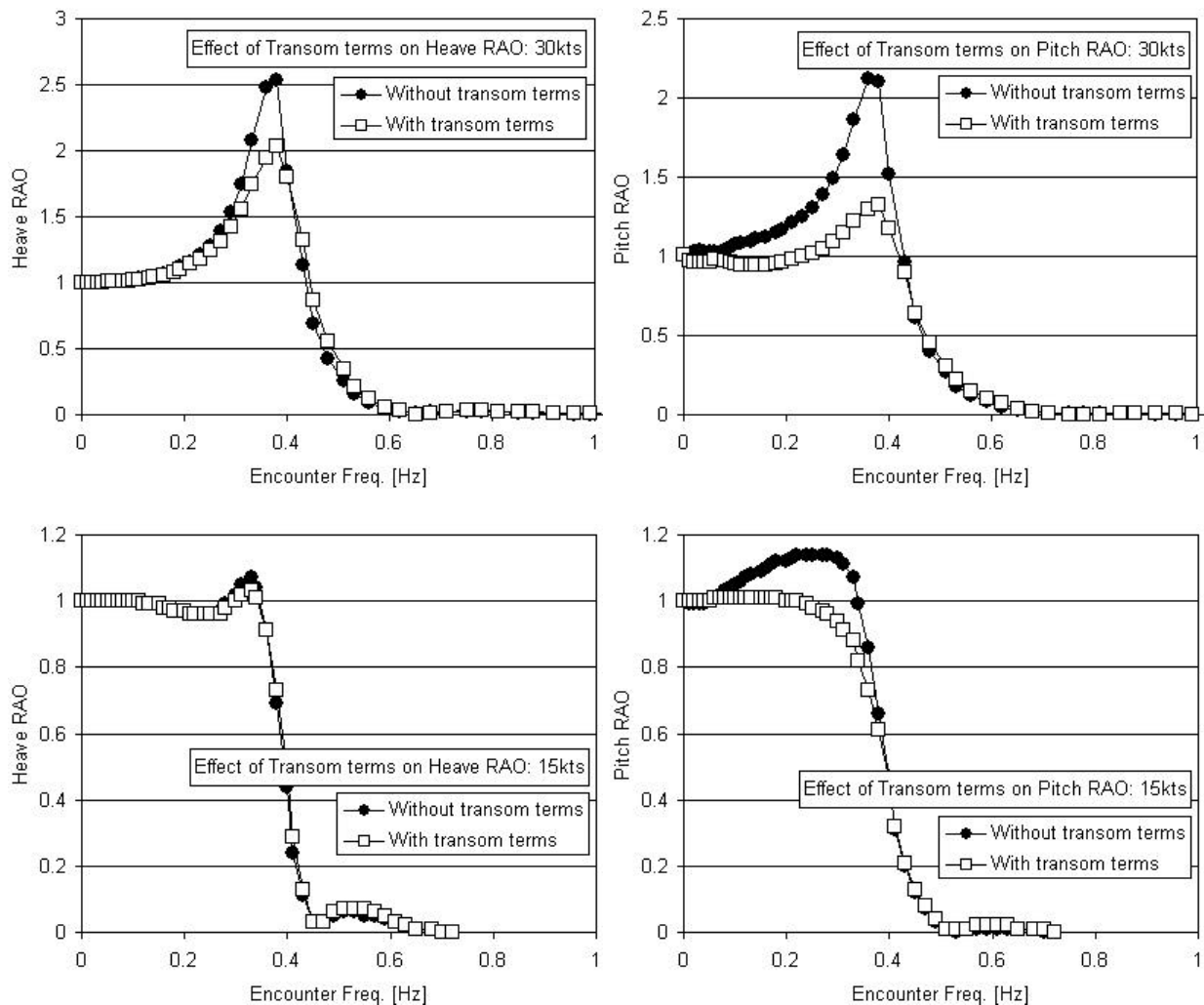
Added resistance

There are three different methods for calculating added resistance in waves. They have slightly different formulations and produce varying results:
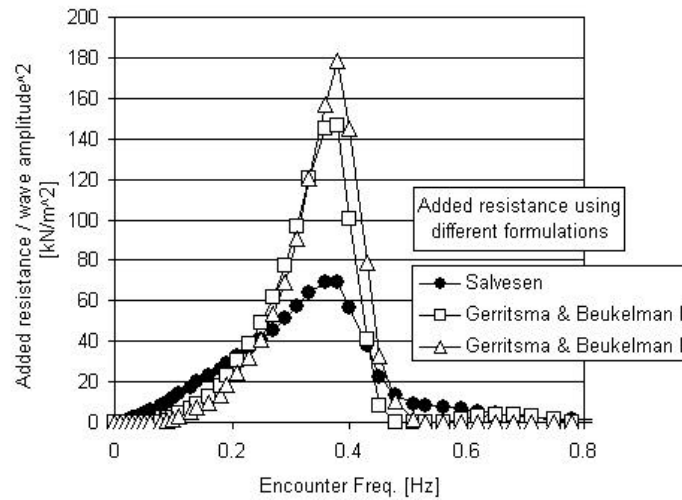
See manual pp64, 65 for further details.

Wave force

There are three methods for calculating the wave excitation force. The first two Salvesen et al. Approximation and Headseas approximation are essentially the same and use an approximation which assumes that the vessel is in head seas. The Arbitrary wave heading method will give better results when the vessel is not in head seas, but is a little slower to calculate.

Vessel properties

There are a number of vessel properties which should be set. These are listed below.

Vessel draught

The vessel is assumed to be at the DWL and at an even keel. You may change the DWL in the Data | Frame of Reference dialog. The sections are calculated with the first and last sections being at the fore and aft perpendiculars respectively.
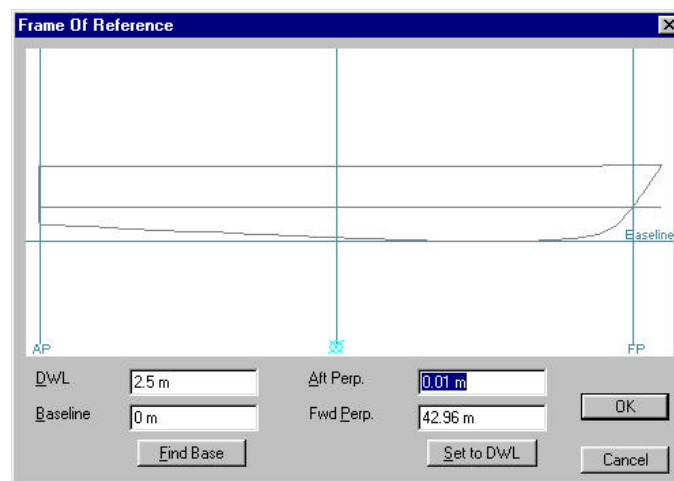
Mass distribution

The mass distribution is required to calculate the pitch and roll response of the vessel. The pitch and roll inertias are specified in terms of gyradii. Default values are 25%LOA for pitch and 40%BOA for roll. Inertia is $k^2 *$ mass.

The height of the VCG will affect the natural roll period.

These values may be set in the Analysis | Mass Distribution dialog:
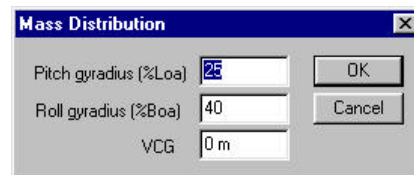
Damping Factor

Roll damping is mainly due to viscous effects which are not modelled by strip theory. Values will depend on the number and type of appendages as well as vessel speed. (Roll damping increases with increasing forward speed.) Some roll damping data is published by number of sources (Lloyd 1989, Vugts 1968 and Lewis 1989). Typical non-dimensional roll damping factors (roll decay factors) for a hard chine hull are given below.

Froude Number	Roll damping factor
0.00	0.085
0.16	0.086
0.23	0.089
0.49	0.102
0.81	0.145

The total non-dimensional roll damping factor is specified in the Analysis | Damping Factors dialog

Motions in a seaway and at specified locations

Once the RAOs have been calculated with sufficient accuracy, you will probably want to calculate the vessel's response to a particular wave spectrum. The Analysis | Environment is used to specify the wave spectrum, vessel speed, wave heading and water density:
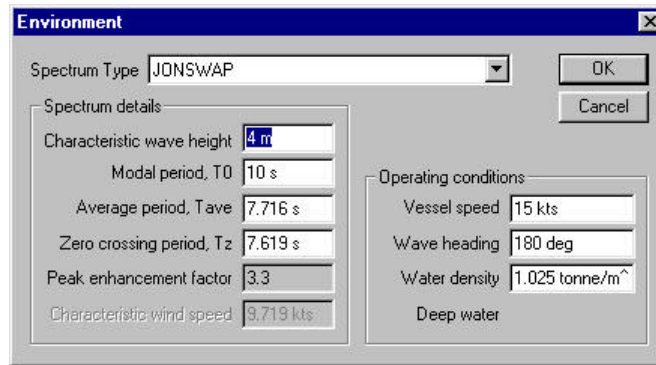
Vertical motion (and velocity and acceleration) may be computed at any part of the vessel. Away from the centre of gravity, the angular motions of roll and pitch will contribute to vertical motions. The motions relative to the wave surface may also be calculated, this is known as relative motion.

The position of interest on the vessel is known as the remote location, and is specified in the Analysis | Remote Location dialog. Enter the position from the zero point of the design; the location of the centre of gravity is for information only.
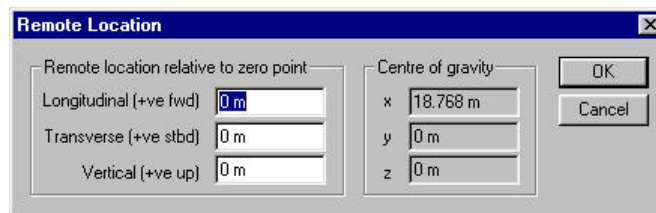
Once, the wave spectrum, vessel speed, etc. and remote location have been specified. You may compute the motion spectra and integrate these spectra by selecting Calculate Seakeeping Data from the Analysis menu. If necessary, Seakeeper will calculate the vessel's RAOs. However, if you have simply changed the position of the remote location, Seakeeper will simply re-compute and integrate the relevant motion spectra.

The results may be viewed in the Summary table in the Results window:

	Item	m0	RMS	Significant
1	Modal period	10 s	--	--
2	Characteristic wave height	0.46 m	--	--
3	Spectrum type	ITTC (2 Param. Br	--	--
4	Wave heading	180 deg	--	--
5	Vessel Speed	30 kts	--	--
6	Vessel displacement	198.39 m^3	--	--
7	Vessel trim	0 deg	--	--
8	Transom method	Transom terms	--	--
9	Wave force method	Salvesen et al. a	--	--
1	Added res. method	Gerritsma and Be	--	--
1	Remote location, x	0 m	-18.8 m	--
1	Remote location, y	0 m	0 m	--
1	Remote location, z	0 m	0 m	--
1	Pitch gyradius	11.25 m	--	--
1	Roll gyradius	2.2 m	--	--
1	Wave spectrum	0.01 m^2	0.11 m	0.23 m
1	Encountered wave spectrum	0.01 m^2	0.11 m	0.23 m
1	Added resistance	1149.72 N	--	--
1	Heave motion	0.02 m^2	0.14 m	0.28 m
2	Roll motion	0 deg^2	0 deg	0 deg
2	Pitch motion	0.15 deg^2	0.39 deg	0.79 deg
2	Heave velocity	0.06 m^2/s^2	0.25 m/s	0.51 m/s
2	Roll velocity	0 (Hz)^2	0 Hz	0 Hz
2	Pitch velocity	0 (Hz)^2	0 Hz	0 Hz
2	Heave acceleration	0.28 m^2/s^4	0.53 m/s^2	1.06 m/s^2
2	Roll acceleration	0 (Hz/s)^2	0 Hz/s	0 Hz/s
2	Pitch acceleration	0 (Hz/s)^2	0.01 Hz/s	0.01 Hz/s
2	Absolute vertical motion at sp	0.03 m^2	0.17 m	0.33 m
2	Relative vertical motion at spe	0.01 m^2	0.09 m	0.18 m
3	Absolute vertical velocity at s	0.11 m^2/s^2	0.33 m/s	0.65 m/s
3	Relative vertical velocity at sp	0.06 m^2/s^2	0.25 m/s	0.5 m/s
3	Absolute vertical acceleration	0.53 m^2/s^4	0.73 m/s^2	1.46 m/s^2
3	Relative vertical acceleration a	0.88 m^2/s^4	0.94 m/s^2	1.88 m/s^2

The first ten rows give a summary of the analysis conditions and options. The next three rows give the position of the remote location and its position relative to the centre of gravity. The next two rows give the roll and pitch gyradii. Then the last 18 rows give the variance (m_0), RMS value and significant amplitude of the various motions, velocities and accelerations. These data are obtained by integrating the appropriate spectrum.

In addition to the summary data and integrated spectral values, the wave and motion spectra are also available, as are the MSI (motion sickness incidence) curves. These data may also be displayed graphically.

Remember that you can easily copy data from the Results window tables and paste it into your favourite spreadsheet.

Hands-On Session Examples

Here are some examples to carry out during the hands-on session. These are the types of investigations you may wish to carry out during the analysis of your design. Extensive use of MS Excel should be used to compare the results from the different conditions.

1) Variation of RAOs with vessel speed

Here we will investigate the effect of forward speed on heave and pitch RAO in head seas. Once you have specified the main analysis parameters, number of hull sections, analysis method, etc. You then simply have to vary the vessel speed entry in the Environment dialog and copy the results to Excel after each run:
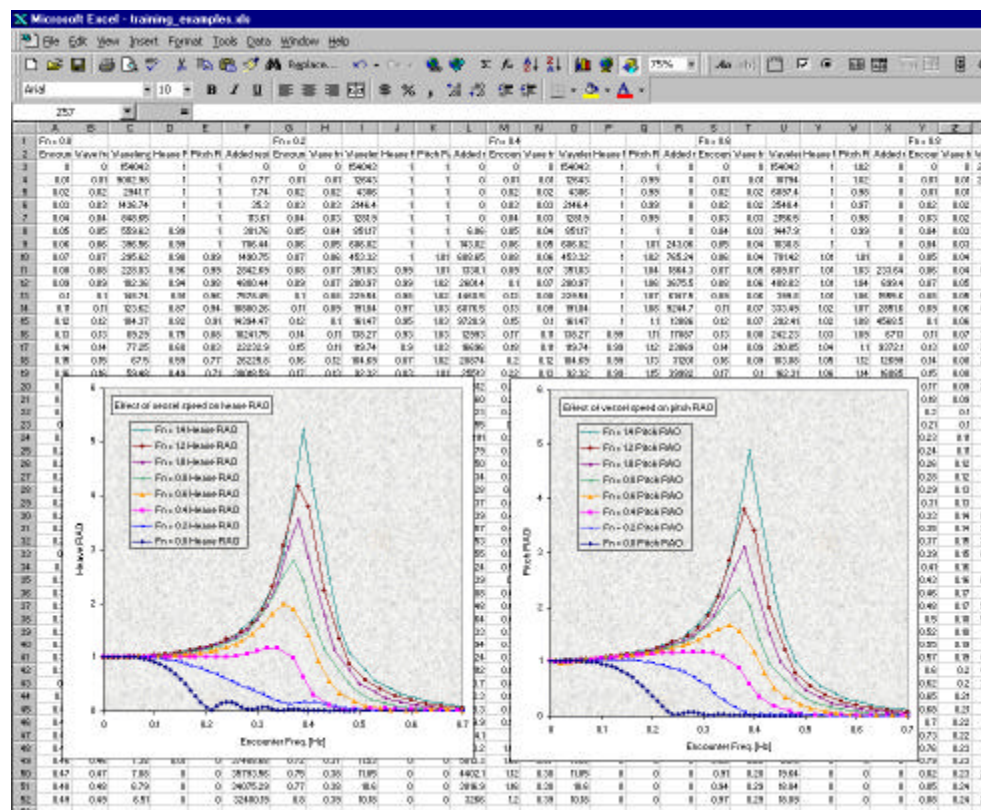
Note that you may need to change the frequency range to get the whole detail of the RAO.

Comparison

Compare the heave and pitch RAOs in head seas for a range speeds from Froude number of 0.0 to 1.4 (Lwl = 42.97m); for example:

Fn	Speed m/s	Speed kts
0.0	0.00	0.00
0.2	4.11	7.99
0.4	8.21	15.96
0.6	12.32	23.95
0.8	16.42	31.92
1.0	20.53	39.91
1.2	24.63	47.88
1.4	28.74	55.87
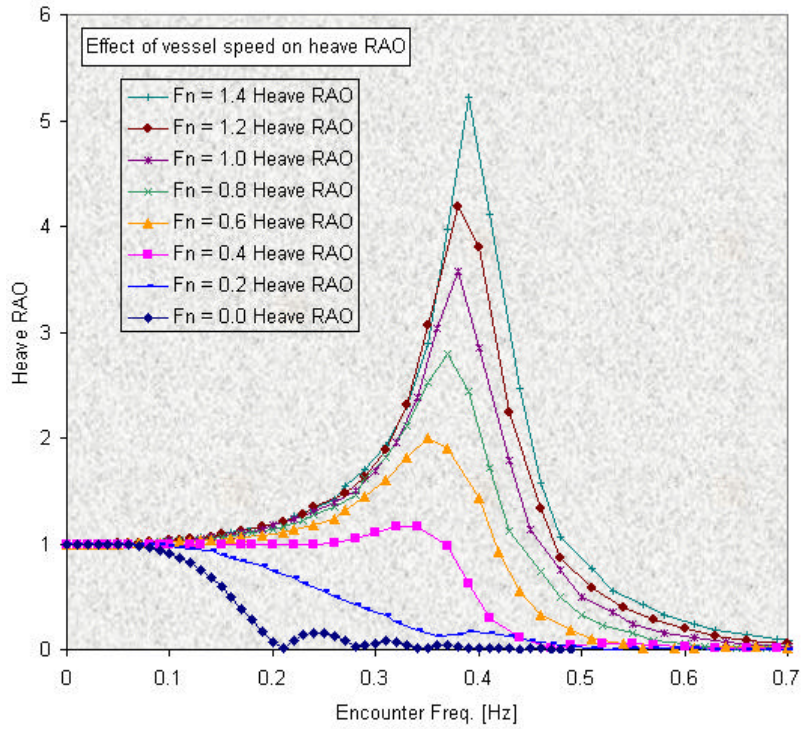
Effect of vessel speed on Heave RAO in head seas
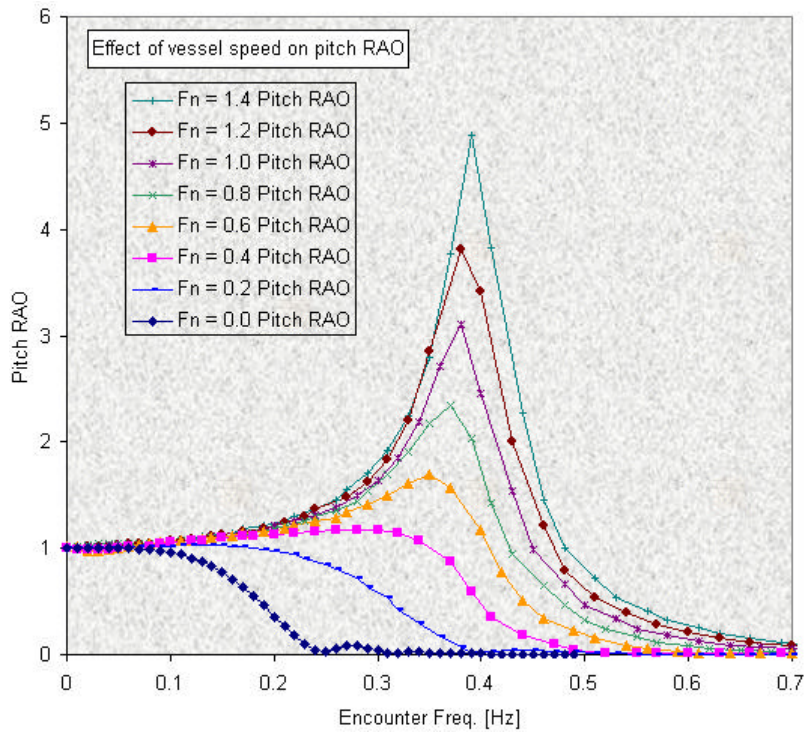
Effect of vessel speed on Pitch RAO in head seas

Hands-On Session Examples   19

2) Variation of RAOs with vessel heading

Calculate the vessel RAOs for different wave headings for constant speed. You may need to vary the frequency range. Use the arbitrary wave heading analysis method for the wave excitation forces.
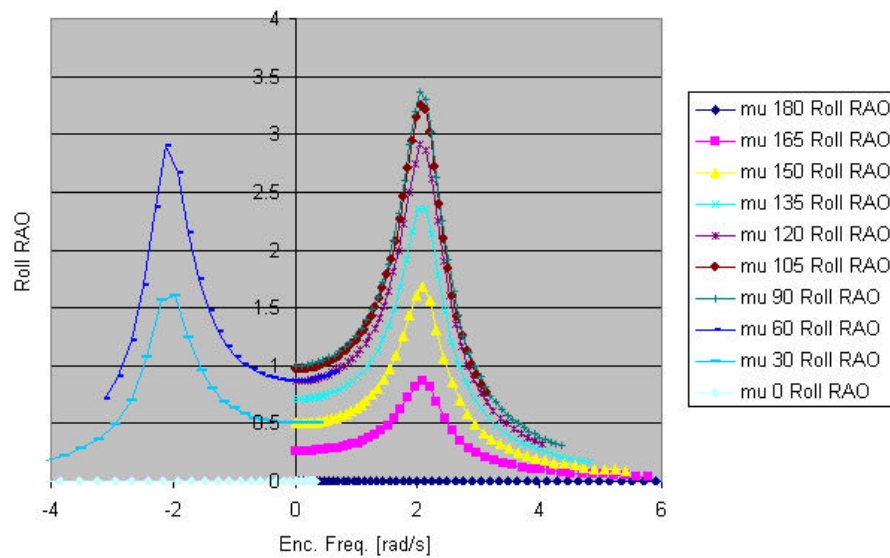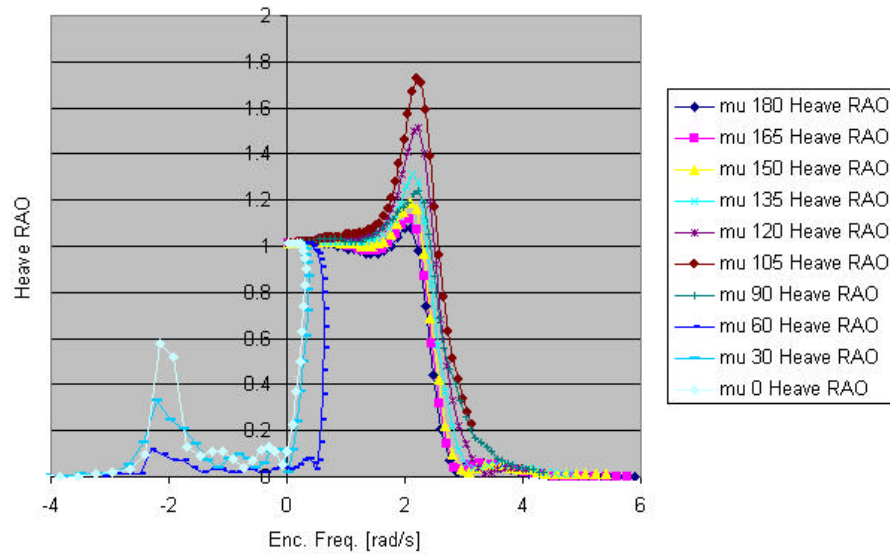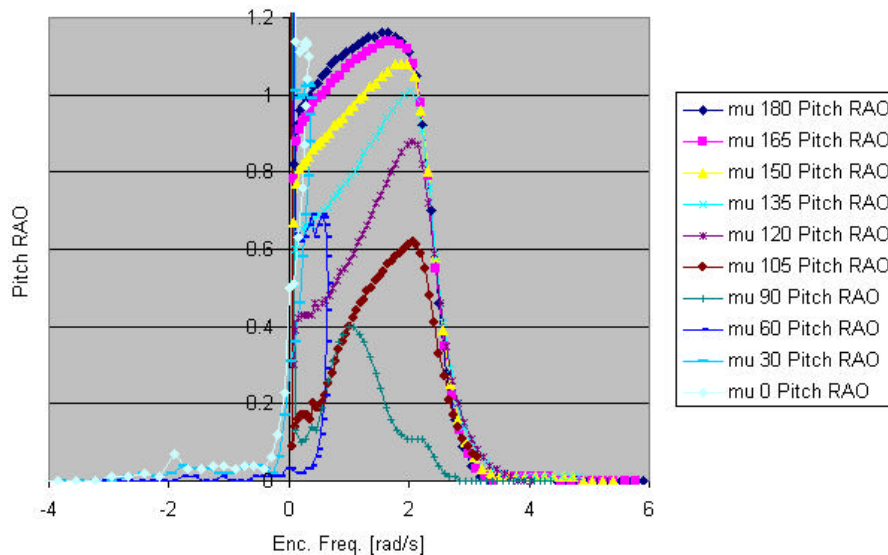
3) Wave spectral comparison and their application

There are several standard wave spectra which may be used in Seakeeper to compute the motions in a seaway. These are:

- Bretschneider or ITTC two parameter
- One parameter Bretschneider
- JONSWAP
- DNV
- Pierson Moskowitz

They all have slightly different shapes. The Bretschneider spectra are typically used to represent fully developed seas which are not limited by fetch or water depth. The one parameter spectrum may be used if only a significant wave height is known; the modal period is derived from the significant wave height.

The JONSWAP spectrum is characterised by its narrower peak and was derived from measurements in the North Sea. These represent wave spectra which are more limited by fetch and water depth.

The DNV spectrum is similar to the JONSWAP spectrum, but the peak enhancement factor varies from 1.0, which produces a Bretschneider two parameter spectrum, through JONSWAP (peak enhancement factor = 3.3) to an even steeper spectrum with a peak enhancement factor of 5.0. The peak enhancement factor used depends on the significant wave height and modal wave period chosen.

The Pierson Moskowitz spectrum is characterised by a nominal wind speed. It represents the fully developed wave spectrum obtained after a constant wind, of specified strength, has been blowing for a sufficiently long time. Both significant wave height and modal period depend on the wind strength.

Examples of the different spectra are plotted below, in the case of the ITTC, JONSWAP and DNV spectra, the significant wave height and modal period were specified as 5m and 10s

respectively, for the One parameter Bretschneider and Pierson Moskowitz spectra, the wave height and wind speed were chosen so as to obtain a modal period of 10s.
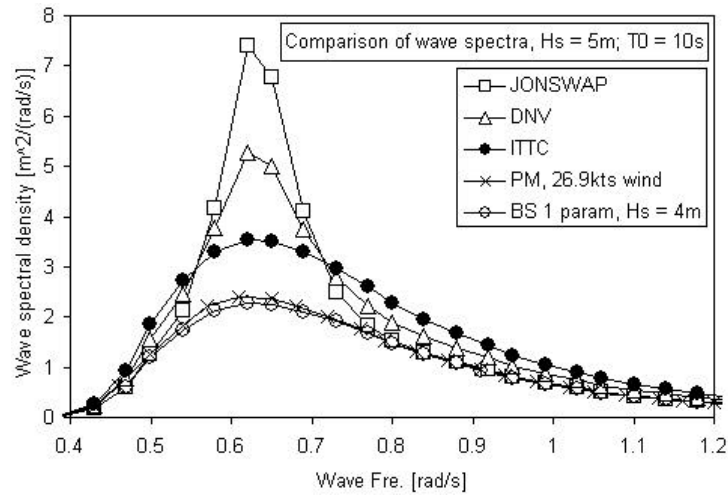
4) Motion distribution along the length of the hull

Calculate the motion RAOs for a specific speed in head seas, then compute the significant motions at different points along the hull. Use MS Excel to produce a graph of the significant vertical acceleration distribution along the length of the hull.
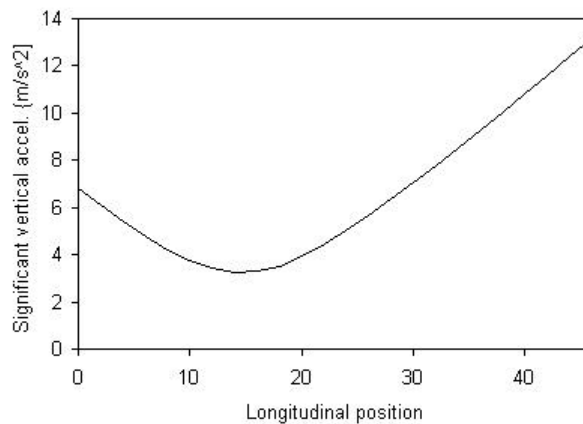
Variation of significant vertical acceleration along the length of the vessel at 15kts in ITTC Hs = 4m, T0 = 10s head seas

If you have time repeat the analysis of other wave headings, and look at points off the hull centreline.

Seakeeping Design Criteria

1. Introduction

So far this course has been focussing on how it is possible to predict the responses of a ship in rough weather. However once you know the vessel's responses, how do you determine whether these motions are acceptable in practise? What is needed are a set of seakeeping design criteria.

Expected Sea Conditions

↓

Resultant Vessel Motions	← compare →	Seakeeping Design Criteria
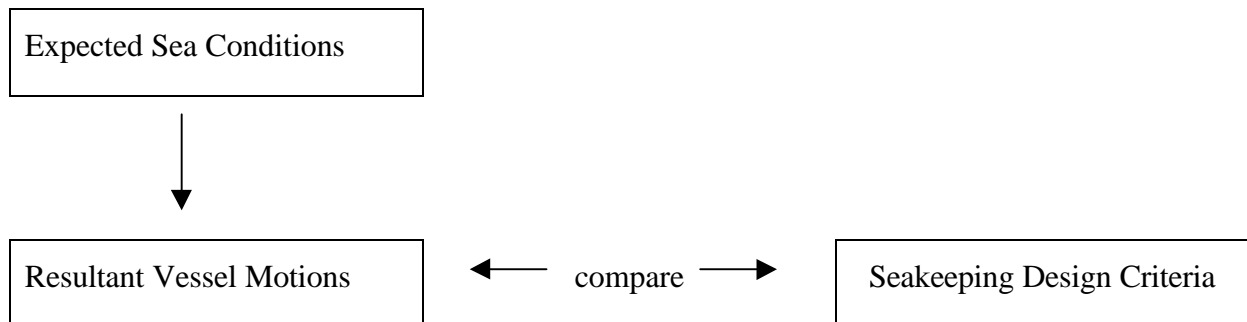
It is then possible to:

- decide if the vessel's performance is acceptable (ie. is it suitable to carry out its designated mission)

- easily compare different designs by comparing their specific responses relevant to the specific criteria.

Different vessel designs are routinely compared, in areas other than seakeeping, via a large number of criteria. For example, calm water resistance is a value which can be easily quantified and compared. However, in regard to motions, ships are required to undertake many different activities and tasks at sea, and criteria for acceptable motions depend on the type of vessel, type of crew and passengers on board and the task in hand.

For example comparing a patrol boat and high speed fast ferry:

- The amount of sea sickness on board the fast ferry is likely to be of more concern than the level of sea sickness on board a patrol boat. Also the patrol boat crew are likely to be less suseptible to sea sickness than ferry passengers.

- The amount of deck wetness on a patrol boat may mean cessation of deck work however deck wetness is unlikely to be important to a fast ferry.

The choice of appropriate criteria is therefore very important.

Fundamental to the assessment of seakeeping performance is the concept of limiting criteria. These criteria specify acceptable limits of specific motions such as relative bow motion, vertical acceleration of the accommodation area, deck wetness, slamming, propeller emergence, etc... These criteria and other methods such as added resistance, MSI (Motion Sickness Incidence) and MII (Motion Induced Interruptions) are discussed in greater detail in the following sections.

2. Seakeeping Criteria Definitions

2.1 Significant Motions

As described in the previous lecture, various statistical properties may be determined from the (linear and angular) displacement spectral density.

In particular the rms displacement is given by:

$$s_0 = \sqrt{m_0}$$

where m_0 is the motion variance given by the area under the motion spectral density:

$$m_0 = \int_0^\infty S_x(w_e)\,\mathrm{d}w_e$$

and the significant motion displacement is given by (for a narrow band spectrum):

$$\text{Heave}_{\text{SIG}} = 4\sqrt{m_0}$$

Similarly rms and significant velocities and accelerations may be determined from m_2 and m_4 (the 2nd and 4th moment of areas of the motion spectral density).

2.2 Absolute Motions

The motions of a vessel are calculated at the centre of gravity, however it is often necessary to compute the absolute motion of a position (p_x, p_y, p_z) on the vessel, for instance the bridge or forward perpendicular. The motion of any point on the vessel can be determined from the motion of the centre of gravity using rigid body dynamics. Simplified, first-order treatments can be found in texts such as Lloyd (1989). Here we present only the results. If the angular motions are assumed small, it may be shown that the absolute vertical motion (due to heave, pitch and roll), s_z, is given by:

$$s_z = z + p_y f - p_x q$$

where: z is the heave response, -ve down; f is the roll response, +ve stbd. side down; q is the pitch response +ve bow up; and the positive, right handed axis system is x forward, y starboard and z down.

Remembering that since the responses are sinusoidal it may be shown that the amplitude and phase of the absolute vertical motion is given by:

$$s_{z0} = \sqrt{A^2 + B^2}$$

and

$$\tan e_z = \frac{B}{A}$$

where:

$$A = z_0 \cos(\boldsymbol{e}_z) + p_y \boldsymbol{f}_0 \cos(\boldsymbol{e}_f) - p_x \boldsymbol{q}_0 \cos(\boldsymbol{e}_q)$$
$$B = z_0 \sin(\boldsymbol{e}_z) + p_y \boldsymbol{f}_0 \sin(\boldsymbol{e}_f) - p_x \boldsymbol{q}_0 \sin(\boldsymbol{e}_q)$$

where ε is the phase in radians

2.3 Velocities and Accelerations

Since the displacement equations are of the form $x = x_0 \sin(\boldsymbol{w}_e t + \boldsymbol{e})$, the velocity and acceleration of the motion may be found by differentiation.

$$\dot{x} = x_0 \boldsymbol{w}_e \cos(\boldsymbol{w}_e t + \boldsymbol{e})$$

$$\ddot{x} = -x_0 \boldsymbol{w}_e^2 \sin(\boldsymbol{w}_e t + \boldsymbol{e})$$

Thus the amplitudes of the velocity and acceleration are related to the amplitude of the displacement by factors of $\boldsymbol{w}_e$ and $\boldsymbol{w}_e^2$ respectively; noting that the velocity will be 90° out of phase and the acceleration 180°. This indicates that even if the transfer function for the displacement has a relatively small value at higher frequencies, the contributions to velocity and acceleration are likely to be significant.

2.4 Slamming

Slamming is the impact of the ship's bottom on the surface of a wave and can cause not only decelerations and local structural damage but transient vibratory stresses (whipping) elsewhere in the hull. A severe slam may be said to occur (Lewis, 1989) when two events occur simultaneously:

- Re-entry of the ship's bow into the water after it has risen above the surface

- The relative vertical velocity between the ship's flat of bottom and the water surface exceeds a certain critical specified value. The value of this critical vertical velocity is 3.66m/s for a 158m ship, at a point 15% of length from the bow (Froude scaling may be utilised to determine the value for ships of other lengths), Ochi and Motter (1973).

Figure 2- A frigate slamming in rough weather, from Lloyd (1989).

2.5 Deck Wetness

Deck wetness occurs when the bow of a ship is buried in the sea and throws solid water and spray into the air. The forward speed of the ship ensures that some of this water lands on the deck, causing deck wetness. This phenomenon may cause injury or drowning of personnel and damage to deck-mounted equipment.

Currently methods available for the numerical prediction of deck wetness frequency are crude: calculating the relative displacement at a chosen station, between local water surface elevation and vessel freeboard at that station. However tank tests can give useful information - the shipping of green or solid water is believed to be modelled correctly in a Froude scaled experiemnt, but spray is not modelled properly.

Figure 2- Deck wetness on a frigate, from Lloyd (1989).

2.6 Speed Loss

Speed reduction in waves occurs in two ways: voluntary and involuntary speed loss.

Voluntary speed loss is a decision, by the captain, to reduce speed in order to reduce motions, slams, deck wetness, propeller emergence etc. to within acceptable limits.

Involuntary speed loss arises from the fact that a vessel travelling through waves will have a greater resistance due to its motions, and the resulting change in load on the propeller usually reduces the propeller efficiency.

2.6.1 Added Resistance

The total added resistance in irregular waves may be calculated in the same way that the motion in irregular waves is calculated — by integrating the contribution of all the individual added resistance components.

Added resistance in waves is obviously of the utmost importance to racing yacht designers who are only interested in motions in so far as they affect the added resistance of the yacht.
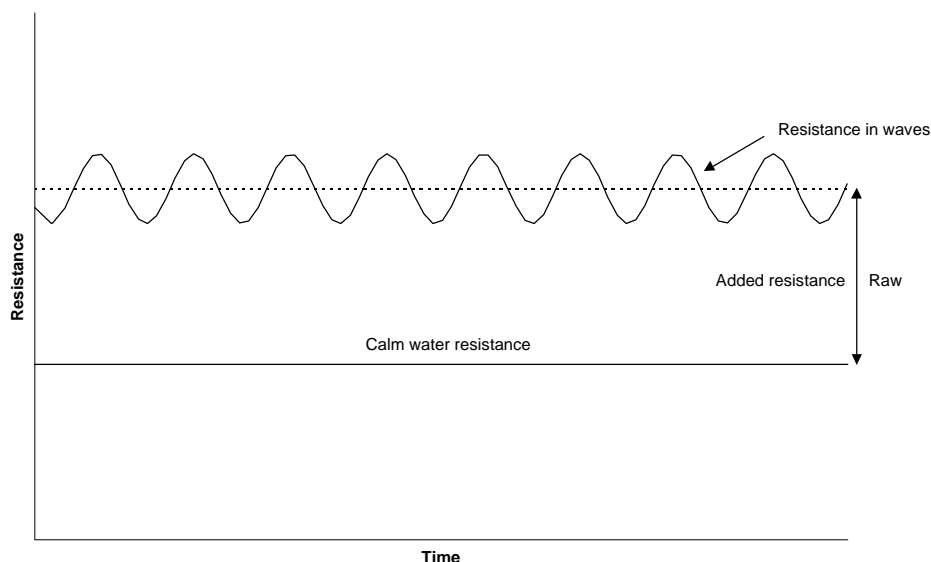
Figure 3 - Resistance in sinusoidal (regular) waves

2.6.2 Propeller Emergence

Propeller racing occurs when the upper tips of the blades emerge from the water due to the motions of the ship. This can lead to engine, propeller shaft or propeller damage as the sudden reduction and subsequent increase in torque loading, as the propeller submerges again, occurs. It may lead to voluntary speed loss as propeller emergence is an undesirable phenomenon and a prudent captain will try and avoid it. An involuntary speed reduction may also arise since the propeller will be less efficient due to the motions and oscillations of the onset stream.

The relative motion of the longitudinal position of the ship where the propeller is located can be utilised to determine the likelihood of propeller emergence.

The concepts of relative vertical motion and velocity are important in calculating the probability of events such as propeller emergence and slams. The relative motion may be calculated by subtracting the local wave elevation from the local absolute vertical motion.

2.7 Human Performance

Ship motions cause two undesirable effects of people onboard:

- Motion sickness

- Impairment of ability to carry out tasks in a controlled manner

The degradation of human performance due to vessel motions is difficult to assess. This is largely due to a lack of understanding of the parameters affecting human performance, in broad terms it depends upon the amplitude and frequency of the accelerations experienced.

2.7.1 Vertical Acceleration

The simplest human performance criterion is a limiting vertical acceleration, however it has been shown that the frequency of the oscillation is also important in assessing the impact on human performance. Both Motions Sickness Incidence and Subjective Motions introduce a frequency dependence.

2.7.2 Motion Sickness Incidence (MSI)

MSI is the percentage of individuals who would become physically ill if subjected to motions of prescribed characteristics for a given time interval. The original experiments to determine the MSI boundaries were carried out by subjecting a group of young caucasian men, unaclimatised to motions, to a series of single frequencies of vertical sinusoidal motion (no roll motion). These experiments had a number of limitations including:

- Experiment subjects limited to young men - it is known that sea sickness incidence varies with age, sex and race.

- Statistically, tolerance to motions increases with time at sea, therefore ferry passengers are likely to be more susceptible to motion sickness than the crew.

- Performance may be degraded before vomiting occurs.

MSI has however become a standard method for comparing seakeeping performance of different designs, particularly passenger vessels. The MSI data may be displayed in two forms:

- The percentage of people likely to vomit within two hours as shown in Figure 4.

- The time period after which severe discomfort (sea sickness) occurs in given conditions, Figure 5. This system has been developed by the International and Australian Standards, Standards Australia (1990).
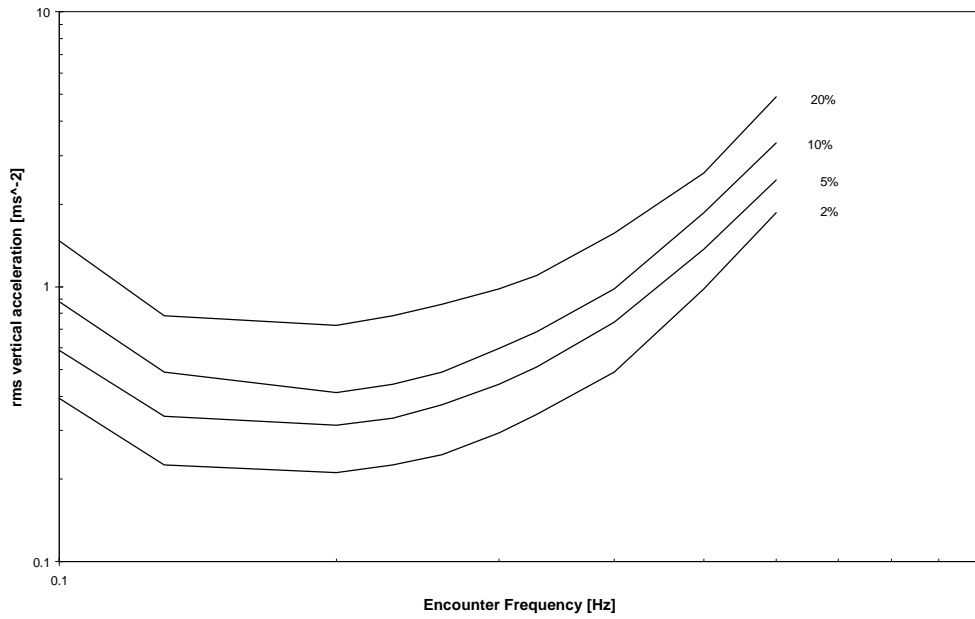
Figure 4 - Motion Sickness Incidence (MSI)
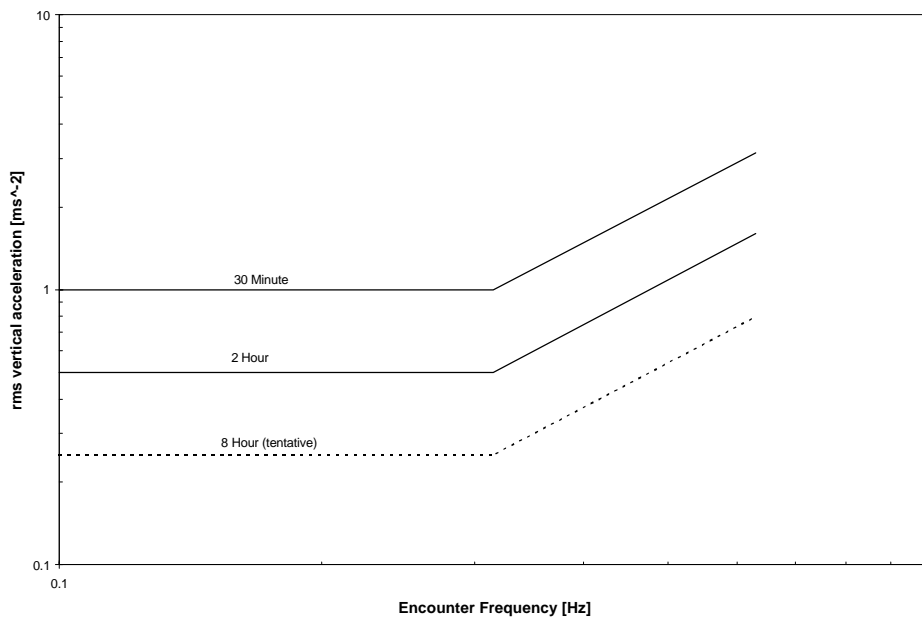
Figure 5 - Severe Discomfort Boundaries (ISO)

The MSI for a vessel operating in a particular seaway is determined by sequentially integrating the acceleration spectral density over 1/3 octave bands and then plotting against the standard curves, as shown in Figures 4 & 5.

It should be remembered that the boundaries shown apply only to vertical accelerations and to infrequent (or inexperienced) travellers amongst the general public. Additional influences such as vision, fear, odours etc. affect sea sickness, but their effects have not yet been quantified. Tolerance also varies with age though no adjustments are given at present to cover this effect.

2.7.3 Subjective Motions

An experienced, well motivated and acclimatised crew will not suffer unduly from seasickness but may still find that vertical ship motions will inhibit their ability to work effectively. Therefore setting vessel motions criteria purely through motion sickness incidence may give a false impression of the performance of a vessel as a working platform. Subjective motions analysis will give an indication on the ability of the crew to perform tasks.

The level of subjective motion experienced may be determined using the following equation, Shoenberger (1975):

$$\text{SM} = \text{A} \left(\frac{\ddot{s}_{30}}{g} \right)^{1.43}$$

where: $\ddot{s}_{30}$ is twice the rms vertical acceleration

A is a parameter which is a function of frequency which may be found from:

$$\text{A} = \left[1 - \exp\left(-1.65 w_e^2 \right) \right] \left[75.6 - 49.6 \log_e w_e + 13.5 \left(\log_e w_e \right)^2 \right]$$
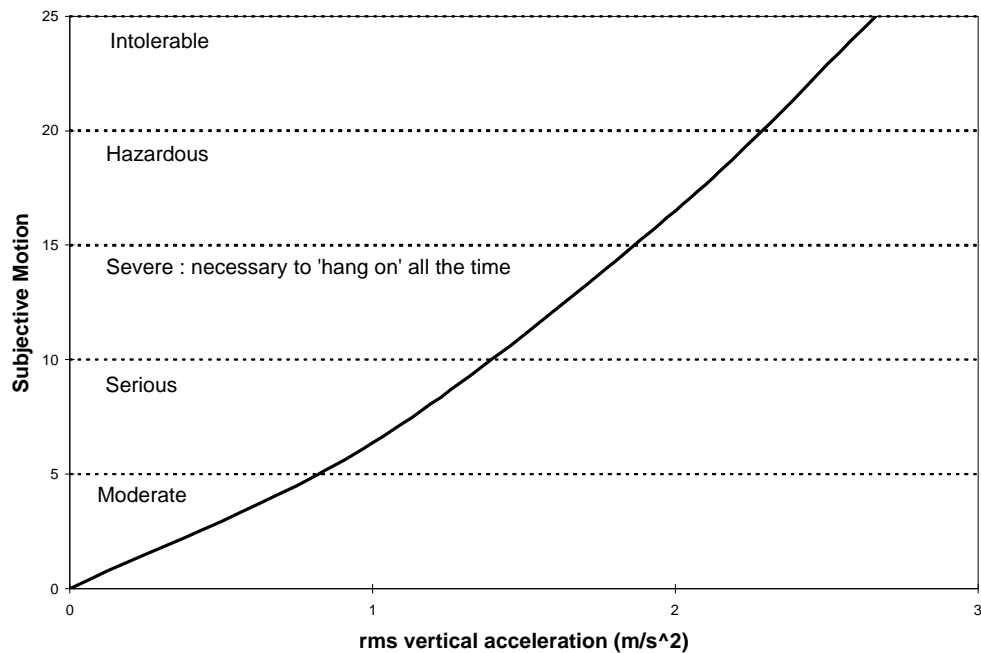
Figure 6 - Subjective magnitude and vertical acceleration at 1.07 radians/second

Figure 6 gives an indication of subjective motions in relation to rms vertical acceleration, at 1.07 radians/second (the encounter frequency at which the parameter A exhibits a maximum).

2.7.4 Lateral Force Estimator

The lateral accelerations experienced on board a vessel in rough weather may cause objects to topple and people to lose balance and stumble. In a similar manner to subjective motions (which are based on vertical accelerations) lateral force estimators may be derived to ascertain the extent of this effect on a crew with the vessel operating in a specific seaway, Baitis et al. (1983).

From this the number of motion induced interruptions (MII), when a crew member has to stop working in order to hold on to prevent loss of balance, per minute may be estimated. Table 1, below, shows the number of MII per minute for ranges of rms lateral acceleration.

Lateral Acceleration m/s2	Motion Induced Interruptions per Minute	Rating Level
< 1.0	< 1	acceptable
1.0 to 1.1	1 to 1.5	serious
1.1 to 1.25	1.5 to 2	severe
> 1.25	> 2	extremely hazardous

Table 1 - Motion Induced Interruption Criteria for a natural roll frequency 0.59 rad/sec

Baitis' estimates were for a ship with a natural roll period of approximately 10 seconds. The number of motion-induced interruptions will increase if the natural roll frequency increases since roll makes the dominant contribution. For a vessel with a different natural roll period the following approximate correction may be used:

$$MII = MII_{0.59} \frac{W_{*4}}{0.59} \qquad \text{per minute}$$

where ω_{*4} is the natural roll frequency

3. Limiting criteria

Outlined above are a number of different seakeeping design criteria. Acceptable limits for these various criteria should be specified in order to ascertain whether the vessel motions will be acceptable. This means that **limiting criteria** or values need to be specified. Different types of vessels and tasks will have different limits and the probability of the vessel exceeding these limits in a given sea state may be calculated and may be used to indicate the relative performance of different designs. Table 2 shows some typical limiting criteria.

General	Motion	Limit (significant amplitude)	Location
	Heave	2.0m	C of G
	Pitch	3.0°	C of G
	Roll	8.0°	C of G
	Vertical acceleration	0.4g	Bridge
	Lateral acceleration	0.2g	Bridge
Specific task	MSI	20% of crew	Task location
	MII	1/min	Task location

Table 2 - Current design criteria for crew performance for naval vessels, after ABCD Working Group on Human Performance at Sea (1995)

Author	Ship type	Slamming	Wetness	Propeller emergence	Vertical acceleration
Kehoe (1973)	Warship	60/hour at 0.15L	60/hour at FP		
Ochi and Motter (1974)	Merchant	Probability 0.03	Probability 0.07		
Shipbuilding Research Association of Japan (1975)	Merchant	Probability 0.01	Probability 0.02	Probability 0.1	
Lloyd and Andrew (1977)	Warship		36/hour		$\overline{SM} = 15$ (subjective motions)
Lloyd and Andrew (1977)	Merchant			120/hour	
Aertssen (1963, 1966, 1968, 1972)	Merchant	Probability 0.03 or 0.04		Probability 0.25	
Andrew and Lloyd (1981)	Warship		90/hour		$\overline{SM} = 12$
Comstock et al. (1982)	Warship	20/hour	30/hour		0.2g RMS at bridge
Yamamoto (1984)	Merchant	Probability 0.02	Probability 0.02 at FP		Probability of exceeding 0.4g at bridge = 0.05
Walden and Grundmann (1985)	Warship	Probability 0.03	Probability 0.07		

Table 3 - Limiting seakeeping criteria, after Lloyd (1989)

4. Probability of Exceeding Criteria

The probability of exceeding the defined design criteria may be calculated and used to guide the selection of an appropriate ship.

By assuming that the probability density function of the motions follow that of a Rayleigh distribution, it is possible to evaluate the probability of exceeding some critical value z_{crit} given the variance of the motion energy spectrum, m_{0z}. This is given below

$$\text{prob}(z > z_{crit}) = \exp\left(\frac{-z_{crit}^2}{2m_{0z}}\right)$$

Take-Home Assignment

A new monohull ferry design has been proposed to service a route in the Timor Sea.

Utilising the given design (details below in Table 2), you are required to determine if it meets the following seakeeping criteria (Table 1) for each of the four specified wave conditions (Table 3).
You should plot the comparison of the actual motions with the limiting criteria.

#	Seakeeping Criteria	Limiting Criteria
1	Significant Heave Amplitude	1.5m
2	Significant Pitch Amplitude	4 degrees
3	rms vertical acceleration at the bridge	0.2g
4	MSI	10% after 8 hours

Table 1 - Seakeeping Criteria

Then for seakeeping criteria # 1, 2 & 3 calculate the probability of exceeding the critical values.

NPL round bilge hull form	
LOA	45 m
LWL	43 m
Draft	2.5 m
Waterline Beam	4.78 m
Volume displacement	197.26 m^3
Speed	15 knots
Bridge position	30m fwd of transom 8m vertical from baseline zero m from centreline

Table 2 - Proposed Ferry Design Details

The following wave data has been collected from the Timor Sea for use in determining the vessel motions.

Significant Wave Height	Zero Crossing Period
2.0 m	6 sec
3.0 m	8 sec
3.0 m	10 sec
3.0 m	12 sec

Table 3 - Wave Data

The **ITTC (2 parameter Bretschneider)** idealised spectrum should be utilised.

Can you comment on the applicability of the various criteria and the design's ability to meet these limiting criteris.

Once you have determined whether the design has met the limiting criteria, you can investigate the influence on the seakeeping criteria of the following factors:

- Mass distribution - what is the influence of changing the longitudinal radius of gyration?
- Number of mapped sections - what is the influence of changing the number of mapped sections?
- No transom terms - what is the influence of not utilising transom terms?
- Vessel speed - what is the influence of changing the speed of the proposed design?
- Idealised sea spectrum - what is the influence of utilising another form of idealised sea spectrum?

Initial Seakeeper Options to utilise:
- 30 mapped sections
- Pitch gyradius = 25% of LOA
- Include transom terms
- 21 frequency steps

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http://www.environment.gov.au/marine/mcdd/
This lists sources of Australian wave data in varying quality, format and availability.

http://www.coastaldata.transport.wa.gov.au/tides/historic_wave.html
Western Australian wave data

http://ns.noaa.gov/NESDIS/NESDIS_Home.html
Good starting point for satellite wave data