Aalto University
School of Engineering

MEC-E2004 Ship Dynamics

Final course revision

Aalto University
School of Engineering

Exam Set up and Rules

- Open book exam from **13:00 - 16 :00 hrs on 31.05.21**
- **The exam starts at 13:00 hrs AND NOT 13:15 hrs ! Please** make yourselves avaliable from 12:50 on the day so that I can answer any questions you may have before hand
- Zoom link : **https://aalto.zoom.us/j/61600758411**
- To access the exam we will use MyCourses System. Access through special tag on the system will be given on 13:00hrs on the day.
- In case you need to take a comfort break ask the invigilators !

Exam Set up and Rules

- You may use calculators, the internet, your books, papers and course notes.
- You cannot talk to each other or text each other. Your cameras will have to be switched on for continuous observation.
- You will be given the option to answer up to 6 questions including one bonus question.
- Out of these 6 questions you will answer your best scores in 5 questions are the ones that will count toward your exam mark.

Exam Set up and Rules

- ❑ Upon completion return the answers in ***.pdf format to** spyros.hirdaris@aalto.fi .

- ❑ The response file should include your student number, name and email. It should be entitled **Name_Surname_Student Number.pdf**

- ❑ Two exam papers

- ✓ **SD final exam.doc** is an exam for the whole course syllabus
- ✓ **2nd Mid term exam.doc** is a test on knowledge from lectures 6 – 10.

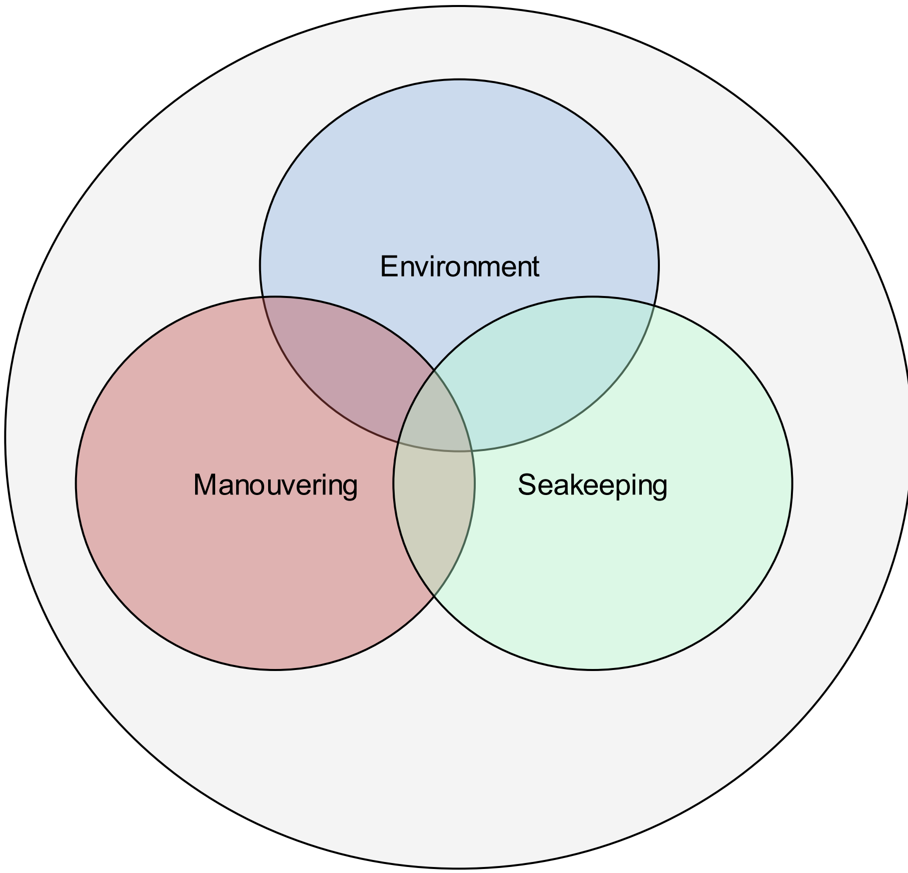
Exam Set up and Rules

- ❑ Students who took the first mid term exam and are not happy with their mark they can take the exam based on the whole course syllabus. In this case I will delete the mark from the first exam and only this exam's mark will account for 50% of their final SD mark

- ❑ Students who are happy with their 1st mid term exam they have to take the 2nd mid term exam paper. This will account for 25% of their final SD mark. The remaining 25% will be from the 1st mid term exam.

- ❑ Students who selected not to seat the 1st mid term exam they have to seat the final exam and this will count for 50% of their final SD mark.

Course Overview



Design Framework

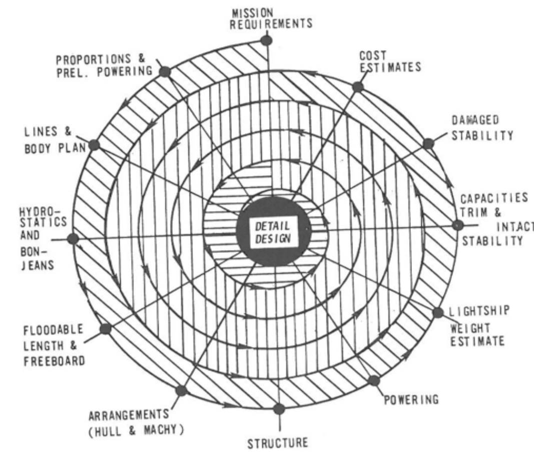


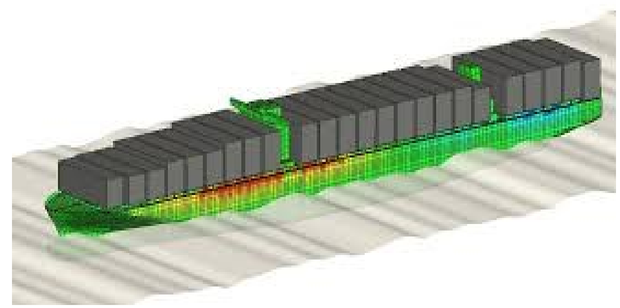
Fig. 1 Basic design spiral

Ship Dynamics – A very broad subject

- The term implies that all operational conditions of a vessel where *inertia forces* play role are important.

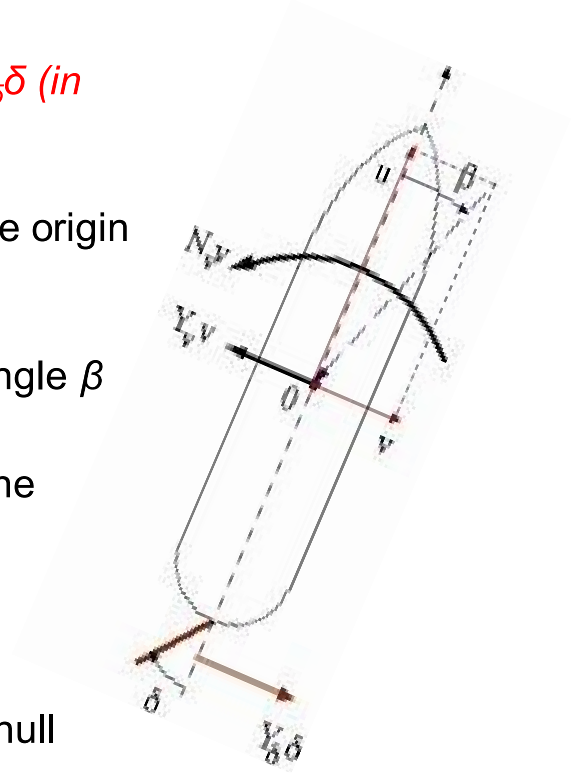
- Thus, all situations that differ from the ideal still water condition, constant heading and constant forward speed should be considered.

- Traditionally different simplified models are used within the context of
  - ✓ *seakeeping*
  - ✓ *manoeuvring*
  - ✓ *structural vibrations*
  - ✓ *hydroelasticity*
  - ✓ *Stability (intact, damage, static/dynamic)*



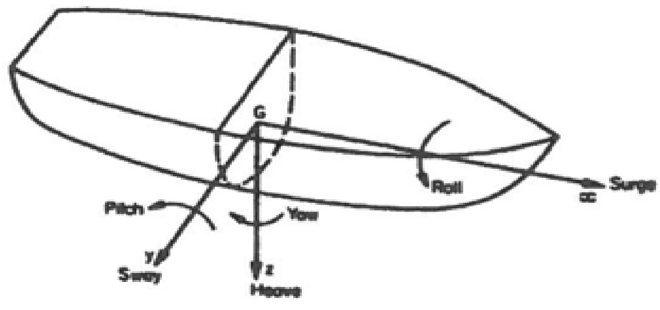
Rudder dynamics

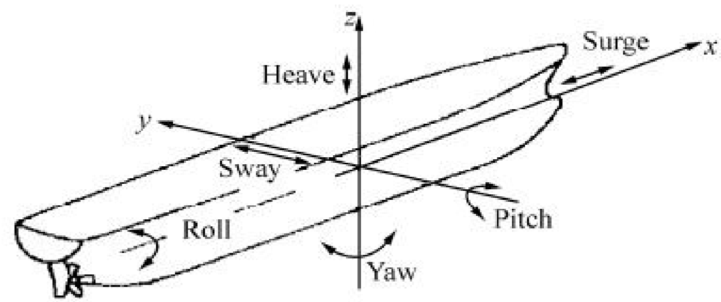
- Rudder set at angle δ develops a +ve force in Y–dir defined as *$Y_\delta\delta$ (in simplified format)*
- As this force acts on the ship's stern aprox. half way aster from the origin [0] a – ve turning moment $N_\delta\delta$ develops
- This moment makes the ship to turn and sets it at a certain drift angle *β*
- The turning motion initiated by the rudder is greatly amplified by the turning moment $N_v v$ developed by a hull set in inclined flow
- Thge rudder action can be modelled by :
  - ✓ **<u>Method 1 :</u>** Stability derivatives (direct representation of the hull forces asdependent to the rudder angle)
  - ✓ **<u>Method 2 :</u>** Modular model (kinematic of inflow into the rudder & modelling of effect of propeller flow on rudder action)



Manouevring vs Seakeeping models

- Time dependent investigations are a norm in manoeuvring but an option in seakeeping
- Manoeuvring is often studied in shallow waters but seakeeping in open seas
- Seakeeping is studied by an inertial coordinate system while manoeuvring by a ship fixed system
- Viscosity is not always neglected in manoeuvring but can be neglected or simply superimposed in seakeeping. This is mostly because of mathematical difficulties and computational cost



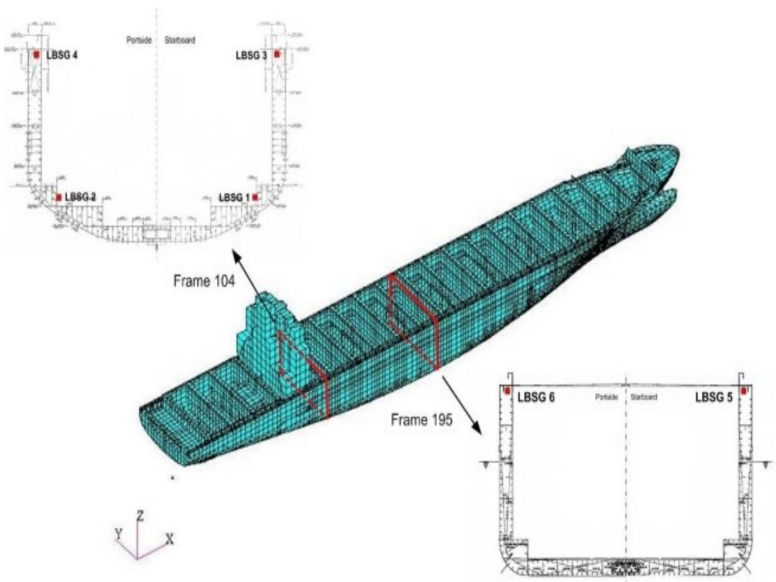


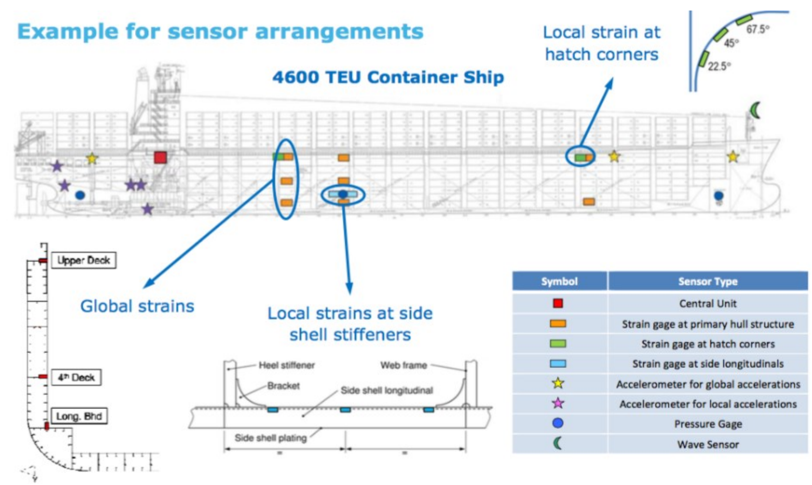
G. Taimuri, T. Mikkola, J. Matusiak, P. Kujala, and S. Hirdaris (2019), The Influence of Hydrodynamic Assumptions on Ship Maneuvering, in *22nd Toowing Tank Symposium - NuTTS, Tomar,* pp. 6.

Engineering Tools – Full Scale Measurements

Ships can be assembled with gyros, strain gauges etc. to measure the responses

- ➢ Accelerometers for motions
- ➢ Strain gauges to extract wave bending moments
- ➢ Uncertainties relate with accurate seaway measurements and measurement equipment failures





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S. E. Hirdaris, N. J. White, N. Angoshtari, M. C. Johnson, Y. Lee & N. Bakkers (2010) Wave loads and flexible fluid-structure interactions: current developments and future directions, Ships and Offshore Structures, 5:4, 307-325, DOI: 10.1080/17445301003626263

Wave Formation

- Waves are typically generated by
  - wind
  - earthquakes etc.

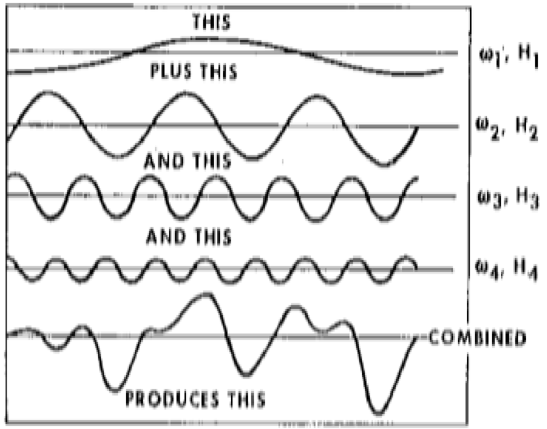
- Two mechanisms for wind-generated waves
  - Pressure fluctuations in the sea surface [Phillips, Phillips, O. M.: 1957, ''On the Generation of Waves by Turbulent Wind'', J. Fluid Mech. 2, 417–445] https://doi.org/10.1017/S0022112057000233
  - Shear force in the interface of water and air [Miles, J. W.: 1957, ''On the Generation of Surface Waves by Shear Flows'', J. Fluid Mech. 3, 185–204]https://doi.org/10.1017/S0022112057000567

- Today we accept that usually the formation of waves starts from pressure fluctuations
  - waves are enlarged by shear forces and then
  - waves interact forming longer waves

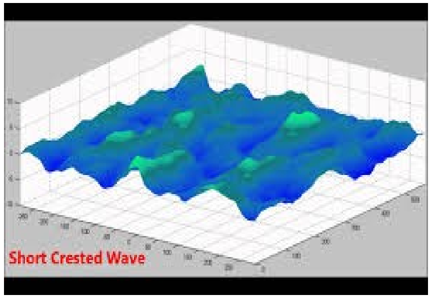
Key wave definitions

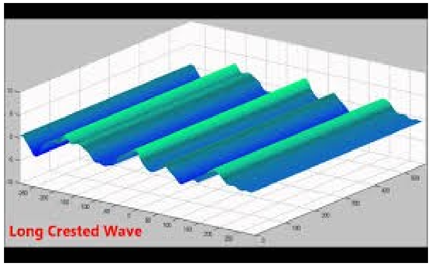
- A **regular wave** (also known as single wave component) has a single frequency, wavelength and amplitude (height)

- **Irregular waves** can be viewed as the superposition of a number of regular waves with different frequencies and amplitudes



- **Long-crested waves** are waves formed toward the same direction; **Short-crested waves** are waves formed toward different directions

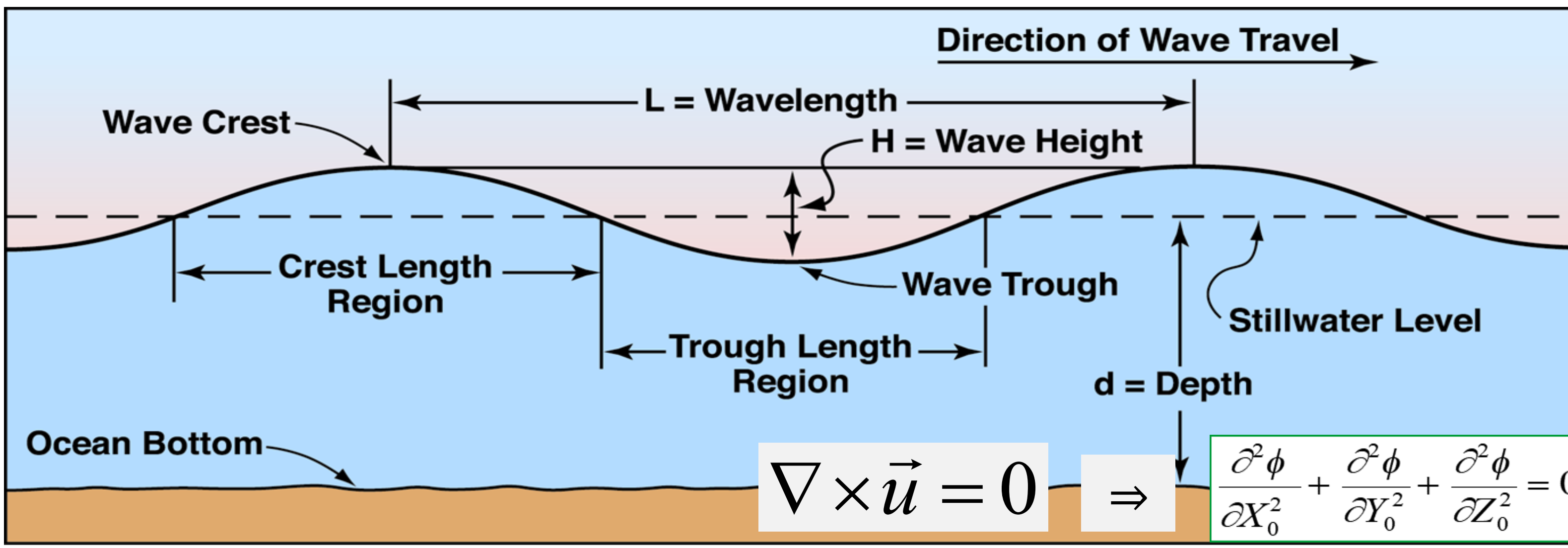




- **Short term (ST) wave loads** generally relate with ocean or coastal wave formations over 0.5h-3h. **Long term (LT) wave loads** are assessed over life time (e.g. 20 years for ships) and comprise of a sequence of short term events. LT predictions consider multiple sea areas, routes, weather (see IACS URS11, Rec. 14, BSRA Stats etc.)

Linear wave - Potential Flow (Airy 1845)

- Single component small amplitude wave
- 2D wave motions do not change with time
- Ideal (i.e. inviscid and irrotational) flow. The water is incompressible and the effects of viscosity, turbulence and surface tension are neglected.
- Laplace velocity potential equation with boundary conditions is used to idealise (1) the sea bed and (2) the deforming sea surface



$$\nabla \times \vec{u} = 0 \quad \Rightarrow \quad \frac{\partial^2 \phi}{\partial X_0^2} + \frac{\partial^2 \phi}{\partial Y_0^2} + \frac{\partial^2 \phi}{\partial Z_0^2} = 0$$

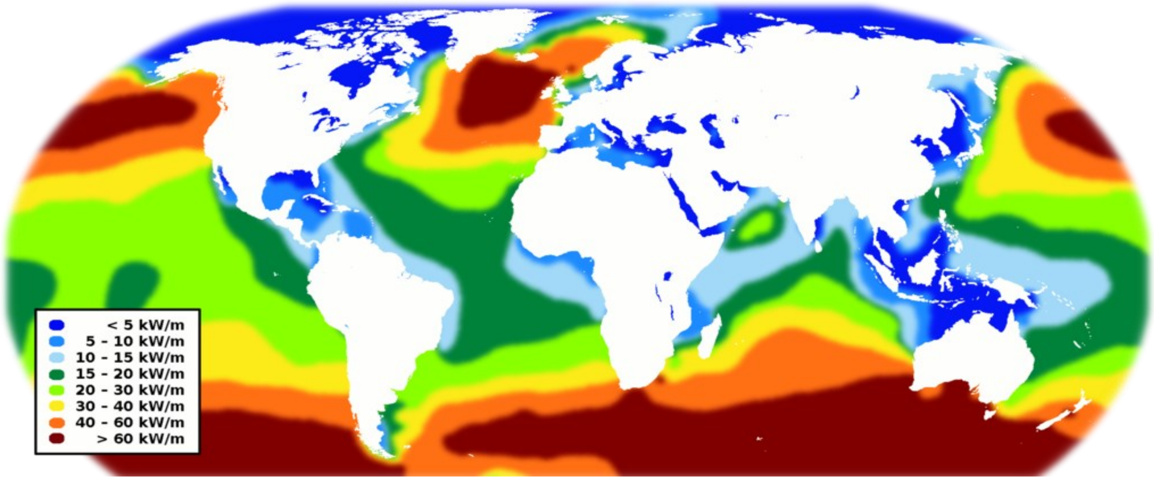
$$\zeta(X,t) = a\cos(kX - \omega t + \alpha) \quad \mathbf{(1)}$$

WAVE ENERGY AND POWER

Kinetic + Potential = Total Energy of Wave System

Kinetic: due to H_2O particle velocity

Potential: due to part of fluid mass being above trough.   (*i.e.* wave crest)



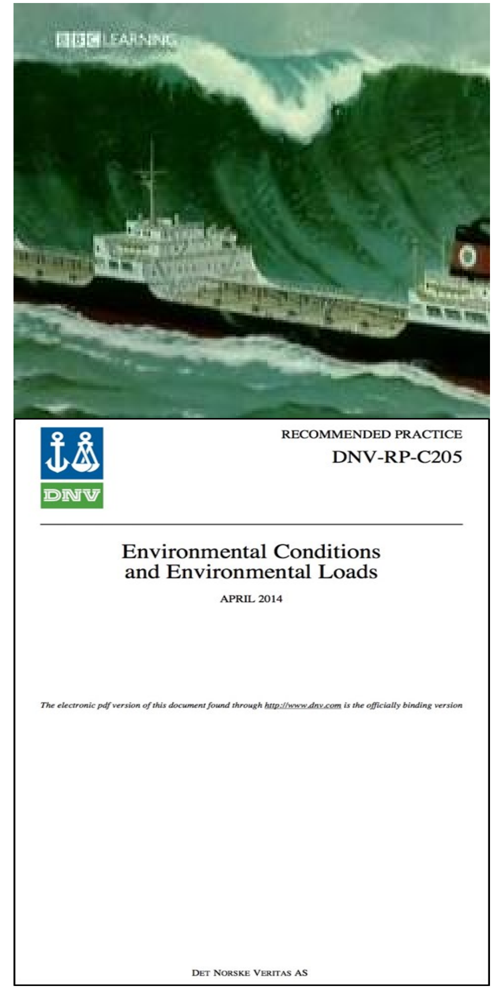
World map showing wave energy flux in kW per meter wave front

Deviations from Linear Wave Theory

- A linear wave model is very useful in practical engineering work. This is because :
  - It is easy to use,
  - it complies well with the linear modelling of ship responses
  - it enables modelling of the sea by superimposing waves of different lengths and heights

- In some cases, certain non-linear effects have to be considered
  - The information provided by the linear wave model up to the still water level is not sufficient, e.g. we are dealing with local wave pressure loads on ship's side shell
  - An increase of wave steepness results in wave profiles that differ from the ideal cosine form
  - In some cases, certain non-linear effects have to be considered

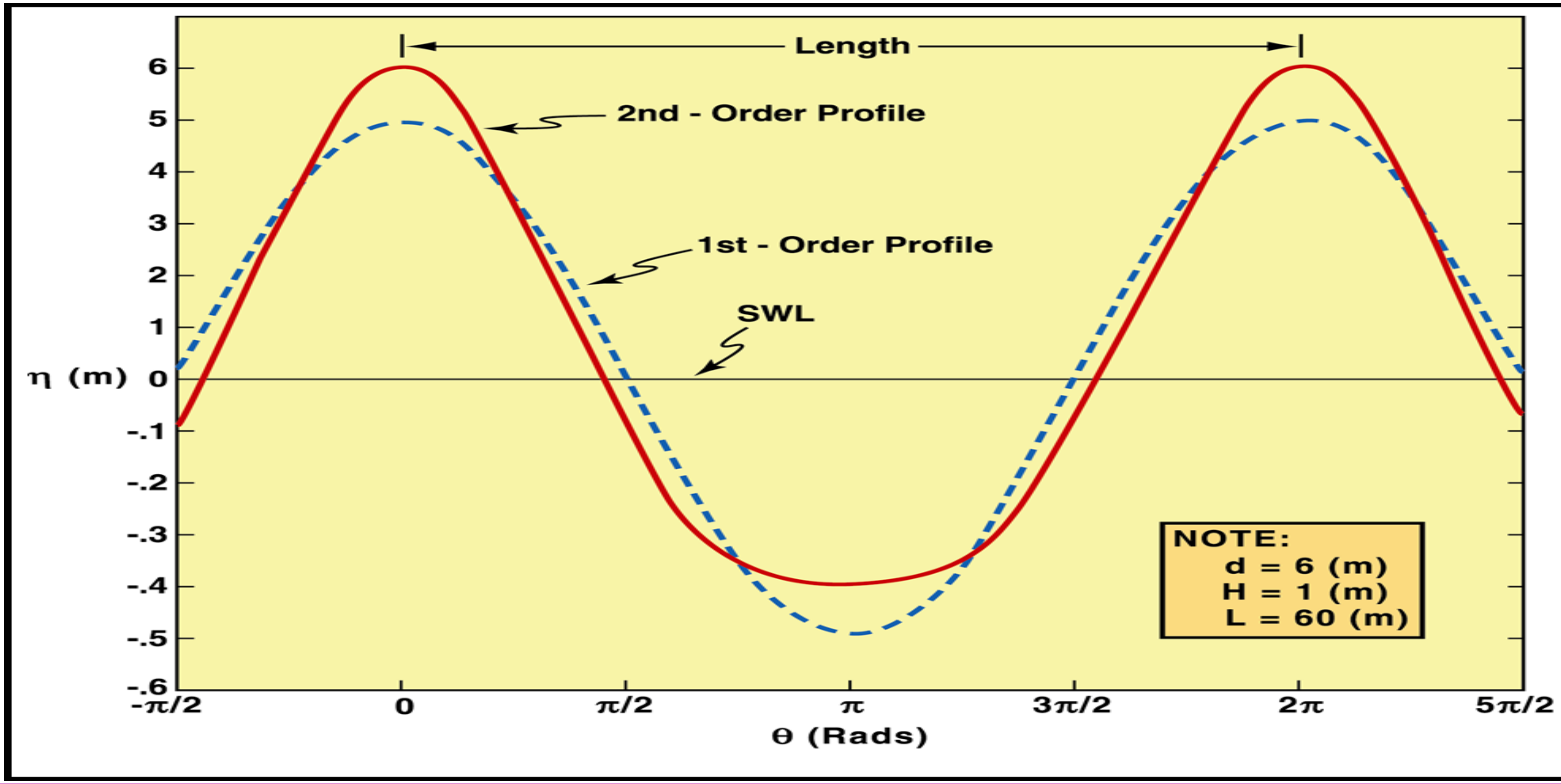
- Suitably validated NL wave theories and hence NL wave idealisations can provide
  - Better agreement between theoretical and observed wave behavior.
  - Useful in calculating mass transport.



Deviations from Linear Theory – Airy vs Stokes waves

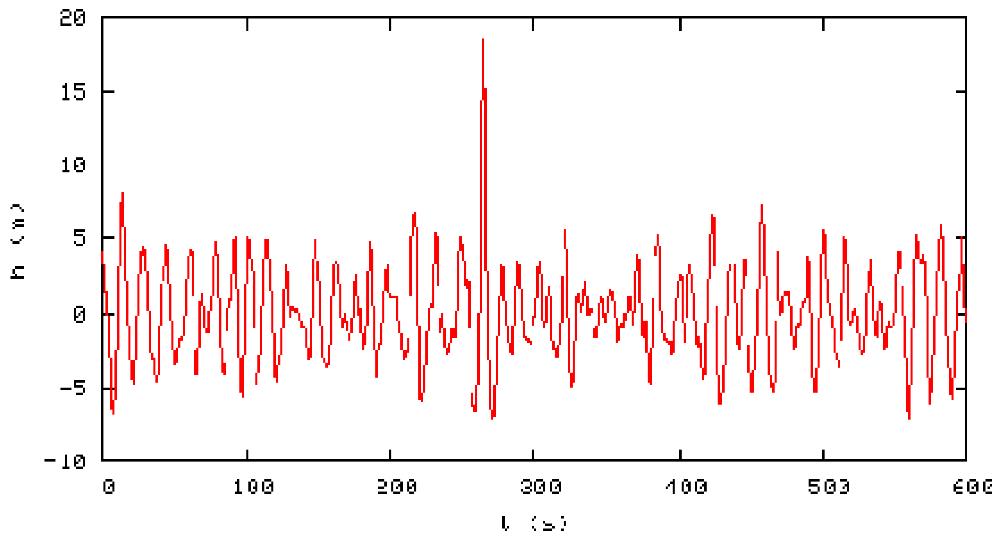
<u>Comparison of second-order Stokes' NL wave profile with linear profile :</u>

Higher order waves are more peaked at the crest, flatter at the trough and with distribution slightly skewed above SWL



Freak Waves

Rogue waves (also known as freak waves, monster waves, episodic waves, killer waves, extreme waves and abnormal waves) are large, unexpected and suddenly appearing surface waves.

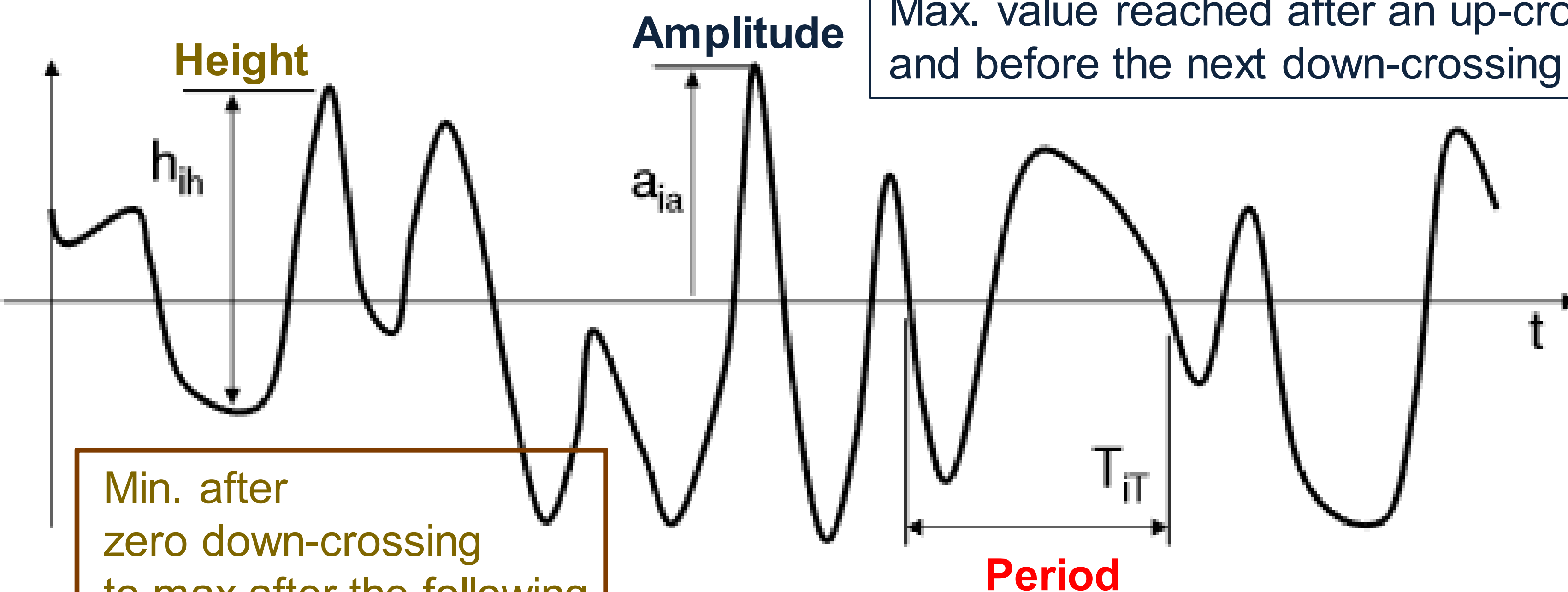


The Draupner wave, a single giant wave measured on New Year's Day 1995, finally confirmed the existence of freak waves, which had previously been considered near-mythical.

https://www.youtube.com/watch?v=eMBU1eXDYDc

https://www.youtube.com/watch?v=qvjJFUTliEM

The Irregular Wave



Max. value reached after an up-crossing and before the next down-crossing

Min. after zero down-crossing to max after the following zero up-crossing

Measured between zero down-crossings

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

© Marine Technology, Vol. 46, No. 2, April 2009, pp. 116–121

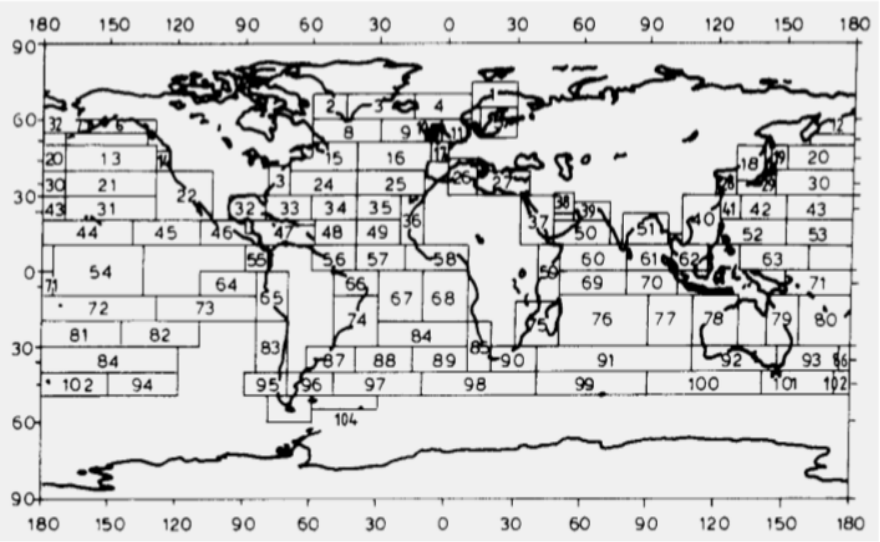
Service Factor Assessment of a Great Lakes Bulk Carrier Incorporating the Effects of Hydroelasticity

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.

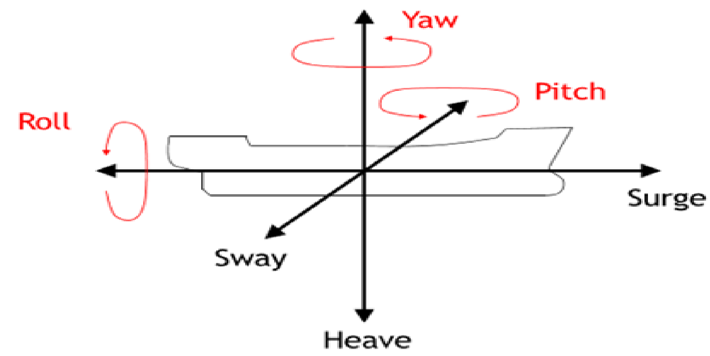
Keywords: Great Lakes; hydrodynamics; longitudinal strength

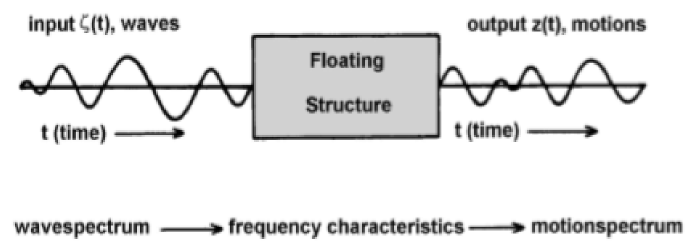
Hogben, N., Dacunha, N.M. and Olliver, G.F. (1986). Global wave statistics, British Maritime Technology.

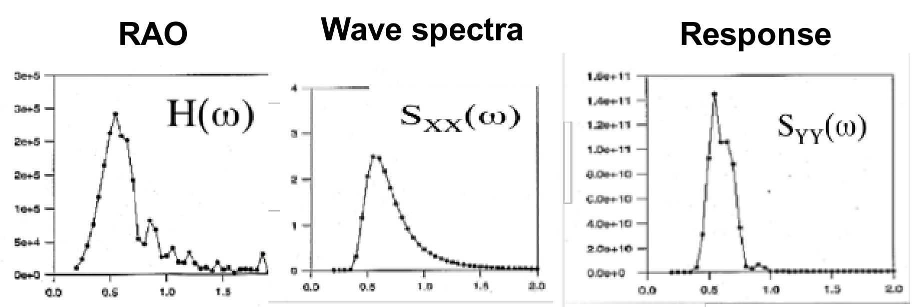


Ship Motions - Introduction

- When ship moves in waves it will have 6 degrees of freedom (DOF)
- This means that for arbitrarily-shaped ship we will have
  - 6 equations of motion
  - 6 unknowns
- These must be solved simultaneously
- For port-starboard-symmetry these equations reduce to two sets of uncoupled EoM containing 3 unknows namely :
  - Vertical: surge, heave, pitch
  - Horizontal: Sway, yaw, roll
- We approximate the response by superposition of elementary waves
  - Different lengths
  - Different directions

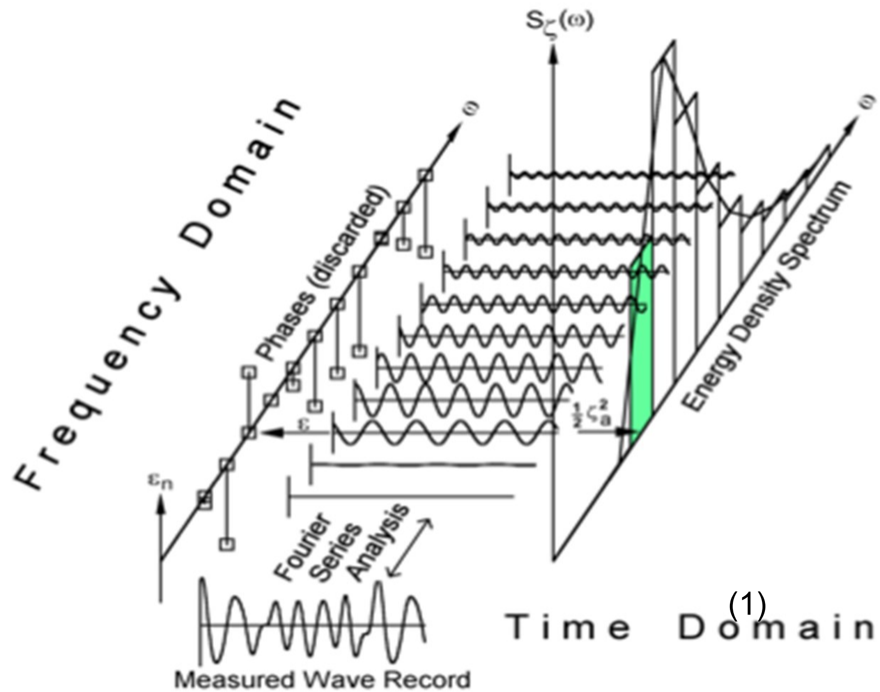






Frequency and Time domains

Frequency domain		Time domain
Wave spectrum	→IFFT→ ←FFT←	Realised wavemotion
↓		↓
Transfer function multiplication (Must be linear)		Time-domain integration (May be non-linear)
↓		↓
Response spectrum	←FFT← →IFFT→	Time trace of response

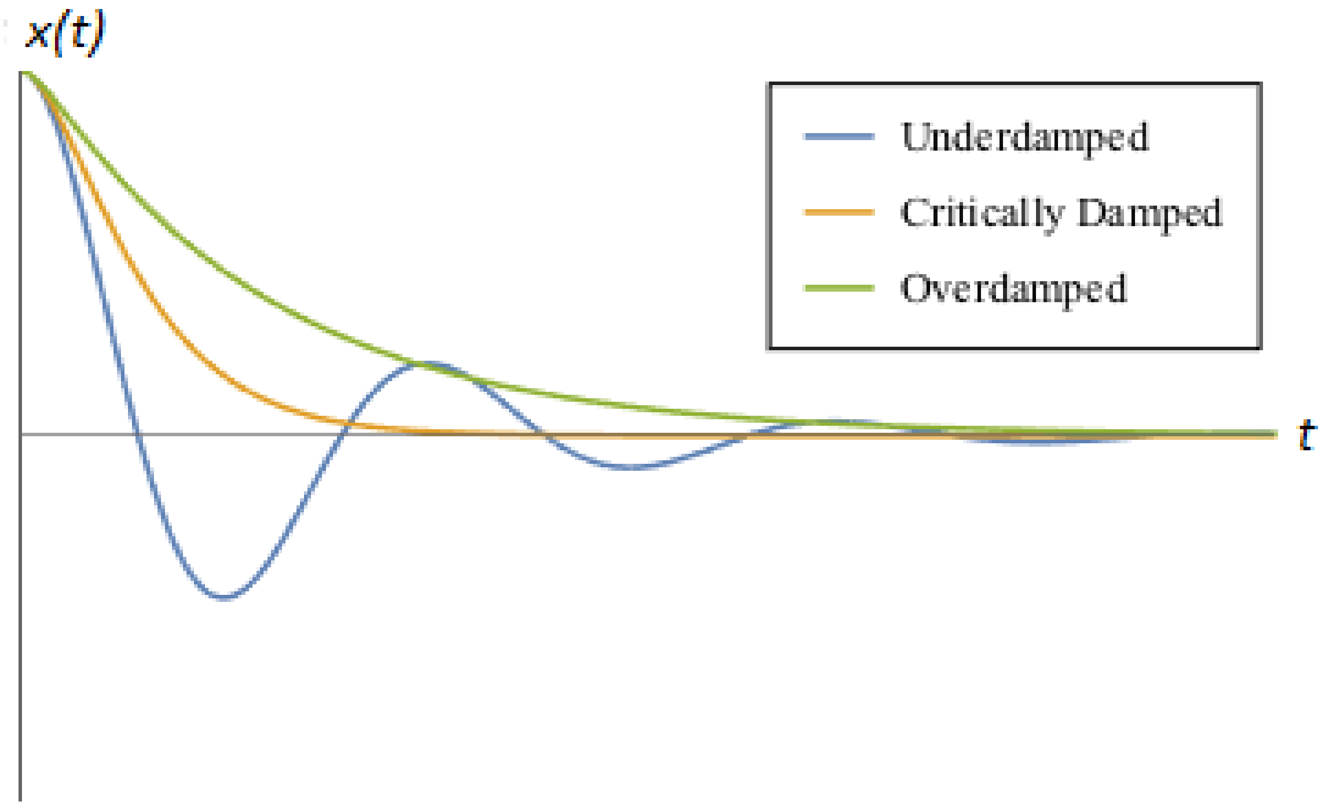


(1)

$$\mathscr{F}^{-1}\{G(f)\} = \int_{-\infty}^{\infty} G(f)e^{2\pi i f t}\,df = g(t) \qquad \mathscr{F}\{g(t)\} = G(f) = \int_{-\infty}^{\infty} g(t)e^{-2\pi i f t}\,dt$$

(2)

Damping cases for 1 dof system



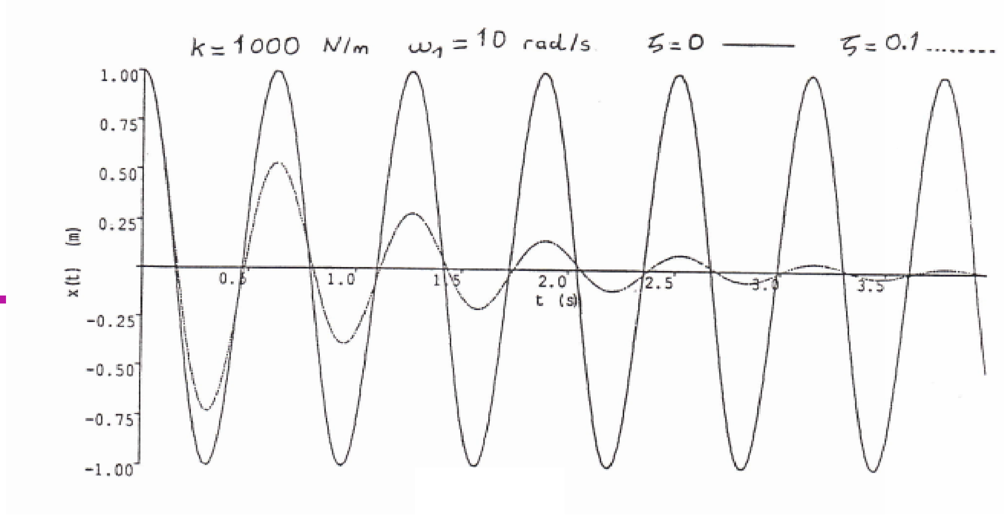
How can we practically assess damping ?

A practical way to assess damping that is broadly applicable in the area of ship hydrodynamics is the damping decay test. This can be mathematically expressed using the log decrement that is the natural logarithm of the ratio of two successive amplitudes.

$$\delta = ln\frac{X_1}{X_2} = ln\frac{Ae^{-\zeta\omega_n t_1}}{Ae^{-\zeta\omega_n(t_1+T_d)}} = ln\, e^{\zeta\omega_n T_d} = \zeta\omega_n T_d$$

$$\because T_d = 2\,\pi/\omega_d \rightarrow \therefore \delta = \frac{2\pi\zeta\omega_n}{\omega_d} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$$

Since the damping ratio is very small in that case, the log decrement can be approximated by: $\delta = 2\pi\zeta$



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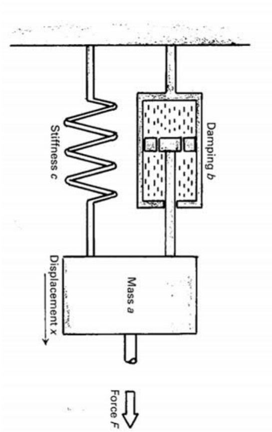
Case 3 : Forced Vibration – 1 DOF

Consider adding harmonic excitation to the vibration system where $F(t)$ varies in sinusoidal manner instead of being arbitrary function in time:



$$m\ddot{x} + c\dot{x} + kx = F(t) = F_0\, cos(\quad \omega t)$$

$$\rightarrow \ddot{x}(t) + 2\zeta\omega_n\dot{x}(t) + \omega_n^2 x(t) = f_0 \cos(\omega t)$$

$$f_0 = F_0 / m$$

This is a differential equation of the 2nd order. Accordingly, it is prone to a general and particular solution which when combined together they may give the response function of the system.

Quasi-Static Response

- **At sub-critical case (also known as quasi-static response)** the system can reach high values of spectral density at small frequencies relative to the natural frequency and the stiffness has the major effect on the system effect on the system
- Only stiffness affects the system response

$$S_x(\omega^*) = \frac{S_P^n(\omega^*)}{\left(1-\omega^{*2}\right)^2 + \delta^2\omega^{*2}} \rightarrow S_x \approx S_P^n$$

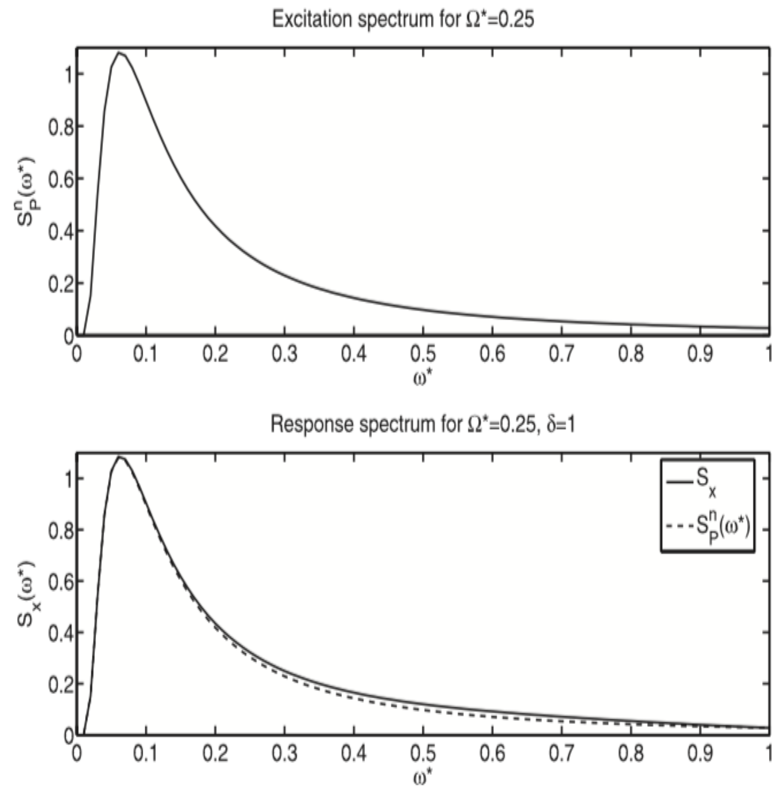


Figure 4.2. Quasi-static or sub-critical response.

Dynamic Response

- At super-critical stage (also known as dynamic response) the highest values of spectral density lie in only high values of frequencies with respect to the natural frequency and damping plays an important role:
- **Only inertia forces affect the system response**

$$S_x(\omega^*) = \frac{S_P^n(\omega^*)}{\left(1-\omega^{*2}\right)^2 + \delta^2\omega^{*2}} \rightarrow S_x \approx \frac{S_P^n}{\omega^{*4}}$$

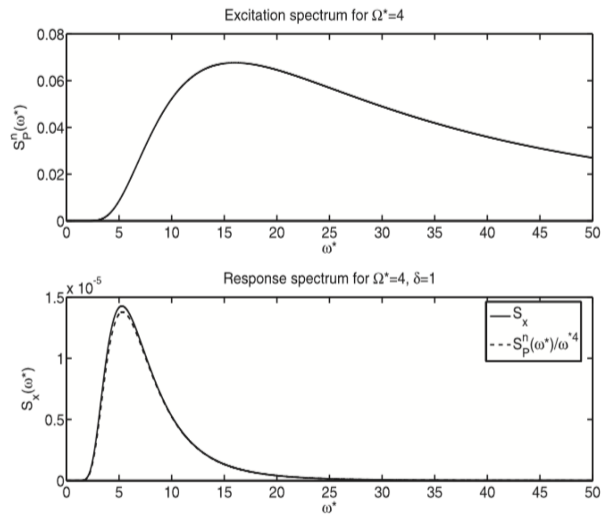


Figure 4.3. Dynamical or super-critical response.

Resonance

- At resonance condition when there is very low damping the frequency ratio ω^*approaches unity. The denominator approaches zero, and the spectral density approaches extremely large value:

- Serious problems which can be controlled only by adjusting damping

$$S_x(\omega^*) = \frac{S_P^n(\omega^*)}{\left(1-\omega^{*2}\right)^2 + \delta^2\omega^{*2} \rightarrow \approx 0} \rightarrow S_x >>>>$$

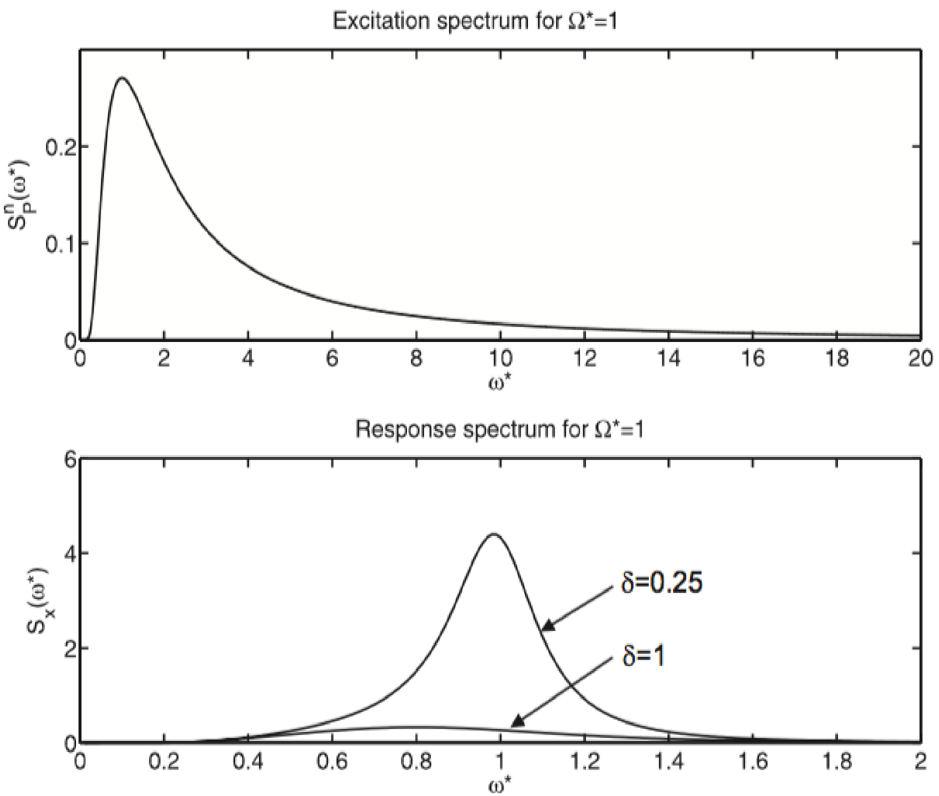
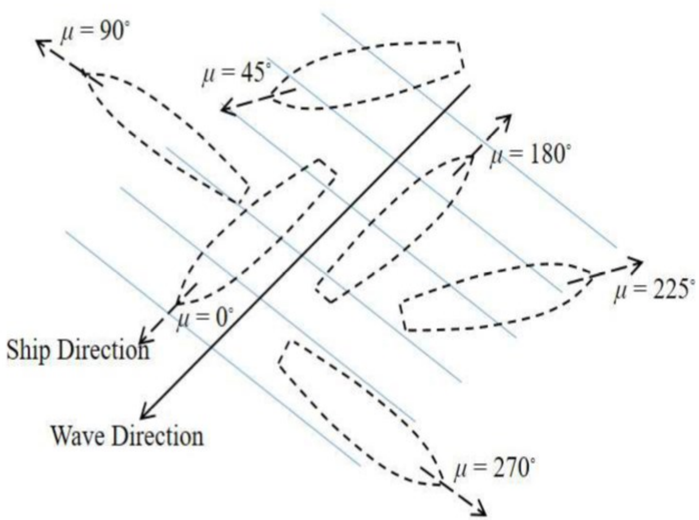
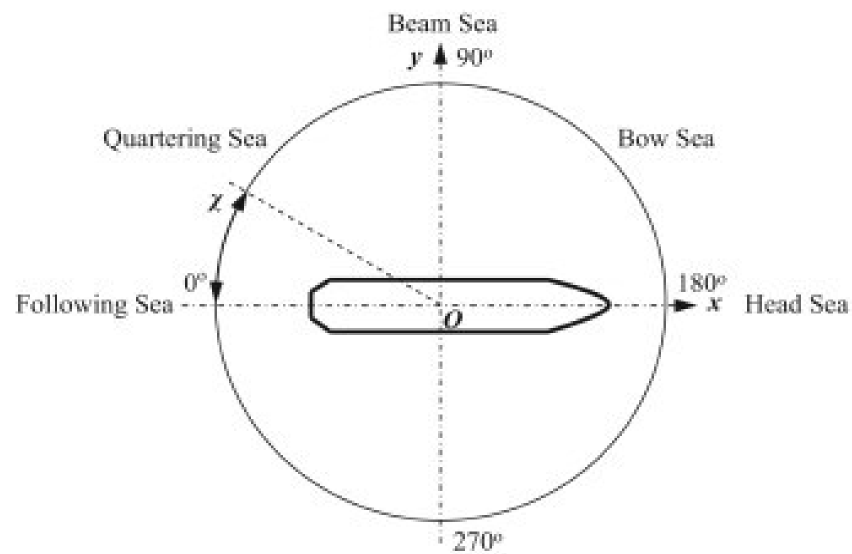


Figure 4.4. Resonant response.

Ship encounter frequency

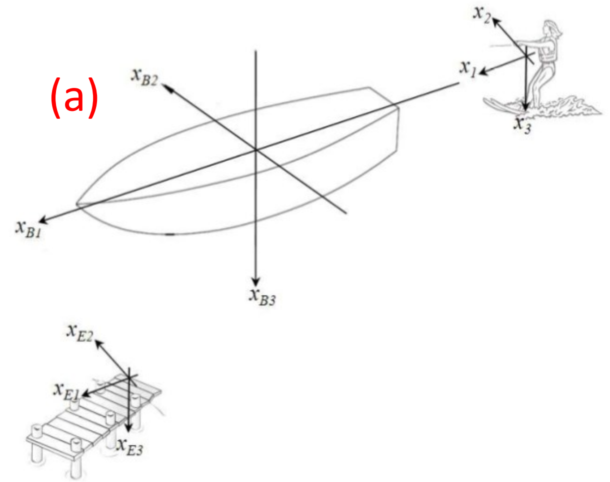
In ship dynamics the encounter frequency with the waves is used instead of the absolute wave frequency. This is because the ship is moving relative to the waves, and she will meet successive peaks and troughs in a shorter or longer time interval depending upon whether it is advancing into the waves or is travelling in their direction.





Coordinate Systems

- We have several coordinate systems for different purposes
  - **Ship CoG or body bound system – xB**
  - **Earth bound system – xE**
  - **Steadily translating system xi**

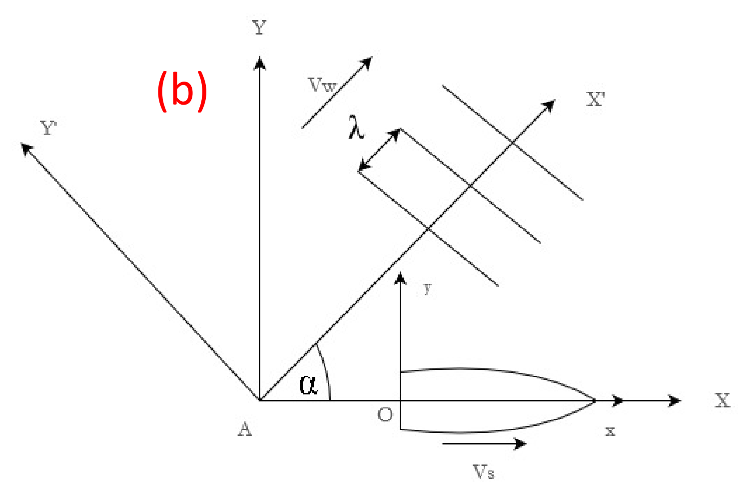


- Considering transformation of coordinates for a regular wave propagating at an angle α (from A X’ Y’ Z’ to A X Y Z) as illustrated in (b)

$$X' = X\,cos\,\alpha + Y\,sin\,\alpha$$

- Then the transformation to the ship’s-fixed coordinate system (oxy) coordinate system:

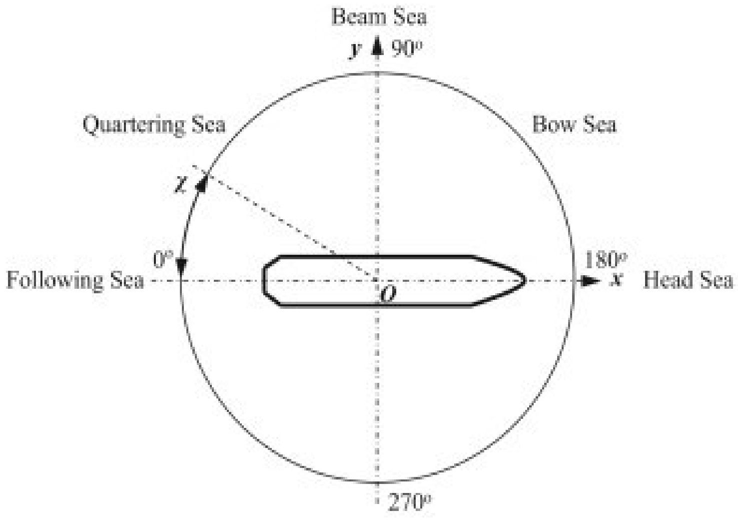
$$X = x + V_s t,\;\; Y{=}y$$



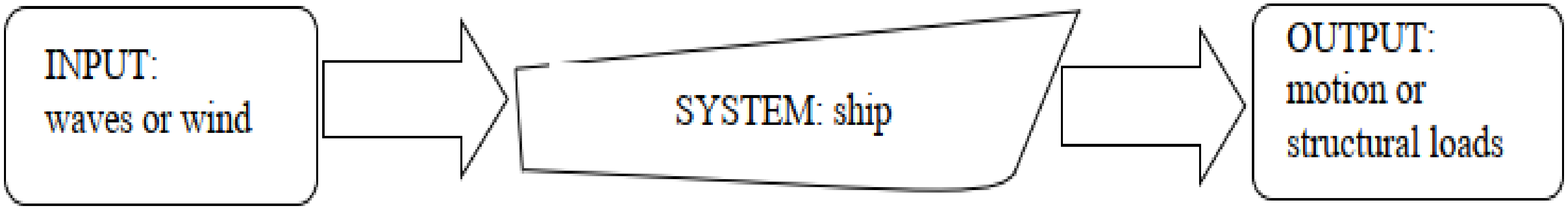
Definition of headings

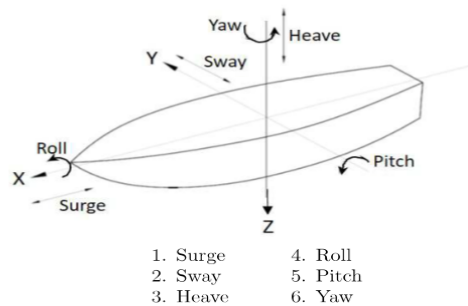
The heading angle determines the “type” of seas the ship experiences. Heading angles are defined as follows :

- $\mu = 0^0$ – following seas
- $\mu = 180^0$ – head seas
- $\mu = 90^0$ – starboard beam seas
- $\mu = 270^0$ -port beam seas
- $0 \leq \mu \leq 90^0$ – quartering waves on the ship starboard side
- $270^0 \leq \mu \leq 360^0$ – quartering waves on the ship port side
- $90^0 \leq \mu \leq 180^0$ -bow waves on the starboard side
- $180^0 \leq \mu \leq 270^0$ – bow waves on the port side



Wave induced responses





- Water is denser and more viscous than air (i.e. damping is increased)
- Added mass represents the amount of total fluid accelerated by the object

Ship Equation of motion (regular waves)

Hydro-damping

Sinusoidal excitation

$$(a + m)\ddot{x} + b\dot{x} + cx = F_0 sin(\omega t)$$

added mass

stiffness

- **Added mass & Hydro-damping** are functions of the frequency of oscillation.
- **Added mass** depends on the shape of the object and the type /direction of motion (linear or rotational)
- **Hydrodynamic damping** depends on fluid viscosity (frictional drag) and waves
- Each degree of freedom that has a restoring force has an associated natural frequency. These natural frequencies depend on the mass and stiffness properties of the system.

Hydrodynamic Forces

- The forces provided due to the effects of added mass and damping are referred to as hydrodynamic forces. They arise from pressure distribution around the oscillating hull.

- In linear hydrodynamic theory the hydrodynamic force has a component proportional to acceleration (i.e. added mass) and a component proportional to the velocity (i.e. damping coefficient).

- The following forces are used to obtain coefficients in the equations of motion :

  - **Radiation forces (or moments)**

  - **Incident wave or Froude - Krylov forces (or moments)**

  - **Diffraction forces (or moments)**

Fundamental EoM (Newton's Law)

$$(a+m)\ddot{x} + b\dot{x} + cx = F_0 sin(\omega_e t)$$

The LHS of EoM contains the dynamic properties of the ship and thus the forces on the ship when it is forced to oscillate in still water conditions (**hydro-mechanical**)

- Structural Mass (M) and Added Mass (a)
- Damping (b)
- Restoring forces (c)

The RHS of EoM contains the forces on the ship when it is restrained from motion and subjected to regular waves (**wave exciting**)

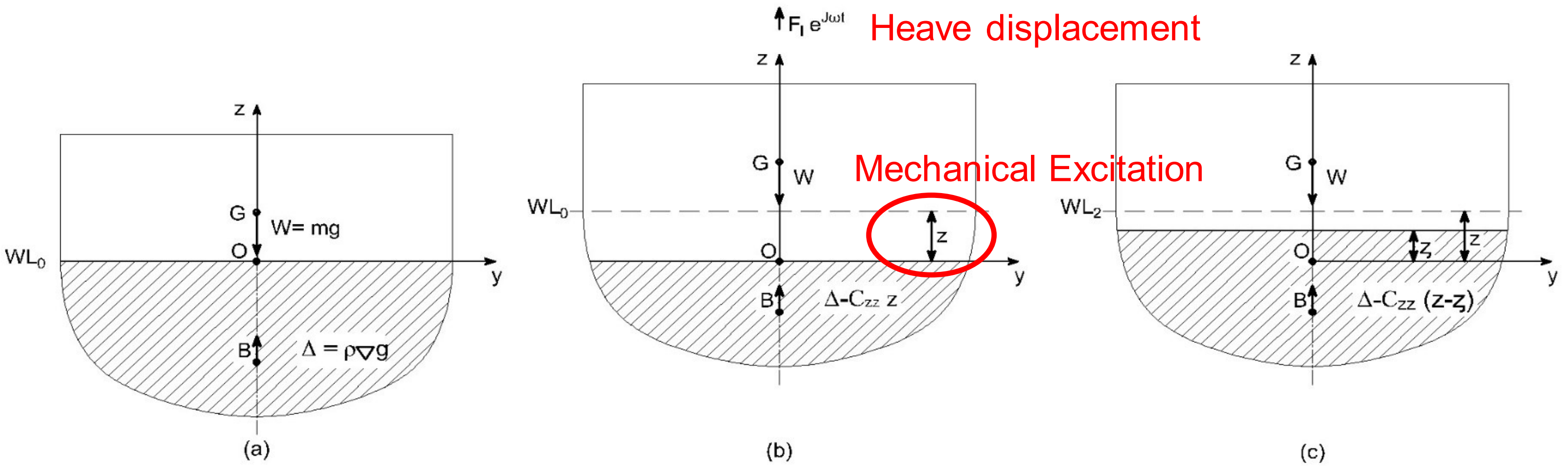
- Incident wave Froude-Krylov
- Diffraction

$$[-\omega_e^2(M+A) + i\omega_e N + S]\hat{\vec{u}} = \hat{\vec{F}}_e$$

$$\boxed{RAO = \frac{F_{e,0}}{N - \left(M + A(\omega_e)\right) \times \omega_e^2 + iB(\omega_e)\omega_e}}$$

The RAO expresses the response. It is a frequency dependent function (also known as FRF). It is a complex number, i.e. it comprises of an amplitude and a phase; where *i* expresses the imaginary unit of this number. It is common to consider the absolute number of the RAO in linear seakeeping.

Uncoupled Heave Motion



Original State
Hydrostatic equilibrium
W = Δ

Mechanical excitation
Still water

Long crested regular waves

Let us consider the case of a ship in still water which is subject to a mechanical excitation in the form of an upward force $F_z(t)$ leading to heave displacement $z(t)$ .The linear equation of motion for this 1 DOF system will be:

$$M_{zz}\ddot{z} + N_{zz}\dot{z} + C_{zz}z = F_z(t)$$

Uncoupled Heave Motion

For a sinusoidally varying mechanical excitation $F_z(t) = F_1 e^{j\omega t}$ Assuming F_1 is a force vector of constant amplitude the response will also be sinusoidal namely $z(t) = Ze^{j(\omega t-\varepsilon)}$ where Z is the amplitude of excitation and ε the phase lag of the response. Accordingly:

$$\mathrm{Z} = \frac{F_1}{\sqrt{(C_{zz} - \omega^2\, M_{zz}\,)^2 + (\omega N_{zz})^2}} \quad \text{and} \quad tan\varepsilon = \frac{\omega N_{zz}}{(C_{zz} - \omega^2 M_{zz})}$$

- ✓ Czz=ρgAwz is the hydrostatic heave restoring force with ρ representing the water density (kg/m^3) ;
- ✓ g the acceleration of gravity (m/s^2)
- ✓ A_w the still water lane area (m^2).'
- ✓ Nzz is the heave damping force
- ✓ $M_{zz} = m + m_{zz}$ is the virtual mass of the ship ($m = \rho\nabla$ and m_{zz} = heave added mass)

Brief Reference to Pitch

- If we consider that the ship is an 1DOF system subject to pitch excitation namely *ϑ(t)*

$$\left[I_{yy} + I_{\vartheta\vartheta}(\omega_e)\right]\ddot{\vartheta} + N_{\vartheta\vartheta}(\omega_e)\dot{\vartheta} + C_{\vartheta\vartheta}\vartheta = \bar{M}_{\vartheta}(\omega, \omega_e)e^{j(\omega_e t+u)}$$

  - ✓ I_{yy} is the mass moment of inertia about axis Oy
  - ✓ $I_{\vartheta\vartheta}$ is the pitch added mass moment of inertia
  - ✓ $N_{\vartheta\vartheta}$ is the pitch damping coefficient
  - ✓ $C_{\vartheta\vartheta} = \rho g I_{long}$ for $I_{long} = \text{longitudinal } 2^{\text{nd}} \text{ moment of water plane area}$
  - ✓ $\bar{M}_{\vartheta}$ is the amplitude of the wave excitation vector

- The pitch natural frequency in water can be approximated as

$$\omega_p = \sqrt{\frac{c_{\theta\theta}}{I_{yy}+\bar{I}_{\theta\theta}}} \qquad \bar{I}_{\theta\theta} = I_{\theta\theta} \to \infty$$

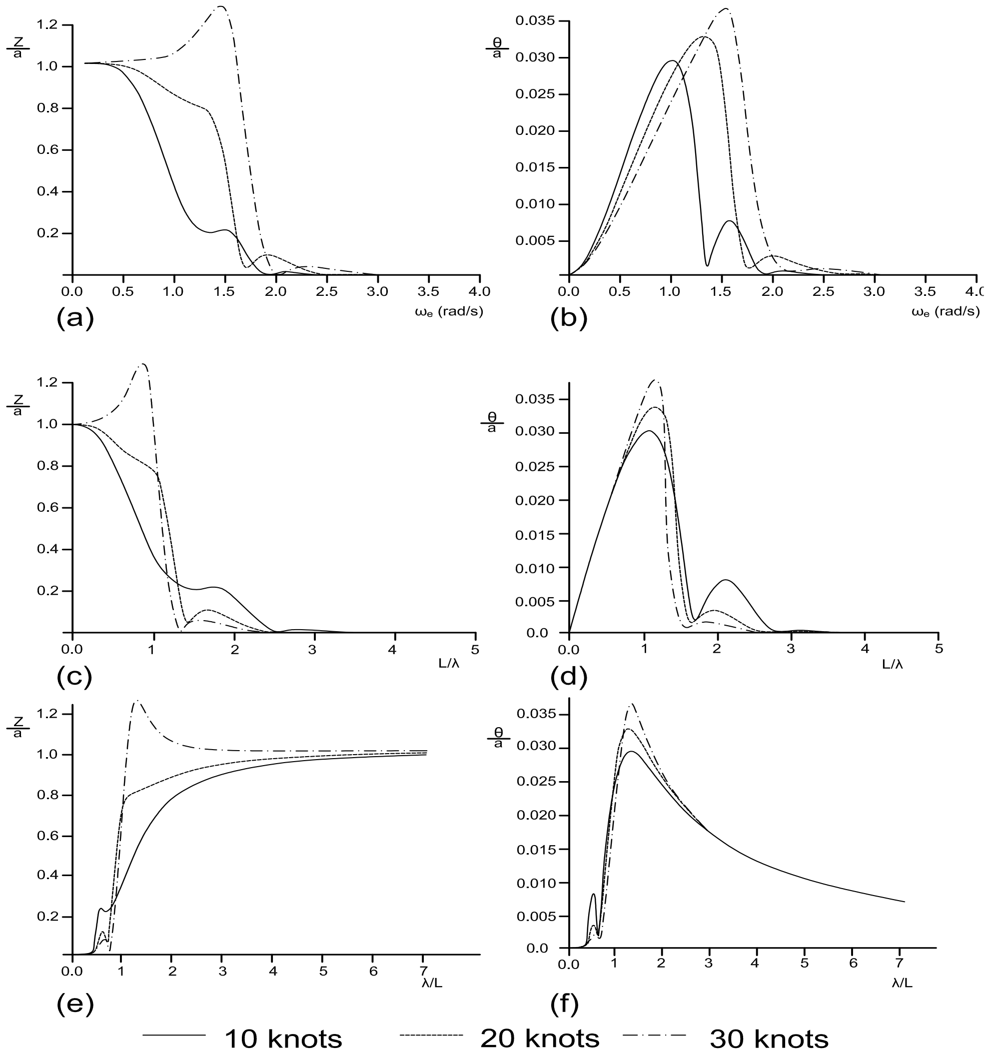
Coupling Heave & Pitch

$$\begin{bmatrix} m + m_{zz} & m_{z\theta} \\ m_{\theta z} & I_{yy} + I_{\theta\theta} \end{bmatrix} \times \begin{bmatrix} \ddot{z} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} N_{zz} & N_{z\theta} \\ N_{\theta z} & N_{\theta\theta} \end{bmatrix} \times \begin{bmatrix} \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} C_{zz} & C_{z\theta} \\ C_{\theta z} & C_{\theta\theta} \end{bmatrix} \times \begin{bmatrix} z \\ \theta \end{bmatrix} = \begin{bmatrix} F_z(\omega, \omega_e) e^{j(\omega_e t + \psi)} \\ \bar{M}_\vartheta(\omega, \omega_e) e^{j(\omega_e t + u)} \end{bmatrix}$$

- In addition to heave added mass m_{zz} and pitch added inertia $I_{\theta\theta}$ we have **heave into pitch** (and ***pitch into heave***) added mass terms namely $m_{z\theta}$ and $m_{\theta z}$
- In addition to heave damping N_{zz} and pitch damping $N_{\theta\theta}$ coefficients we have the heave into pitch (and pitch into heave) terms defined as $N_{z\theta}$ and $N_{\theta z}$ respectively.

- The heave into pitch restoring terms are defined as $C_{z\theta} = C_{\theta z} = \rho g M_l$
- $M_l = \int_L x B(x) dx$ represents the longitudinal first moment of water plane area and $B(x)$ is the beam in way of the water line.

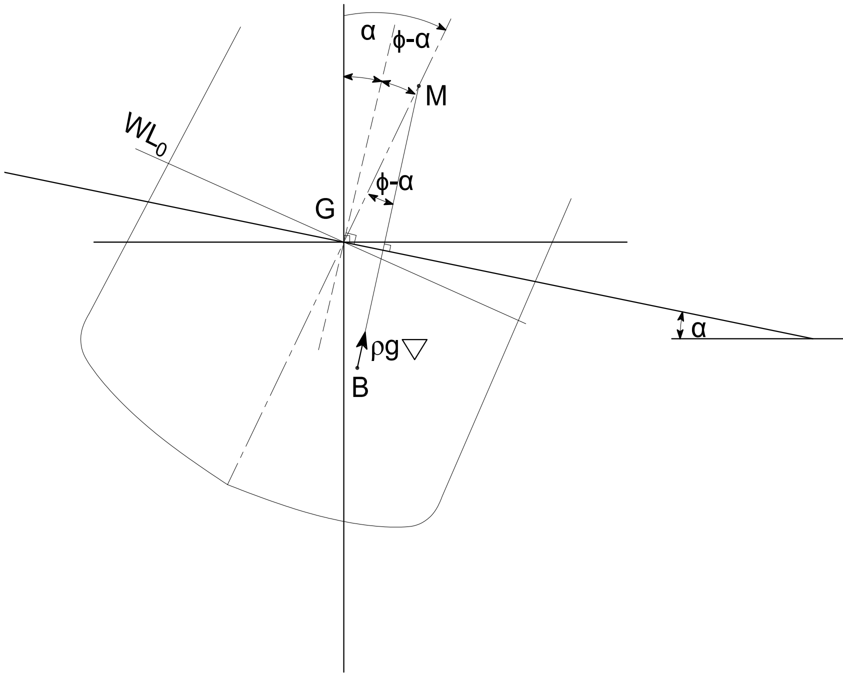
RAO demo for Heave & Pitch (Head waves)



Roll – small amplitudes

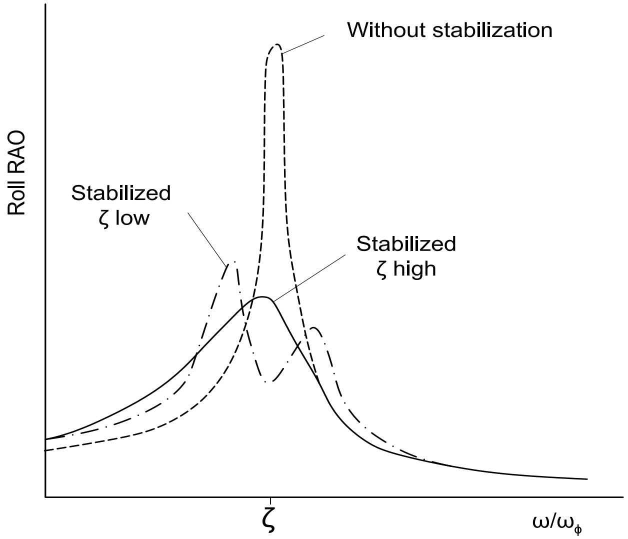
$$\left[J_{xx} + I_{\varphi\varphi}(\omega)\right]\ddot{\varphi} + N_{\varphi\varphi}(\omega)\dot{\varphi} + C_{\varphi\varphi}\varphi = K_{\varphi}(t) = K_1 e^{j\omega t}$$

- $K_{\varphi}(t)$ is a sinusoidal mechanical excitation producing a rolling moment $K_{\varphi}(t) = K_1 e^{j\omega t}$ φ is the angle of roll
- I_{xx} is the mass moment of inertia about the longitudinal axis through the centre of mass
- $C_{\varphi\varphi} = \Delta GM_T = \rho g \nabla GM_T$ is the hydrostatic roll restoring coefficient
- $I_{\varphi\varphi}$ = roll added inertia (frequency of oscilation dependent)
- $N_{\varphi\varphi}$ = roll damping coefficient due to hydrodynamic effects associated with fin and tank stabilizaers



Roll – large amplitudes

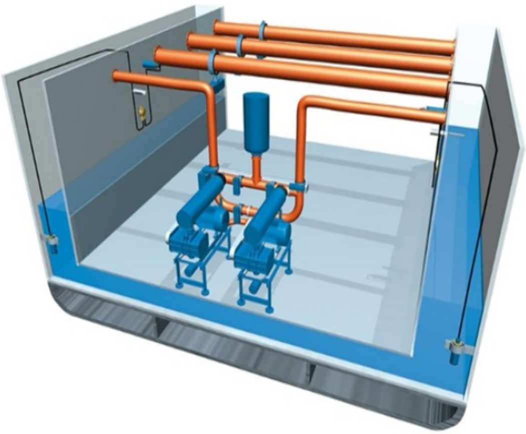
- Large amplitude of roll may cause discomfort compared to other motions.
- The amount of damping which is provided by the fluid is not always sufficient to reduce the roll amplitude to acceptable levels.
- Solution 1 : passive systems which make use of the roll motion and do not require any power source and control system
- Solution 2 : active systems which use power to move masses or control surfaces and a control system

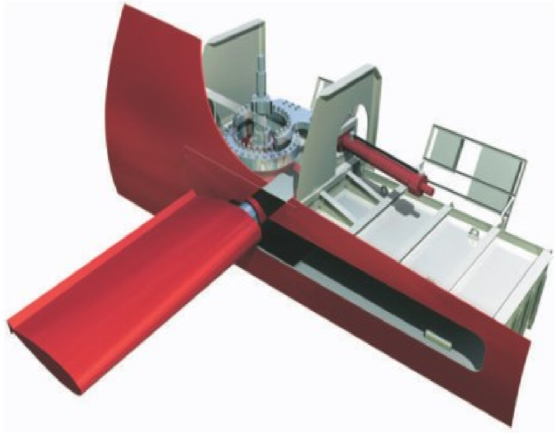


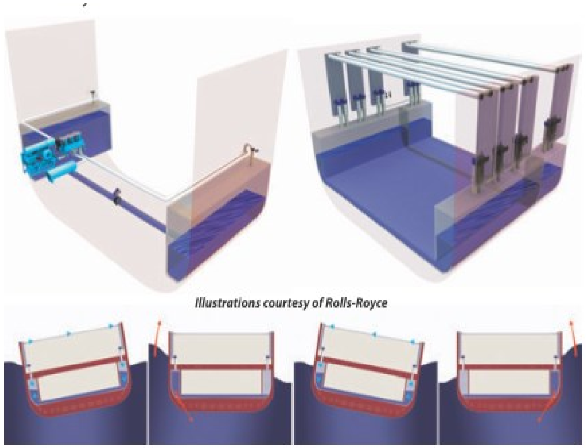
$$\left[I_{xx} + I_{\varphi\varphi}(\omega) - CC_1\right]\ddot{\varphi} + \left(N_{\varphi\varphi} + CC_2\right)\dot{\varphi} + \left(C_{\varphi\varphi} - CC_3\right)\varphi = K_\varphi(t)$$

C_1 and C_3 decrease with virtual mass moment of inertia and restoring moment whilst C_2 increases the damping. C is associated with the lift generated by the fin stabilizers

Ship Stabilisation systems







Strip theory

- Three different types of forces, in addition to the restoring forces of hydrostatic origin:
  - **Radiation forces** (or moments),
  - **Incident wave or Froude-Krylov forces** (or moments) and
  - **Diffraction forces** (or moments).

- Two basic types of linear methods (potential flow analysis) are used :
  - **Strip theory**
  - **Panel methods**.

- **Strip theory is a 2D analysis method** where the hull is divided into a uniform number of strips.
  - Hydrodynamic properties are obtained for each strip considering the flow around an infinitely long uniform cylinder with the cross section of a slice.
  - Each strip is independent and interactions in flows are neglected
  - The sectional added inertia and damping coefficients are obtained for **heaving and coupled swaying - rolling slices**.
  - To obtain the added inertia and damping coefficients for the entire hull the sectional properties are integrated along the hull using the moments for the pitch and yaw coefficients.
  - Diffraction effects are formulated w.r.t. added inertia and damping coefficients as

$$(m+m_{zz})\ddot{z}+N_{zz}\dot{z}+C_{zz}\,z=m_{zz}\ddot{\zeta}+N_{zz}\dot{\zeta}+C_{zz}\,\zeta=F_z(t)$$

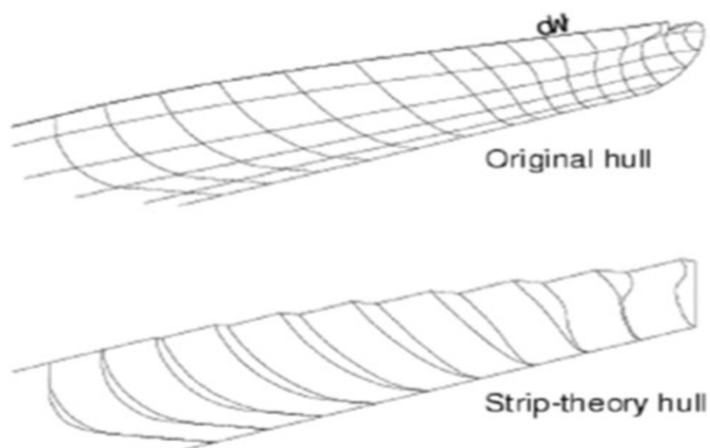
Reference : Tuck & Faltisen, Ship Motions and Sea Loads, Trans SNAME, 1970, 78:250-287

Strip theory

- Strip theory ignores the influence of longitudinal effects on the flow around the ship. This influence is important when forward speeds are high. So **strip theory is limited to small or moderate Froude numbers**.

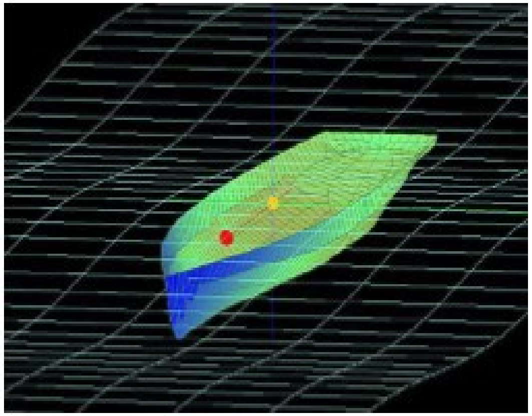
- **In strip theory the 2D velocity potential can be formulated by** :
  1. Source or dipole distributions on the section contour. This method is preferred due to irregular frequencies leading to added mass and damping coefficients tending to infinite values at these frequencies
  2. A source + a dipole (in the case of roll) representing the oscillations of a **semi circular cross section + conformal mapping** to transform semi circle into a contour shape form.

- **In conformal mapping the so called Lewis sections are broadly used**. They are accurate in terms of mapping beam, draft and area. Another more accurate technique is the multi-parameter conformal mapping. It maps better the section contour.



Reference : Tuck & Faltisen, Ship Motions and Sea Loads, Trans SNAME, 1970, 78:250-287

Panel Methods



- To overcome the restrictions imposed by strip theory the **3D potential flow analysis** was developed.

- The method discretises the mean or still water wet surface of the hull by panels and places a pulsating (or translating and pulsating source) in each panel.

- After the evaluation of the strength of all sources the radiation and diffraction forces can be obtained by integration over the mean water surface of the hull. This is also known as **boundary element method**

- The **velocity potentials** associated with the singularities are referred to as **green functions**. This is also known as a ***near field method***

- Another approach is the Rankine singularity method. In this case the domain of idealisation is extended to include also the free surface boundary conditions to infinity **–** ***far field method***

- Green Function and Rankine Panel methods can be combined to include both near- and far-field effects simultaneously

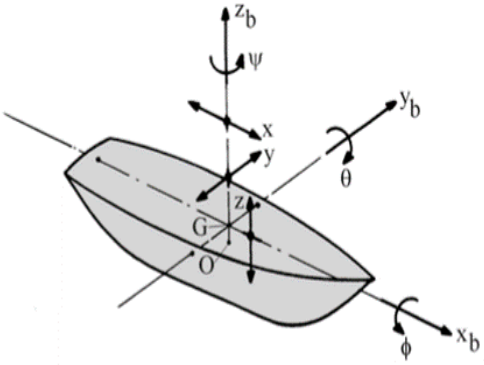
Hirdaris, S.E et al. (2016) The influence of nonlinearities on the symmetric hydrodynamic response of a 10,000 TEU Container ship. Ocean Engineering, 111:166-178.

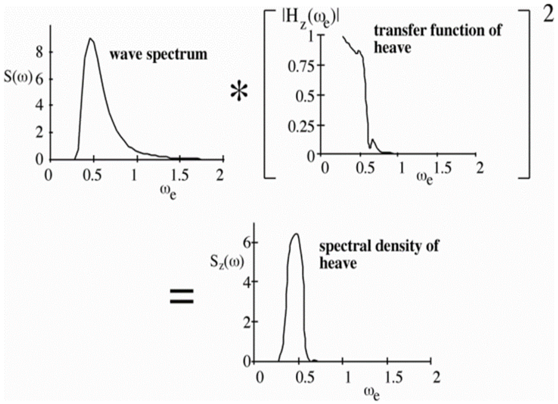
The perfectly linear seakeeping problem

<u>Assumptions :</u>

- Arbitrary shaped ship with port/starboard symmetry moves in waves in 6 dof.
- The ship is slender (i.e. length is much larger than the beam or draught)
- The hull is rigid (i.e. it does not deform due to waves)
- Speeds are low to moderate, there is no planning lift, the ship sections are wall sided (no wave elevation), motions are small
- The water depth is much greater than wave length (deep water aprox. is valid)
- The presense of the hull has no effect on waves ; the waves are linear
- There are no moving masses on the ship (e.g. free surface effects) that interfere with motions

<u>Aim :</u>To evaluate the RAOs and use relevant sea spectra to assess motions by **Strip Theory aprox.**





Linear vs NL models

Linear model disadvantages

- Large amplitude effect neglected;
- Not capable to simulate non-linear phenomena, like parametric rolling.

Non-Linear model

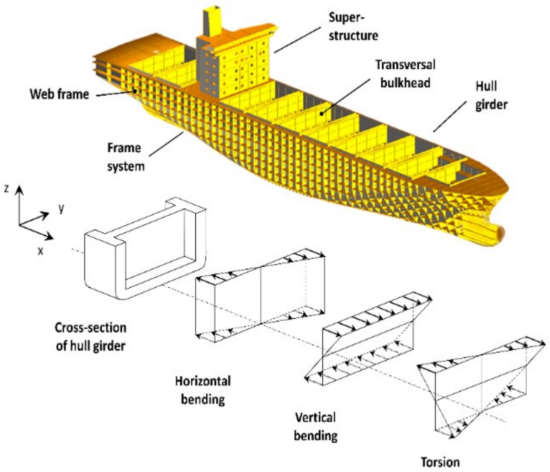
- Restoring and Froude-Krylov actions evaluated on the effective immersed hull in wave at each time step;
- Memory effect on damping and added mass actions;
- Time domain simulation.

Non-Linear model advantages

- More precise on large amplitude responses;
- Suited to simulate Parametric Roll;
- Precise axial forces, usually approximated in the linear model.

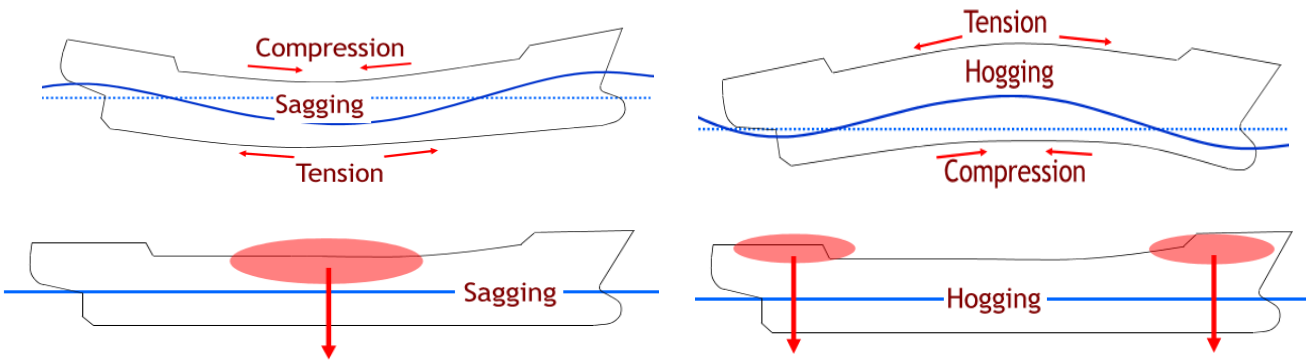
Motivation – Hull Girder Loads

- In the structural design of the ships, a common practice is to express the design loads by sagging and hogging bending moments and shear forces
- The sagging and hogging bending moments and shear forces are hull girder loads
- The hull girder loads are balanced by internal forces and moments affecting the cross-section of the ship hull (stress resultants)
- The accurate prediction of the extreme wave loads is important for safety
- For ships in a heavy seas, the sagging loads are larger than the hogging loads
- Linear theories cannot predict differences between sagging / hogging loads



Global Loads – Hogging and Sagging

- **Hogging and sagging** are the major global loads the ship must survive. They create tension and compression in way of the keel/deck. **In still water** – in the lightship condition – the mass and buoyancy forces are equal and opposite and generally act fairly evenly along the ship. **In waves** the distribution of buoyancy changes especially in head seas and following seas. This is most apparent where the wave length is similar to ship length.



- <u>**Sagging :**</u> *Peaks are at bow/stern and the trough amidships.* The buoyancy force shifts to the ends of the vessel. The bow experiences forces upwards by buoyancy and the vessel in pulled downwards amidships by gravity.

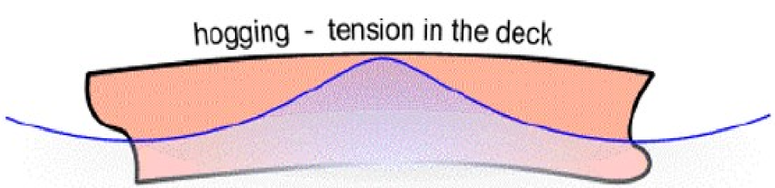
- <u>**Hogging:**</u> *Troughs at bow/stern and peaks amidships.* The buoyancy force is shifted to the centre of the vessel. Amidships is forced upwards by buoyancy and the bows are pulled downwards by gravity.

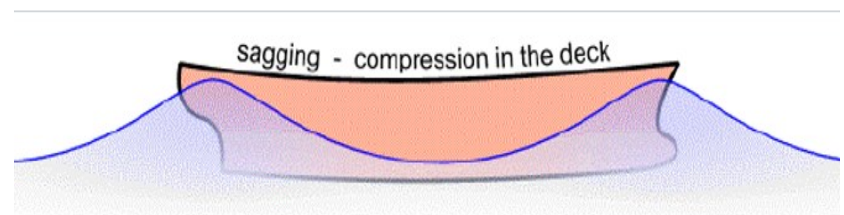
Quasi Static Response – wave actions

Two basic RULES : The 1/20 Rule and the L = lambda Rule

- When we consider the wave forces on the ship to be quasi static it means that they can be treated as a succession of equilibrium states.

- **MAX hogging BM** occurs when the ships' mid body is on the crest of the wave . Conversely, **MAX sagging BM** occurs when the mid-body is on the trough and the bow / stern are on crests.





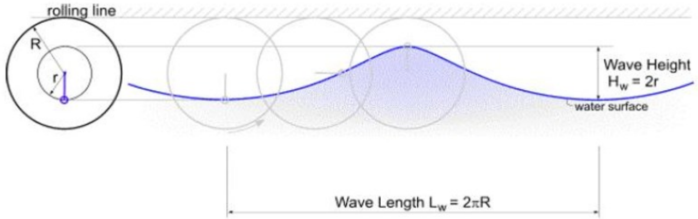
L = lambda RULE

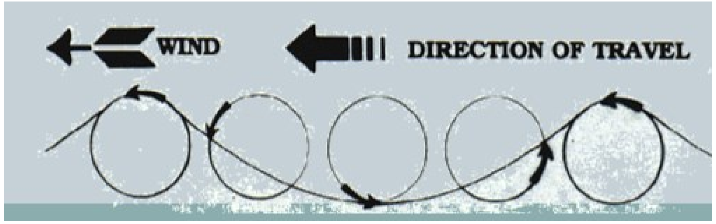
The highest BM will occur when the wavelength approaches the vessel length. The design wave of a vessel therefore has a wavelength equal to the vessel length

Quasi Static Response – wave actions

- The shape of an ocean wave is often depicted as a sine wave, but waves at sea can be better described as **"trochoidal".** A trochoid can be defined as the curve traced out by a point on a circle as the circle is rolled along a line. The discovery of the trochoidal shape came from the observation that particles in the water would execute a circular motion as a wave passed without significant net advance in their position.

- The motion of the water is forward as the peak of the wave passes, but backward as the trough of the wave passes, arriving again at the same position when the next peak arrives. (Actually, experiments show a slight advance of the water with the waves, but that advance is small compared to the overall circular motion.)





1/20 RULE

The wave height (peak to through) may be generally assumed to be the 1/20th of the wave length else the ship will break (1/20 RULE).

Hydroelasticity of Ships – brief Introduction

Wet matrices (Green's function)

Principal coordinate Amps.

Dry matrices (FEA)

$$[\boldsymbol{a} + \boldsymbol{A}(\omega_e)]\,\ddot{\boldsymbol{p}}(t) + [\boldsymbol{b} + \boldsymbol{B}(\omega_e)]\,\dot{\boldsymbol{p}}(t) + [\boldsymbol{c} + \boldsymbol{C}]\,\boxed{\boldsymbol{p}(t)}$$
$$= \boldsymbol{\Xi}(\omega, \omega_e)\exp(i\omega_e t)$$

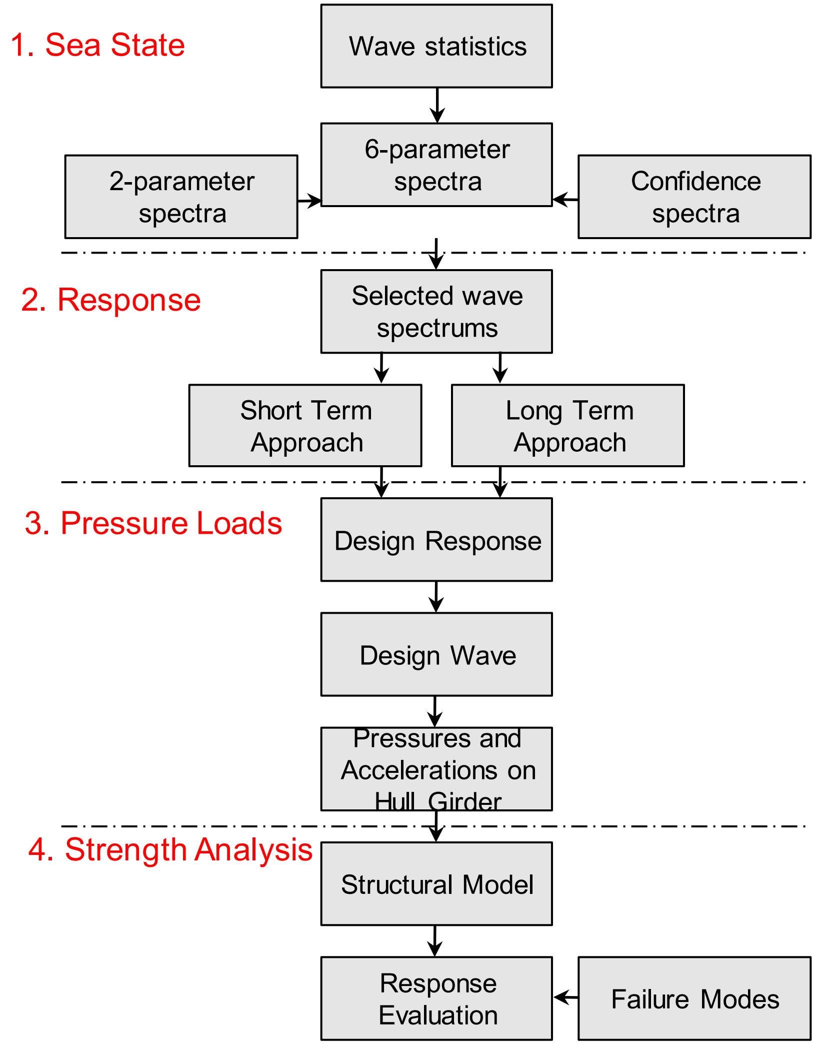
Encounter frequency

Unified Hydroelasticity	**DRY analysis**	**WET analysis**
2D	Beam theory (Analytical, FD, FEA)	Strip theory (conformal mapping)
3D	3D FEA (shell, beam elements)	Green function (pulsating source)

Hirdaris, S.E., Price, W.G. and Temarel, P.: Two- and Three-dimensional Hydroelastic Analysis of a Bulker in Waves. *Marine Structures* ,16:627-65.

Design for Lifetime Service

- The basis is the description of sea state with wave spectrum
  - ➢ Years of wave measurements and resulting statistics such as H_S, T_Z, (BMT wave stats)
  - ➢ Wave spectrums
- Two things are of interest
  - ➢ Short term response *(M, Q)*
  - ➢ Long term response *(M, Q)*
- Short term response is used when ultimate strength is considered, i.e. strength against extreme loads
- Long term response is used when fatigue strength is considered, i.e. cumulative damage from years of operation – can be used also to predict the ultimate loads (pay attention to extrapolation from short term maxima)

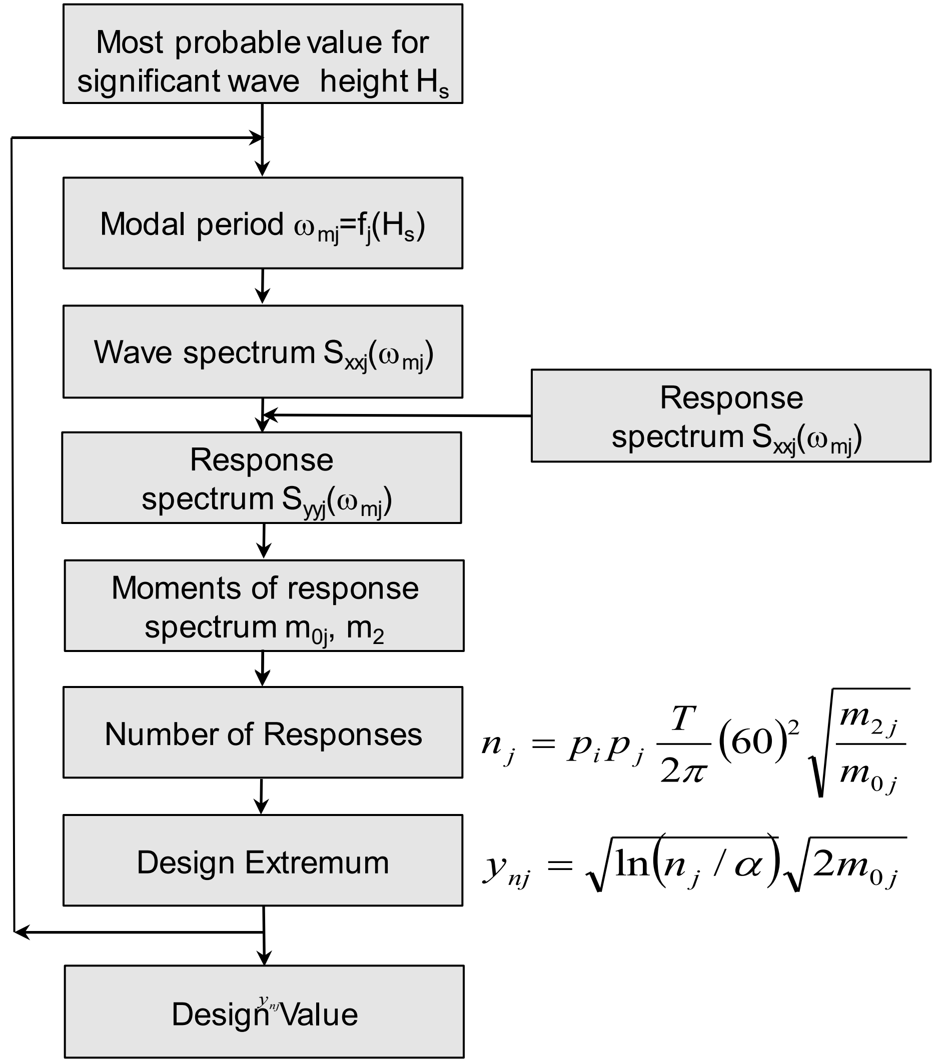


ST Response from Extreme Sea State

- The aim is to find the response under extreme load conditions, i.e. reserve for ultimate strength

- The interesting failure modes are those which can happen during one load cycle:
  - Rupture
  - Buckling

- The idea is to find the extreme value for wave height H_s
  - Wave statistics
  - Entire lifetime, 20-25 year for ships, 100 years for offshore
  - 20 years is T =20*365*24h.



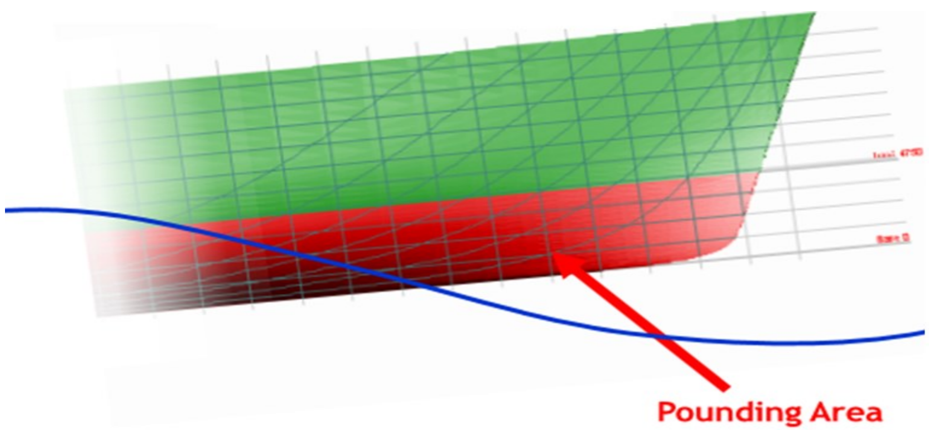
$$n_j = p_i p_j \frac{T}{2\pi}(60)^2\sqrt{\frac{m_{2j}}{m_{0j}}}$$

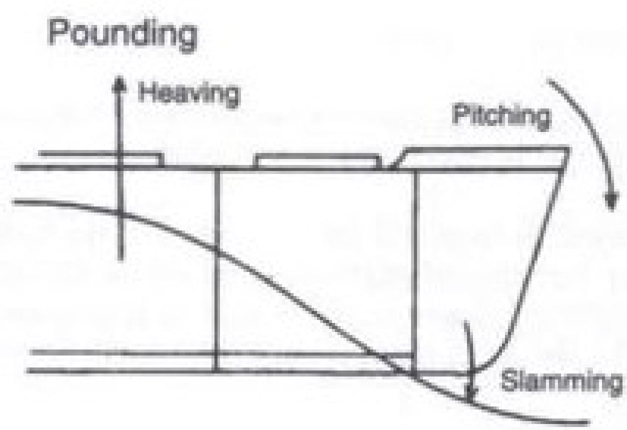
$$y_{nj} = \sqrt{\ln\left(n_j/\alpha\right)}\sqrt{2m_{0j}}$$

Local Loads – *Pounding leading to bow slamming*

- As a ship moves through the water fluid actions (i.e. hydrodynamic forces) push in and out in a cyclic fashion in way of the waterline / bow area of the vessel. As the ship moves trough the water especially in large head seas the bow tends to lift clear of the water. As it drops back to the sea the vessel slams at the forefoot. **The phenomenon in known as pounding or bow slamming.**

- The phenomenon is linked up with heavy pitching assisted by heaving as the whole ship is lifted in a seaway. Based on in service experience it is believed that that greatest effect is experienced in the lightship condition. To compensate for this the bottom over 30% fwd of the ship strengthened for ships exceeding 65m in length when min draft is less than 0.045L(OA) in any operating condition.



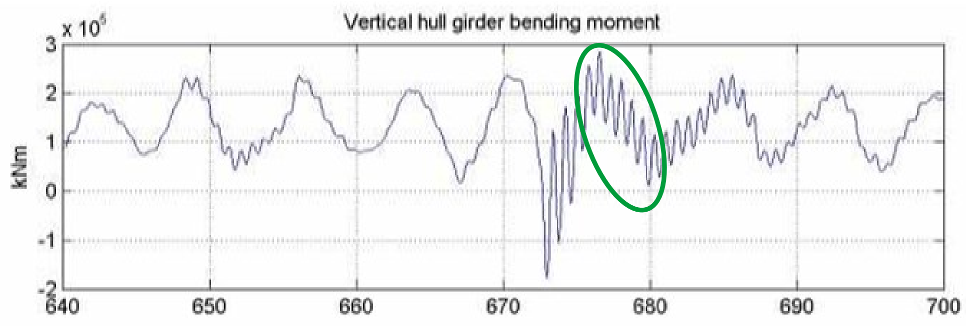


Local Loads – *Slamming leading to Whipping*

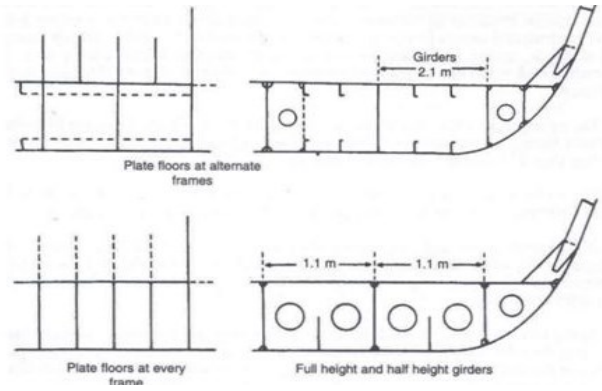
- Whipping is usually defined as a transient hydroelastic ship structural response due to impulsive loading such as slamming, green water, underwater explosion, etc. **Slamming induced whipping** is observed both in experiments and in full scale measurements for any kind of ships as far as they encounter heavy seas in which the slamming type of loading is likely to occur.

- The figure below represents the time evolution of the VBM, following severe slamming event, at the midship of a small (Lpp = 124m) general cargo/container vessel.

- The whipping contribution to the overall vertical bending moment is important but it also lasts for a relatively long time due to the low structural damping. One slam event increases multiple extremes in the bending moment which makes the whipping phenomena to be relevant both for extreme and fatigue loading of the ship structure.



Typical whipping event



Measures of Ship Performance - MSI

- **Motion Sickness Incidence (MSI).** Experience shows that the principal cause of sea sickness appears to be a result of vertical accelerations. Experiments carried out in the 70s with 300 male volunteers in the USA positioned in a cabin subject to sinusoidal vertical motion with amplitude up to 3.5 m. MSI has been defined as the percentage of participants who vomited in the first 2 hrs of the experiment.

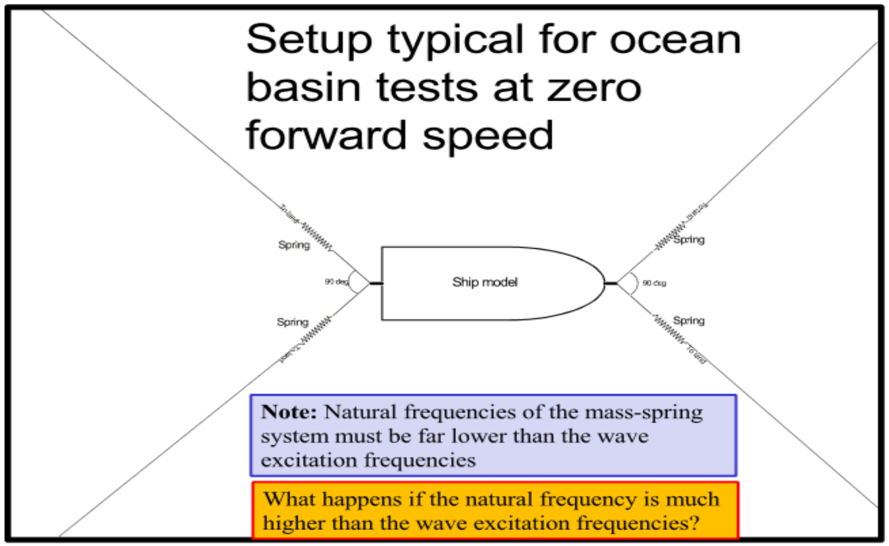
- Subjective Magnitude **(SM)**. In mid 70s a number of pilots were subjected to an experiment of sinusoidal vertical motions using a chair capable of amplitudes up to 1.5m. The objective of the experiment was to quantify the influence of motions on their ability to work effectively. A reference motion at 1 Hz with acceleration of 0.6g was assigned an SM (10).A motion judged to be twice as severe was assigned SM (20), half as severe SM (5) etc.

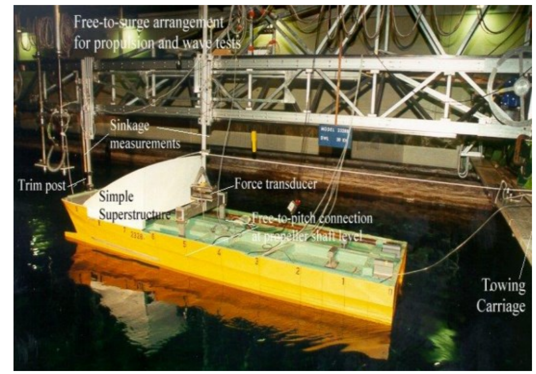
- Motion Induced Interruption **(MII)**. This is a reasonably adequate parameter for judging the severity of motion for passengers derived form research carried out in 80s and 90s. However, it is not very relevant to the ability of crew to function effectively. It is based on the frequency that a member of the crew has to stop work and hold on to a suitable anchorage to prevent loss of balance due to sliding or tipping *e.g. roughly SM(10).

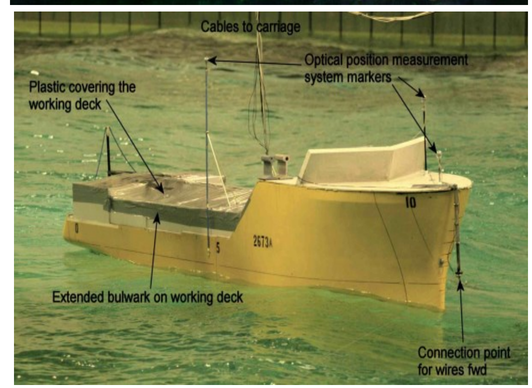
Seakeeping tests – Free models classification

- Seakeeping tests are carried out to reveal possible seakeeping problems with a new design, to determine operational limits, optimise and validate the design, to validate R&D, measure design loads , understand capsize and loading effect sequences, carry out safety studies or to develop and test damping systems.

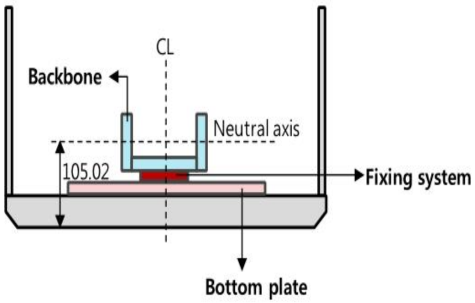
A free model is a model that is free to heave, pitch and possibly surge. In some occasions we allow for the model to have restricted horizontal motions. In other occasions the model may be completely free

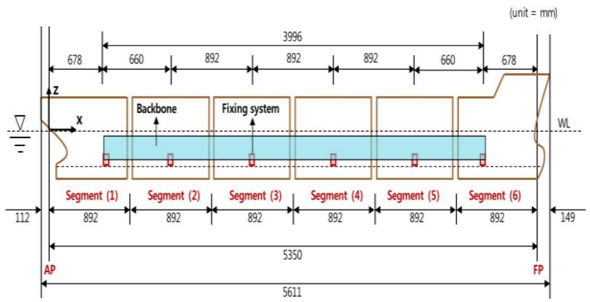


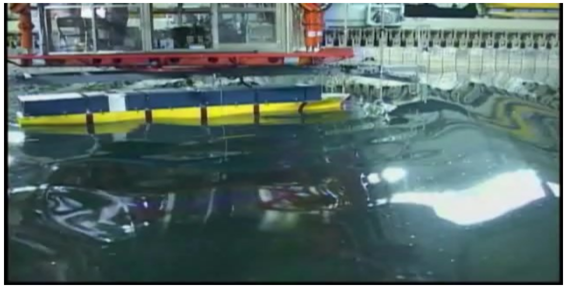


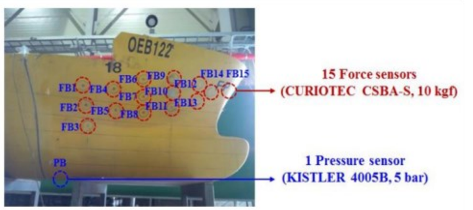


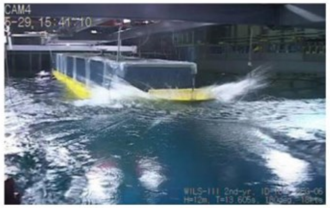
Seakeeping tests – Hydroelastic models (segmented)

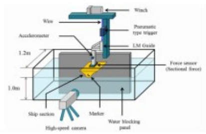


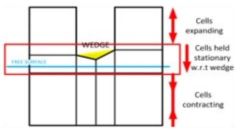


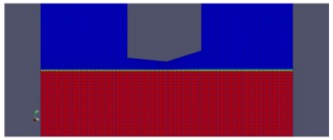


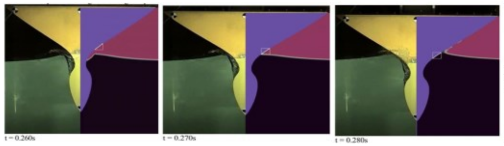


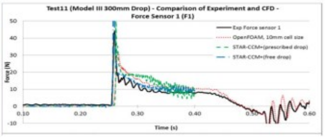


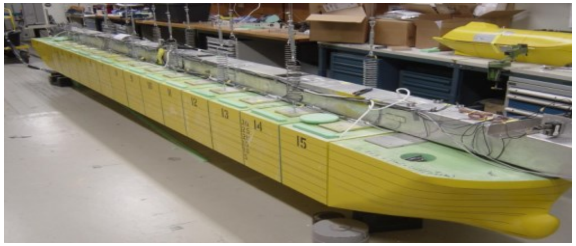












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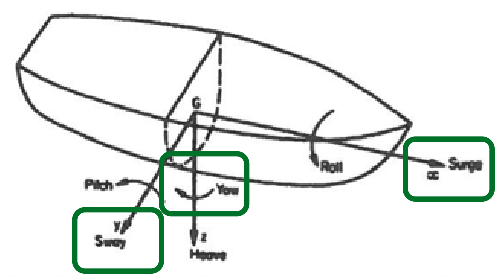
Lee, Y., Nigel White, N., Wang, Z., Hirdaris, S.E. and Zhang, S. Comparison of springing and whipping responses of model tests with predicted nonlinear hydroelastic analyses. The International Journal of Offshore and Polar Engineering (IJOPE), 22(3), pp. 1-8.

Manouevring – focus and basics

- In manoeuvring the design aspects are
  - Course-keeping and changing
  - Track keeping
  - Speed-changing
- The terms directional stability and control are also used
- Manoeuvring concerns shipyard / owner
  - IMO sets minimum requirements for all ships (IMO A751)
  - Ship-owners may be much more strict (e.g. port of Miami)
  - *Practical Questions: Does the ship keep straight course? Is tug assistance needed to berth and under which wind speeds? Could the vessel initiate/sustain/stop turning? Could the vessel stop and accelerate safely?*
- Manoeuvring requirements affect the equipment to be selected (e.g. rudders and pods, waterjets, fixed fins, jet thrusters, propellers, ducts and steering nozzles etc.)



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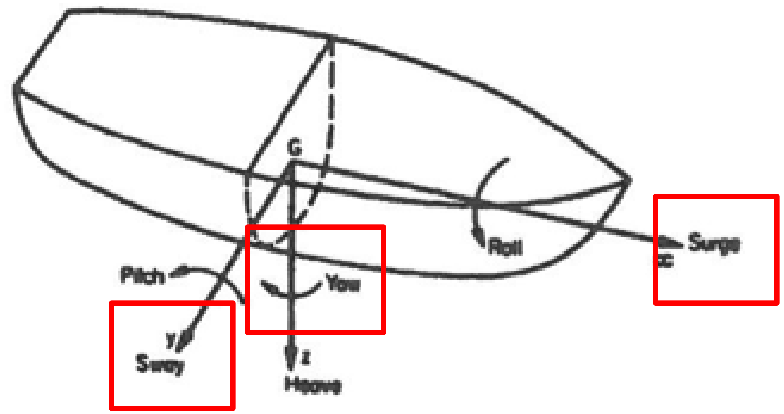
J. E. Matusiak, *Dynamics of a Rigid Ship*. Aalto University publication series on Science and Technology, e-ISBN: 978-952-60-7262-3; e-ISSN: 1799-490X, 2017.

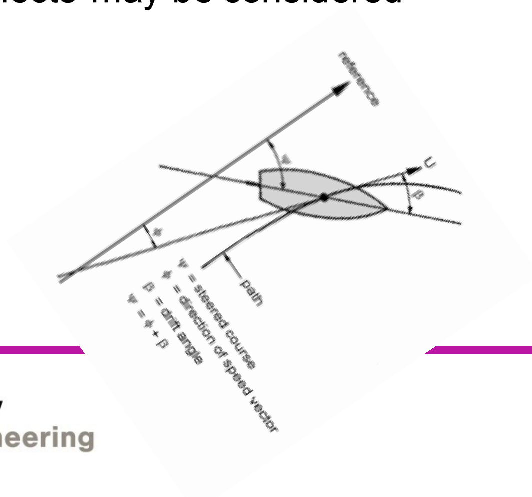
Simple kinematic model assumptions

- Calm water conditions
- 3 dof : surge- translation along x-axis; sway - translation along y-axis and yaw - rotation around z-axis.
- Heel is usually disregarded, although it may be important during manoeuvring if it is higher than 10 degrees; wind is an add on feature.
- The drift angle (the angle between the path of the center of gravity and the middle line plane of the ship) should not show large fluctuations
- The rudder angle, required to compensate for external disturbances by wind and waves, should not be too large
- Forward speed effects may be considered



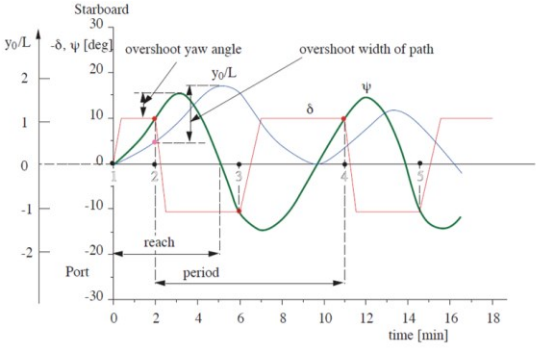
Translation or rotation	Axis	Description	Positive sense
Translation	Along x	Surge	Forwards
	Along y	Sway	To starboard
	Along z	Heave	Downwards
Rotation	About x	Roll	Starboard side down
	About y	Pitch	Bow up
	About z	Yaw	Bow to starboard

Fig. 12.1 Ship motions

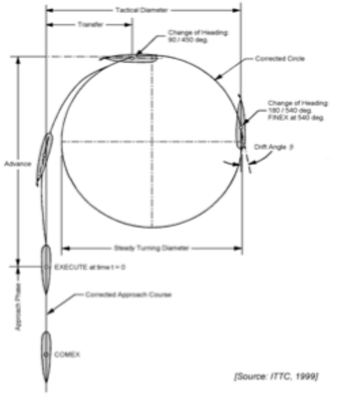


Zig-Zag / Turning manouvering test

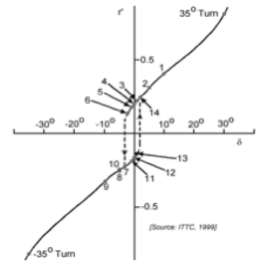
- **Zig zag :** To express course changing and course keeping qualities
  Information obtained:
  - initial turning time,
  - time to second execute,
  - the time to check yaw
  - the angle of overshoot.
  - Steering indices K (gain constant) and T (time constant) for the linearized response model



- **Turning :** to determine the turning characteristics of the ship at different speeds and rudder angles.
  Information obtained:
  - advance,
  - transfer,
  - tactical diameter,
  - steady turning diameter,
  - final ship speed
  - turning rate in the steady state

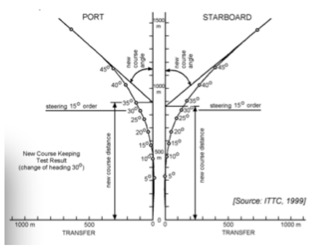


Direct spiral, new course keeping, acceleration tests

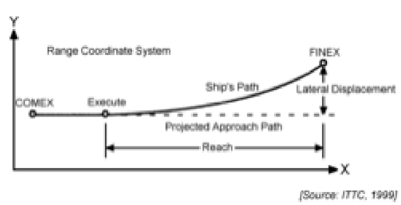


- **Direct Spiral :** The purpose is to find out if the ship is directionally stable or not. Important parameters are width and height of the loop for an unstable ship

- **New course keeping :** The test provides info for changing a ship course. The obtained data is ship heading versus advance and transfer



- **Acceleration :** These tests determine speed and reach along the projected approach path versus elapsed time for a series of acceleration/deceleration runs using various engine set-ups



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Good Luck !!!