Aalto University
School of Engineering

MEC-E2004 Ship Dynamics (L)

Mid term assessment and course revision

Exam Set up and Rules

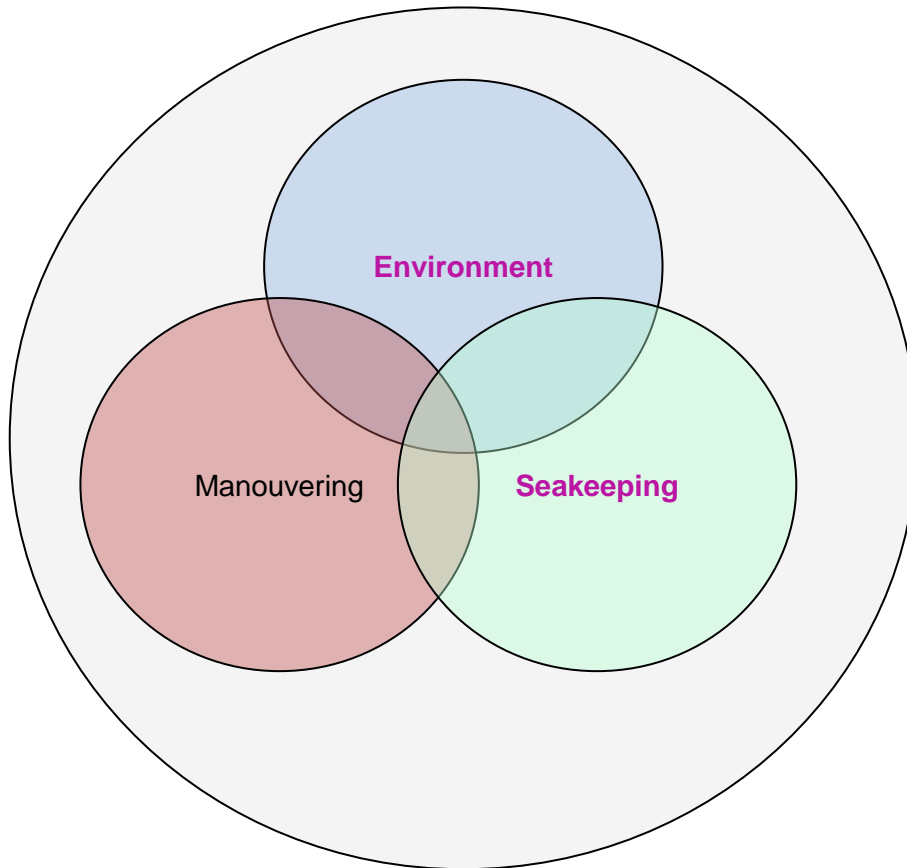❑Open book exam from 11:00 - 14 :00 hrs on 03.04.2022

❑**The exam starts at 11:00 hrs AND NOT 11:15 hrs ! Please** make yourselves avaliable from 10:50 on the day so that I can answer any questions you may have before hand

❑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.

❑ You will be given the option to answer up to 6 questions

❑ Your answers in 5 questions are the ones that will count toward your exam mark.

Course Overview

Environment

Manouvering

Seakeeping

Design Framework

MISSION REQUIREMENTS
COST ESTIMATES
PROPORTIONS & PREL. POWERING
DAMAGED STABILITY
LINES & BODY PLAN
CAPACITIES TRIM & INTACT STABILITY
HYDRO-STATICS AND BON-JEANS
DETAIL DESIGN
LIGHTSHIP WEIGHT ESTIMATE
FLOODABLE LENGTH & FREEBOARD
POWERING
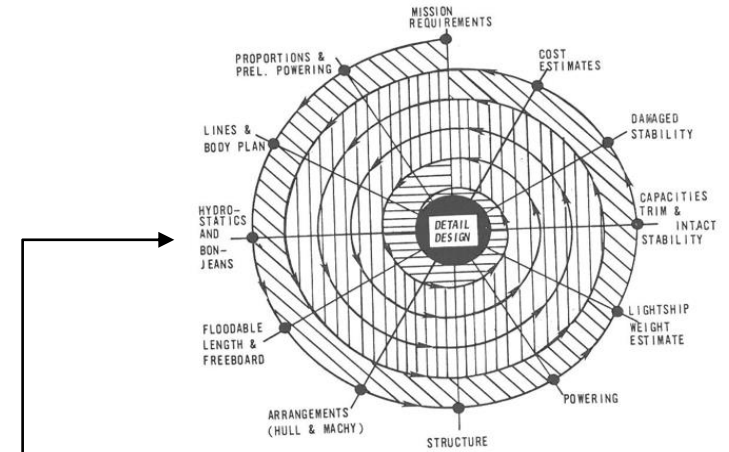ARRANGEMENTS (HULL & MACHY)
STRUCTURE
Fig. 1 Basic design spiral

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)*
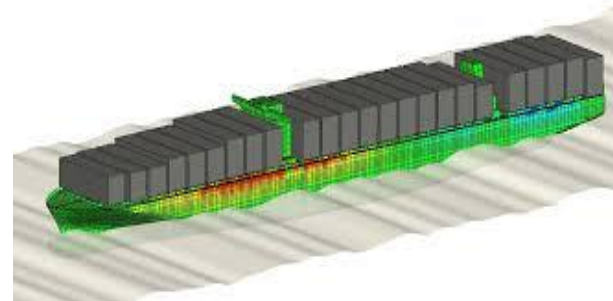
Motivation ... (cont.)

- A ship should be able to operate according to her mission in various environmental conditions

- The dynamics are affected by the hull form and the appedanges (propulsive equipment)

- A ship is a body moving in 6 rigid dof + N distortions

- The hull form interaction with water waves affects the seakeeping performance and loading / dynamics of the ship

- Appendages (propeller, rudder, pods, thrusters, etc.) imply forces and moments on the hull and they interact with the wave environment

- Moving cargo loads and onboard equipment (e.g. Heavy lift Cranes) may also affect motions and should be considered if/as applicable
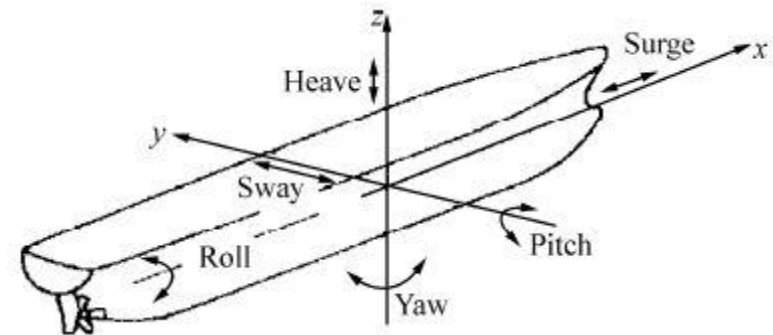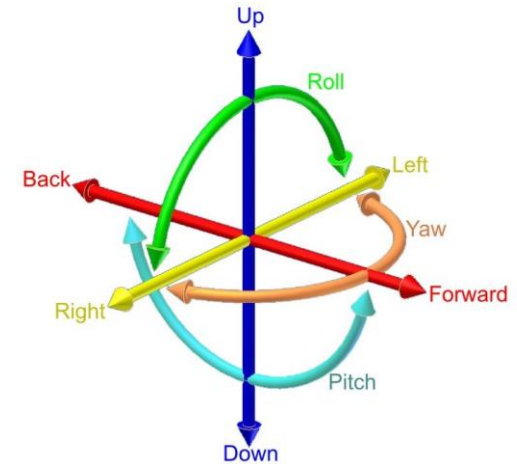
Manouevring – focus and basics

- 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)

- Manoeuvring requirements affect the equipment to be selected (e.g. rudders and pods, waterjets, fixed fins, jet thrusters, propellers, ducts and steering nozzles etc.)
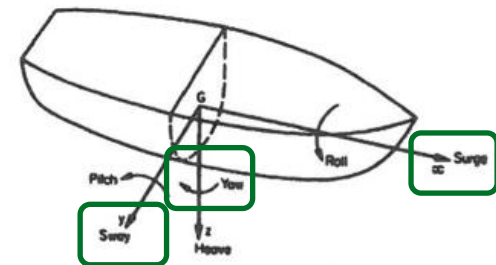
Rudder dynamics

- 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 :

  - ✓ **Method 1 :** Stability derivatives (direct representation of the hull forces asdependent to the rudder angle)

  - ✓ **Method 2 :** Modular model (kinematic of inflow into the rudder & modelling of effect of propeller flow on rudder action)
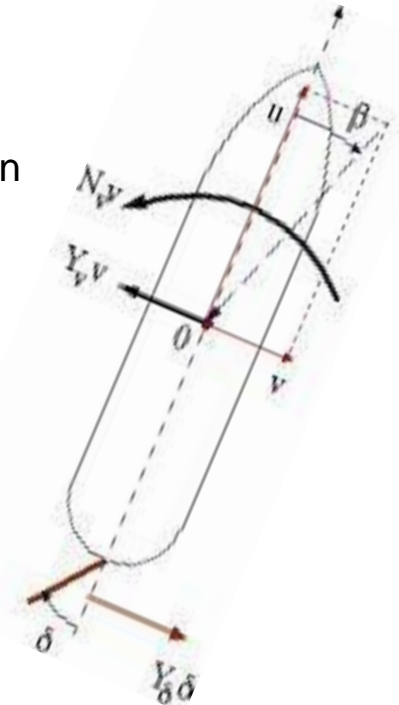
Manouevring vs Seakeeping models

➢ 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
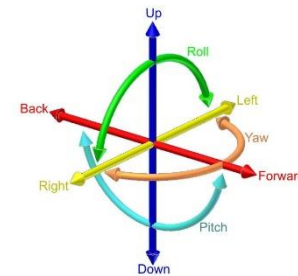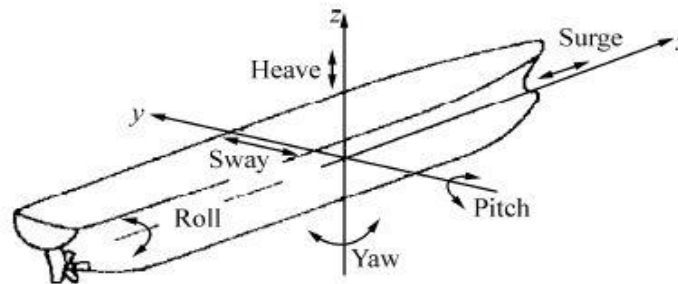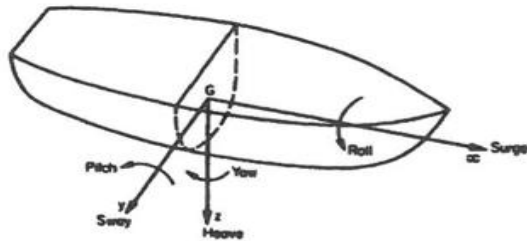
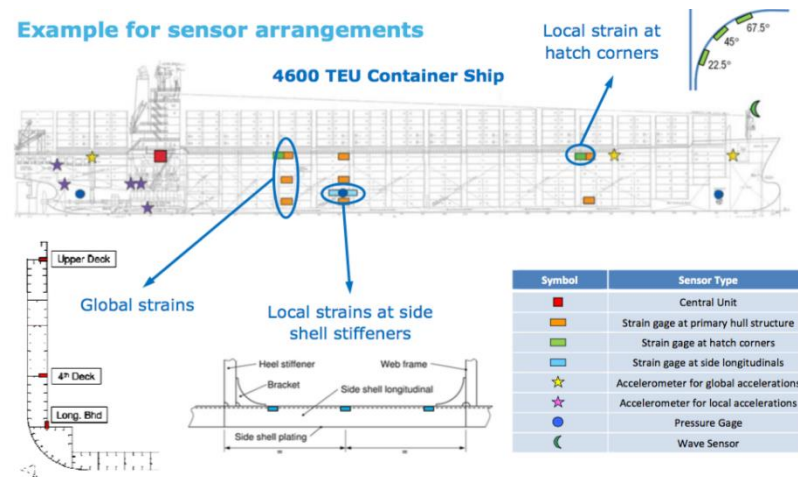# Engineering Tools – Full Scale Measurements

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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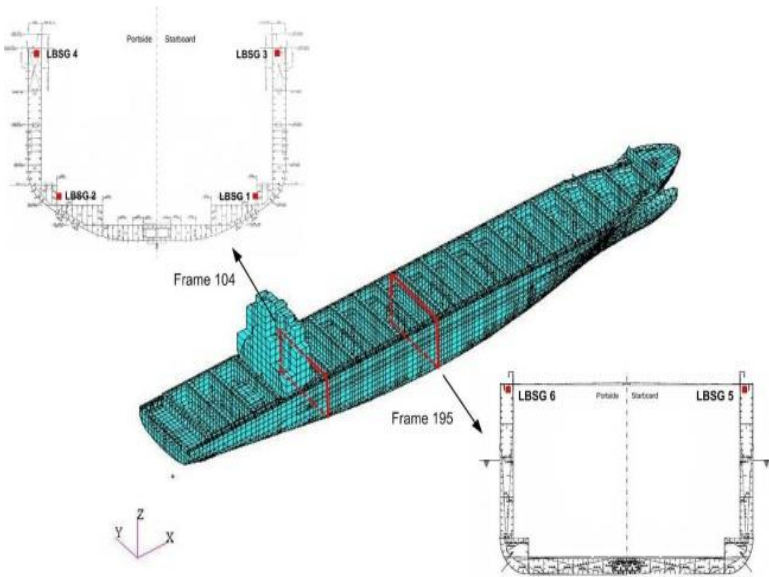
Hull form dynamics - Motion Reduction

- The key idea of motion reduction is to reduce the levels of kinetic energy lost in the system. In terms of dynamics this means that we should attempt by re-design the ship along the lines of 'conservative system' dynamics.

- Loss of kinetic energy is implied by wave making, friction, production of eddies and additional forces

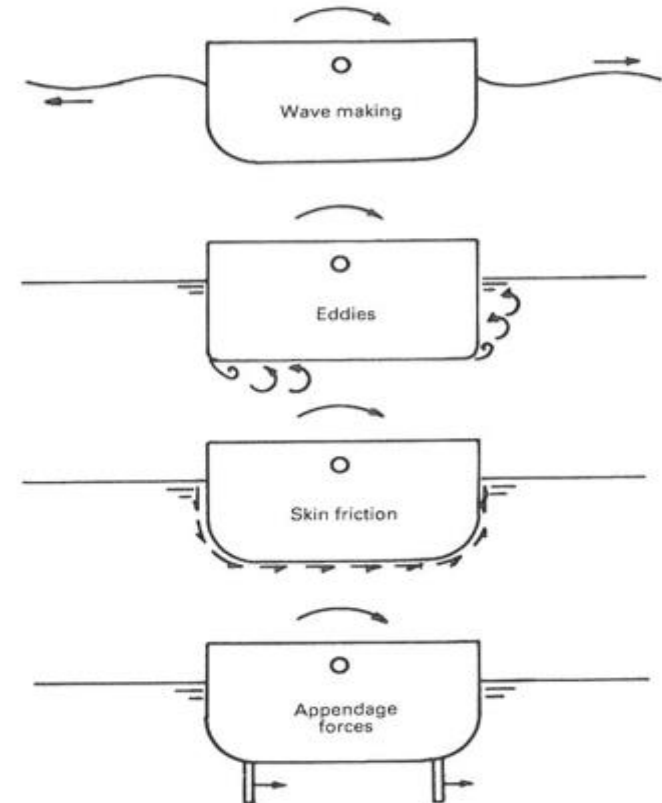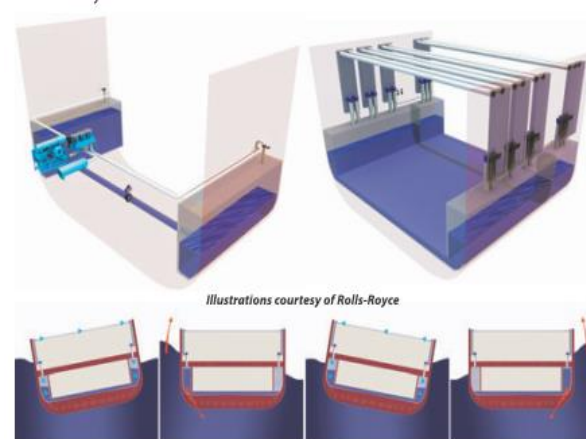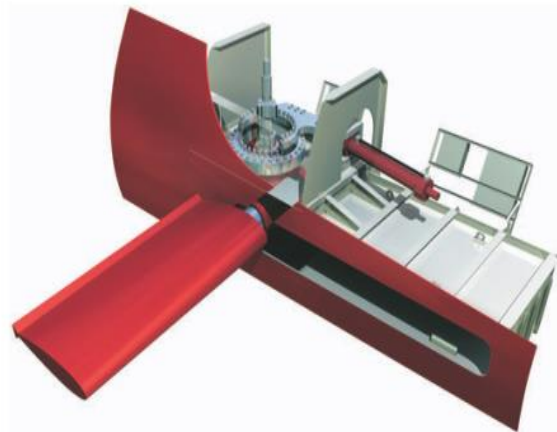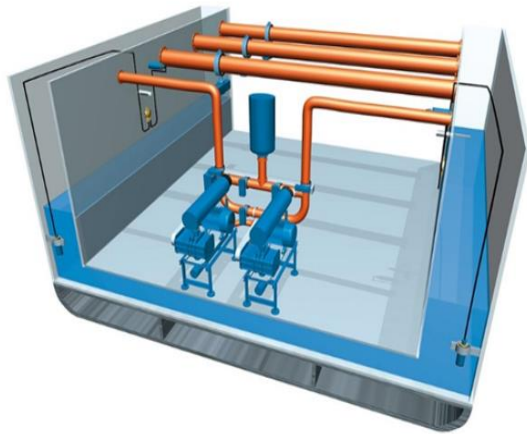- Motion reduction systems may also produce unwanted side effects, e.g. added resistance

Fig. 12.1 — Sources of roll damping.

Ship Stabilisation systems

Illustrations courtesy of Rolls-Royce

Wave Formation and classifications

- Waves can be classified according to their generation mechanism, regularity and intensity.

- 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

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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.)

Short Crested Wave

Long Crested Wave
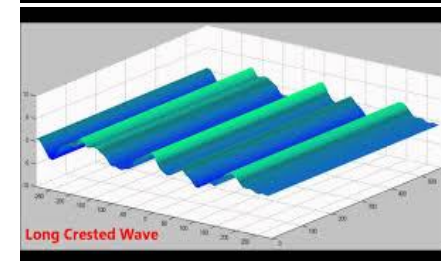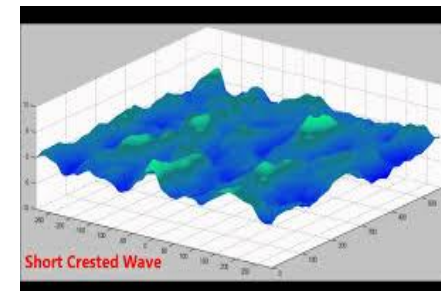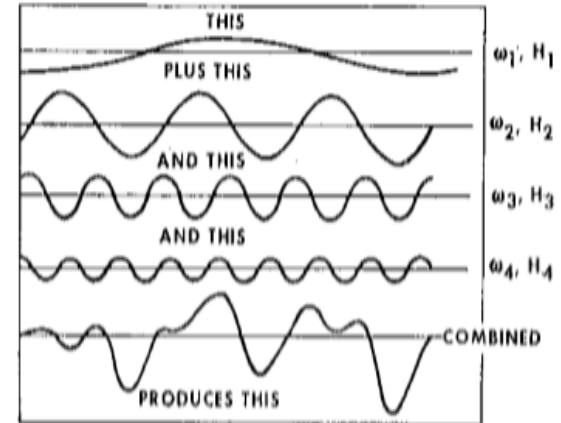
Linear wave - Potential Flow (Airy 1845)

- 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

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

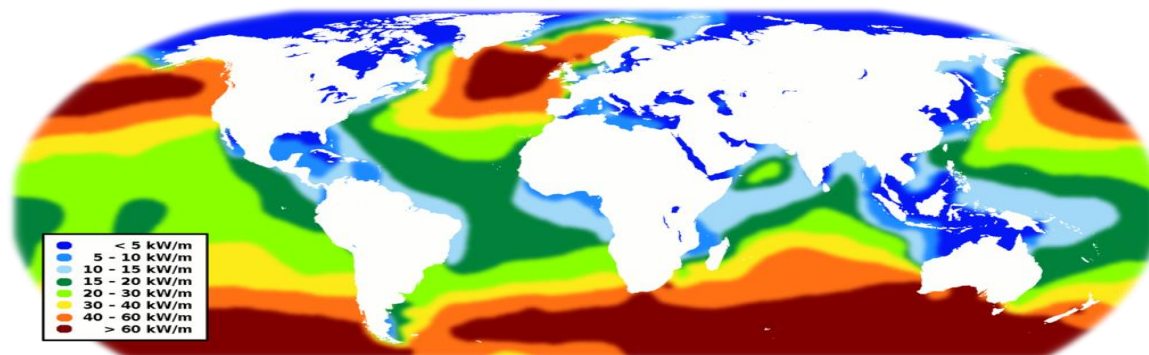$$\zeta(X,t) = a\cos(kX - \omega t + \alpha) \quad (1)$$
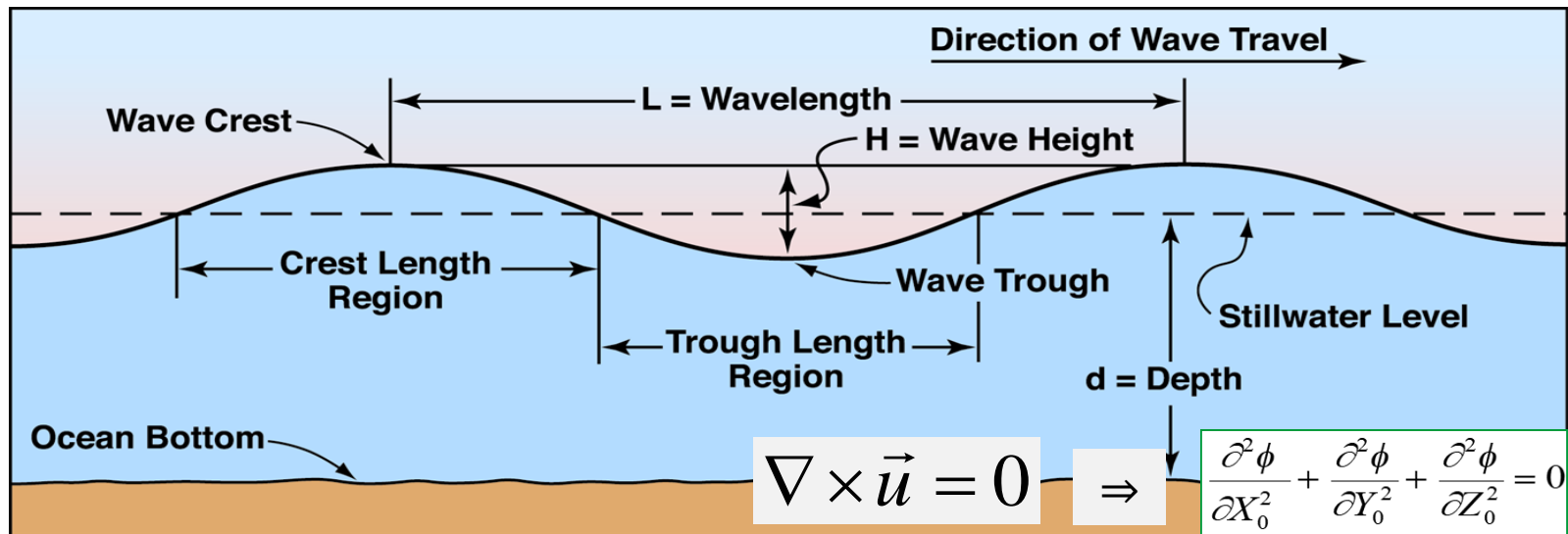
WAVE ENERGY AND POWER

Kinetic + Potential = Total Energy of Wave System

- Mathematical proof

- Kinetic: due to H_2O particle velocity

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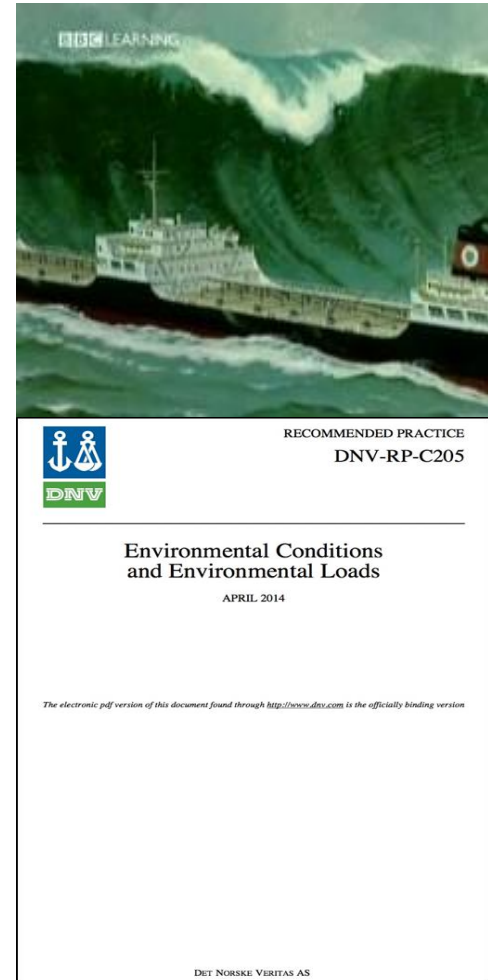

World map showing wave energy flux in kW per meter wave front

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.

BBC LEARNING

RECOMMENDED PRACTICE
DNV-RP-C205

Environmental Conditions and Environmental Loads

APRIL 2014

The electronic pdf version of this document found through http://www.dnv.com is the officially binding version

DET NORSKE VERITAS AS

# **Deviations from Linear Theory** – Airy vs Stokes waves

Comparison of second-order Stokes' NL wave profile with linear profile :
Higher order waves are more peaked at the crest, flatter at the trough and with distribution slightly skewed above SWL
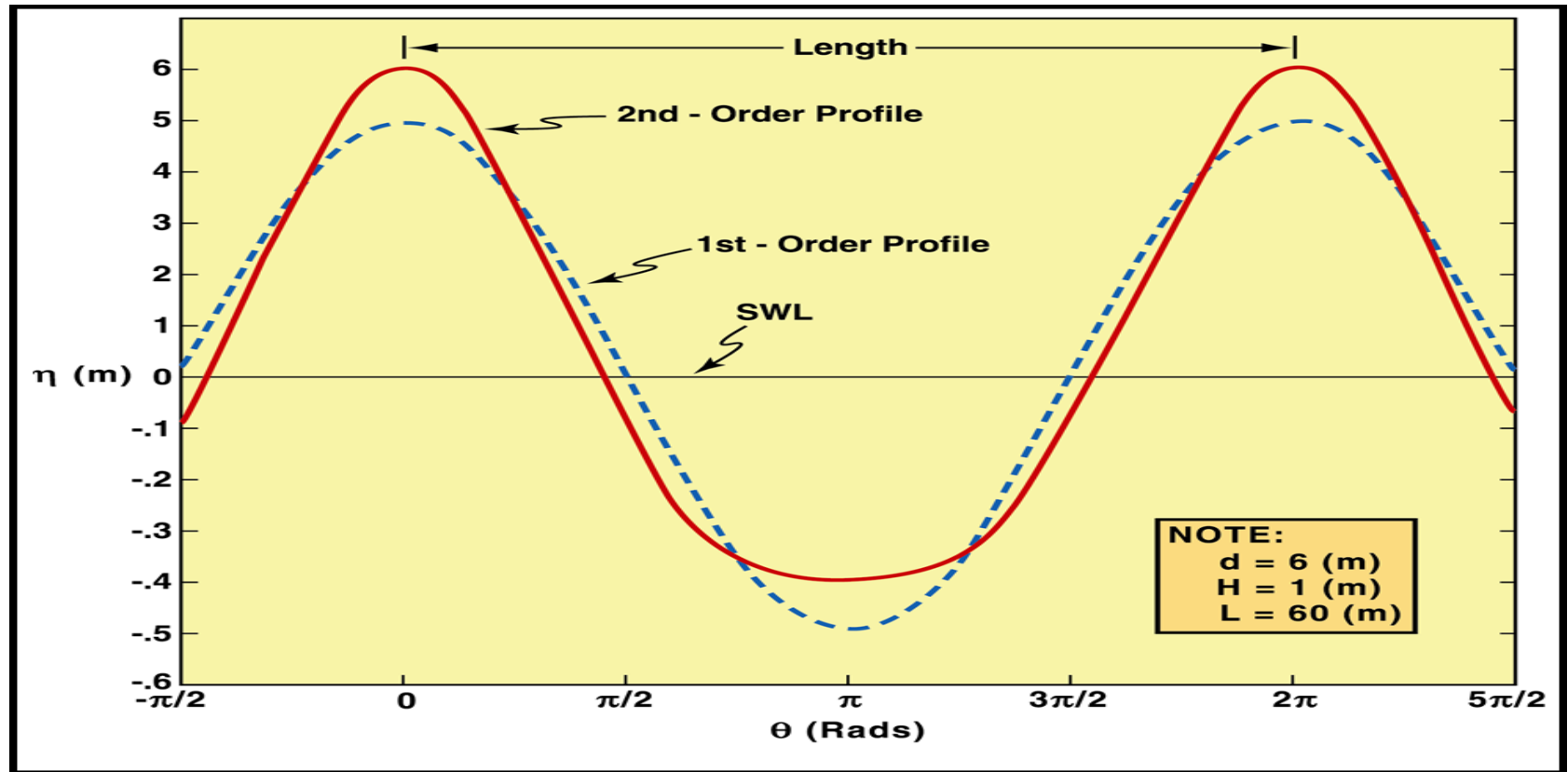
Freak Waves

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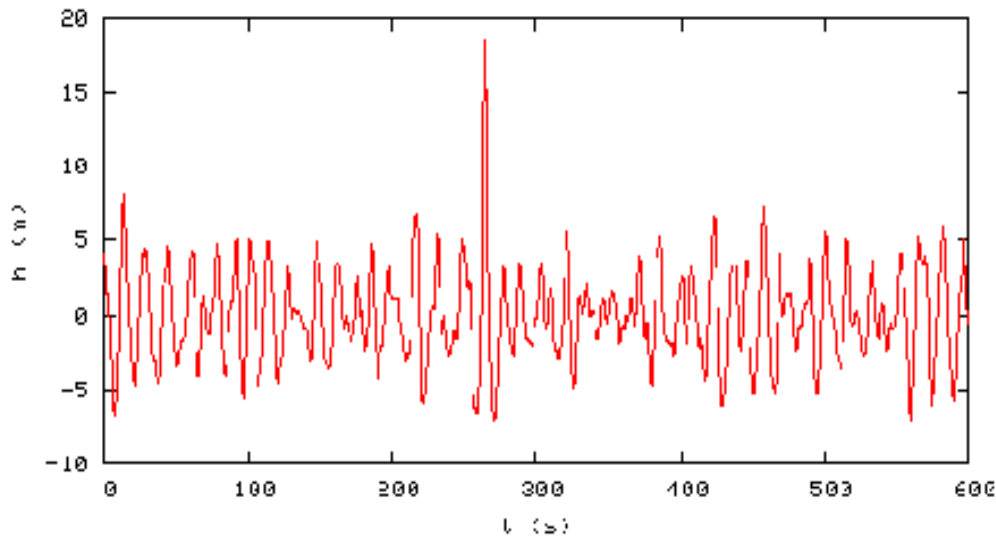
The Draupner wave, a single giant wave measured on New Year's Day 1995, finally confirmed the existence of freak waves, which had previously been considered near-mythical.

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

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The Irregular Wave

Height

h_{ih}

Amplitude

a_{ia}

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

T_{iT}

Period

Measured between zero down-crossings

t
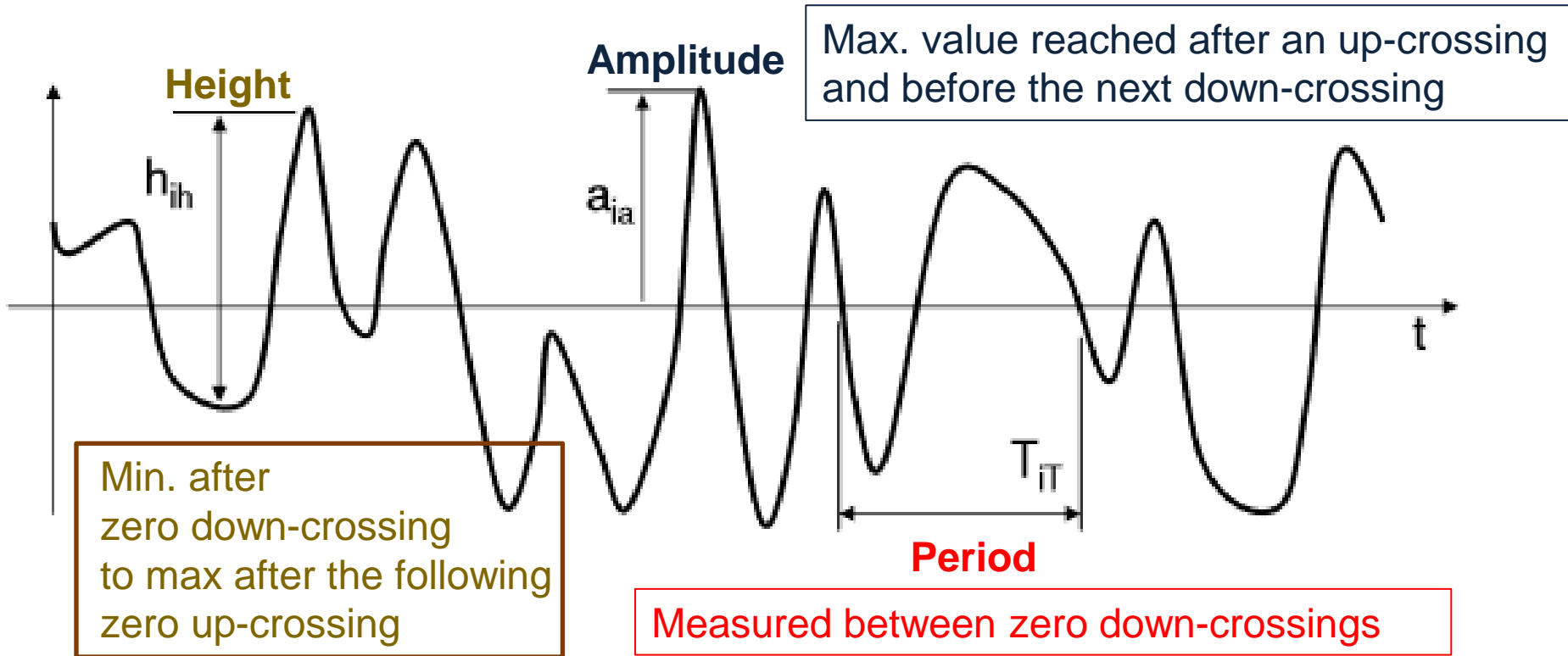
Statistics on Sea States

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

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

- The sea states are described in global wave statistics

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

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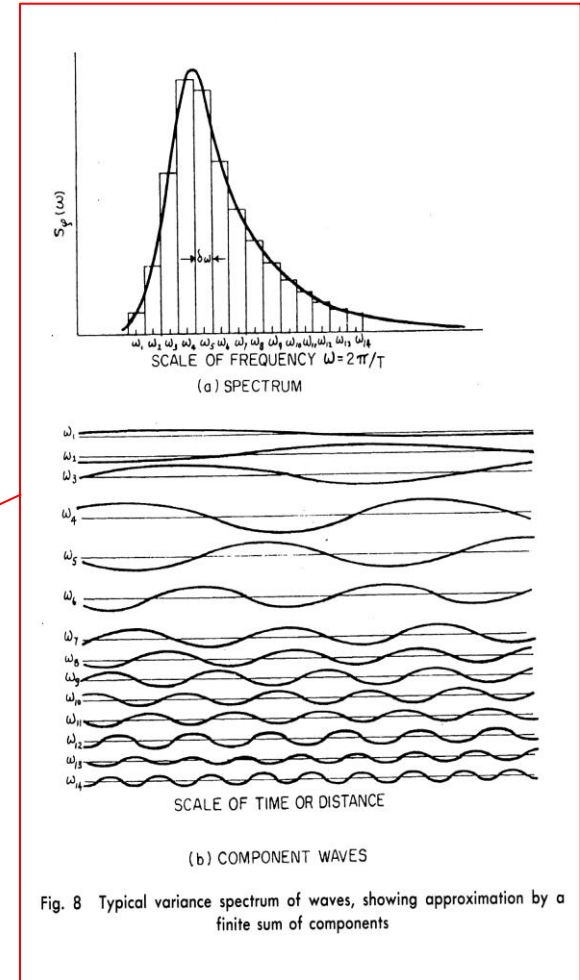
Fig. 8 Typical variance spectrum of waves, showing approximation by a finite sum of components

Sea spectra

The ISSC wave spectrum is defined as:

$$S_w(\omega) = 0.11 \left(\frac{2\pi}{T_z} \right)^4 \frac{H_{1/3}^2}{\omega^5} e^{-\frac{0.44}{\omega^4} \left(\frac{2\pi}{T_z} \right)^4}$$
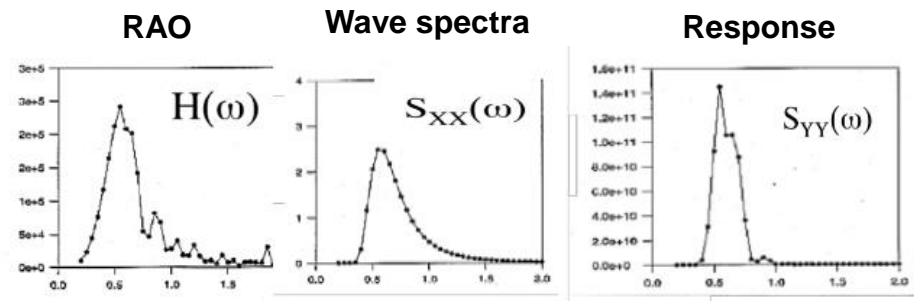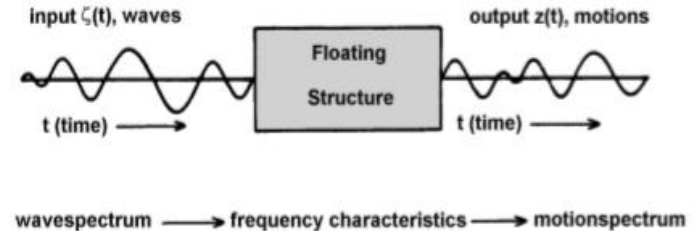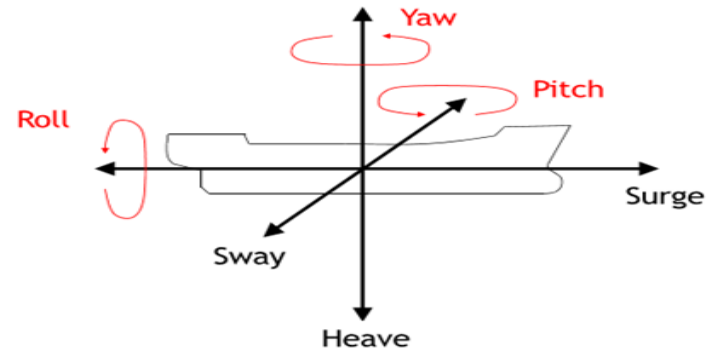
For $Tz = 7s$ and $H1/3 = 2.6$m the RAO of the bending moment of the ship is given by frequency and a corresponding RAO vector [ton^2/m^2]:

$$W_{RAO} = \left\{ \begin{array}{ccccc} 0.3 & 0.4 & 0.5 & 0.6 & 0.7 \end{array} \right\},$$

$$RAO = \left\{ \begin{array}{ccccc} 0 & 4\times10^9 & 2\times10^9 & 3\times10^9 & 0 \end{array} \right\}$$

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

input $\zeta(t)$, waves — output $z(t)$, motions

Floating Structure

t (time) → → t (time)

wavespectrum ⟶ frequency characteristics ⟶ motionspectrum

RAO — $H(\omega)$

Wave spectra — $S_{XX}(\omega)$

Response — $S_{YY}(\omega)$

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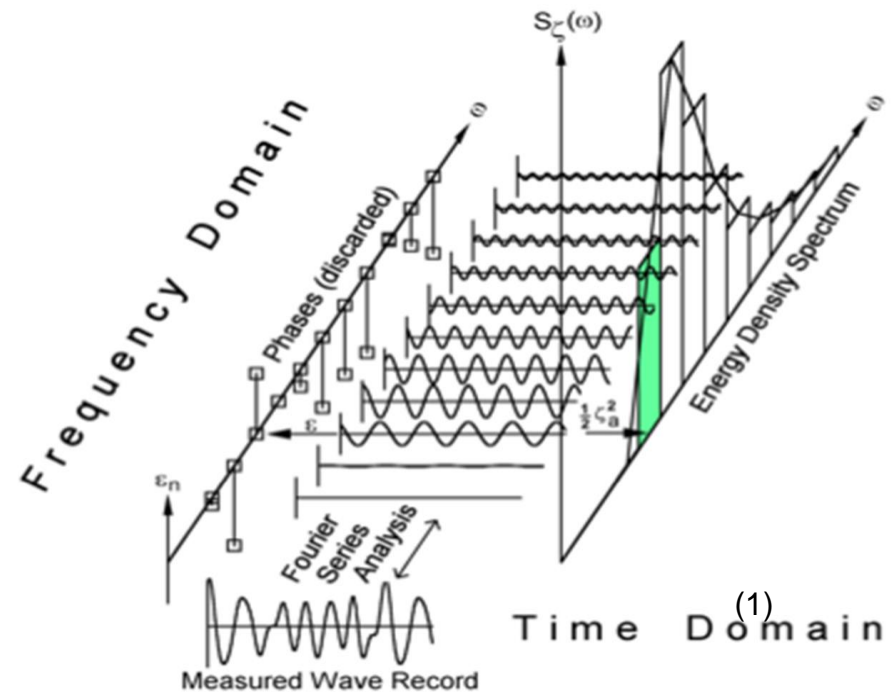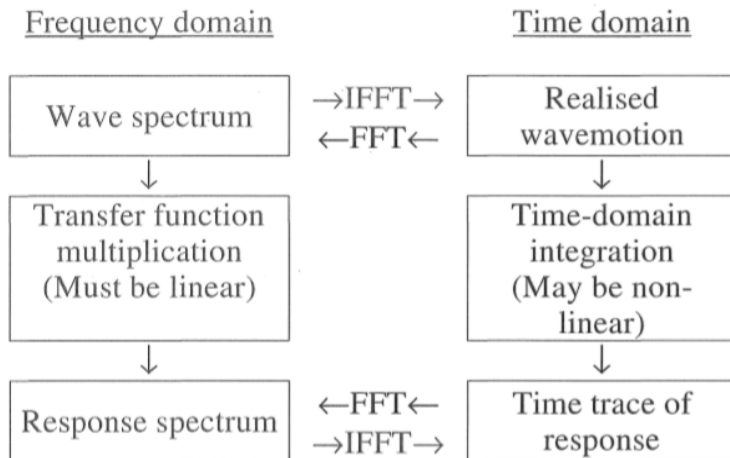
$$\mathscr{F}^{-1}\{G(f)\} = \int_{-\infty}^{\infty} G(f)e^{2\pi ift}\,df = g(t)$$

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

(1)

(2)

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.
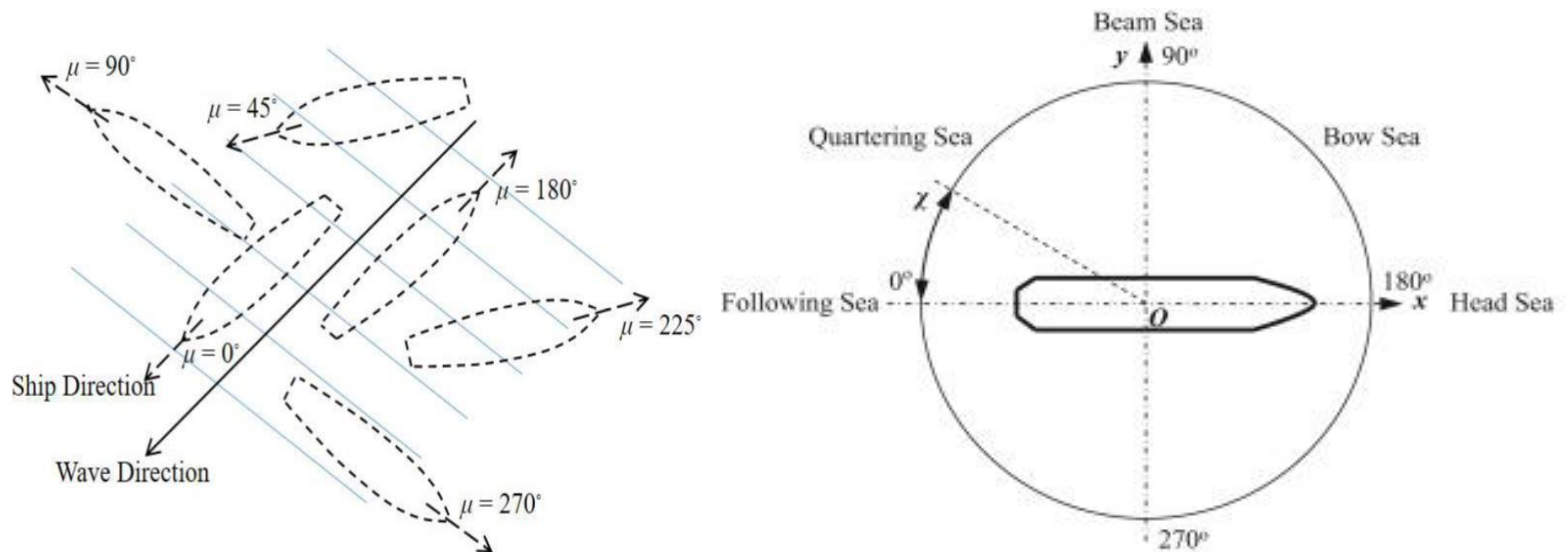
Dynamic response

- Definitions and practical meaning
  - ✓ Quasi static, dynamic, resonance responses
  - ✓ Overdamped, underdamped and critically damped systems
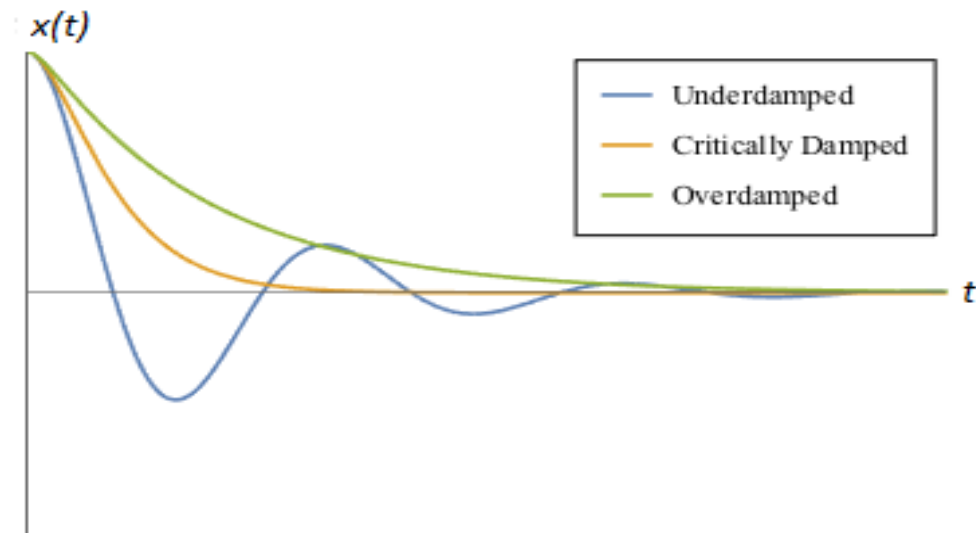
Quasi-Static Response

- **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

- Only stiffness affects the system response

$$S_x(\omega^*) = \frac{S_P^n(\omega^*)}{\left(1 - \omega^{*2}\right)^2 + \delta^2 \omega^{*2}} \rightarrow S_x \approx S_P^n$$
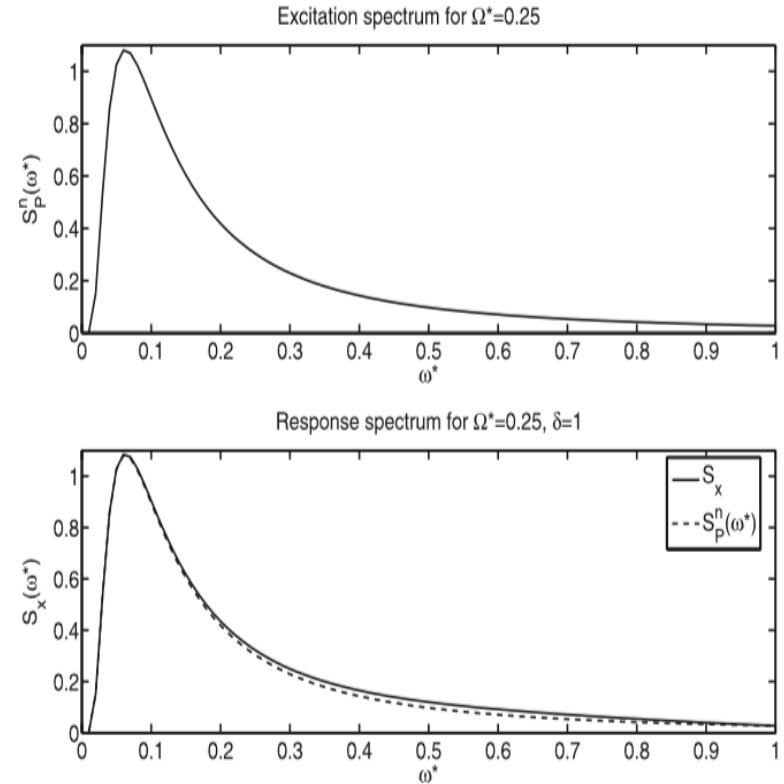
Figure 4.2. Quasi-static or sub-critical response.

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**

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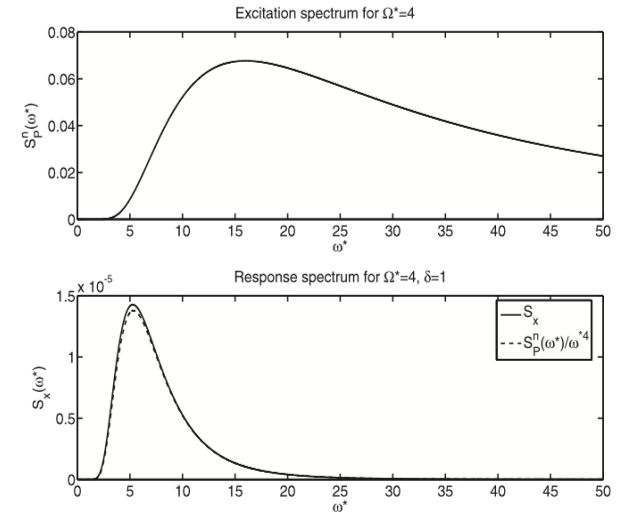

Figure 4.3. Dynamical or super-critical response.

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

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

Excitation spectrum for $\Omega^*=1$

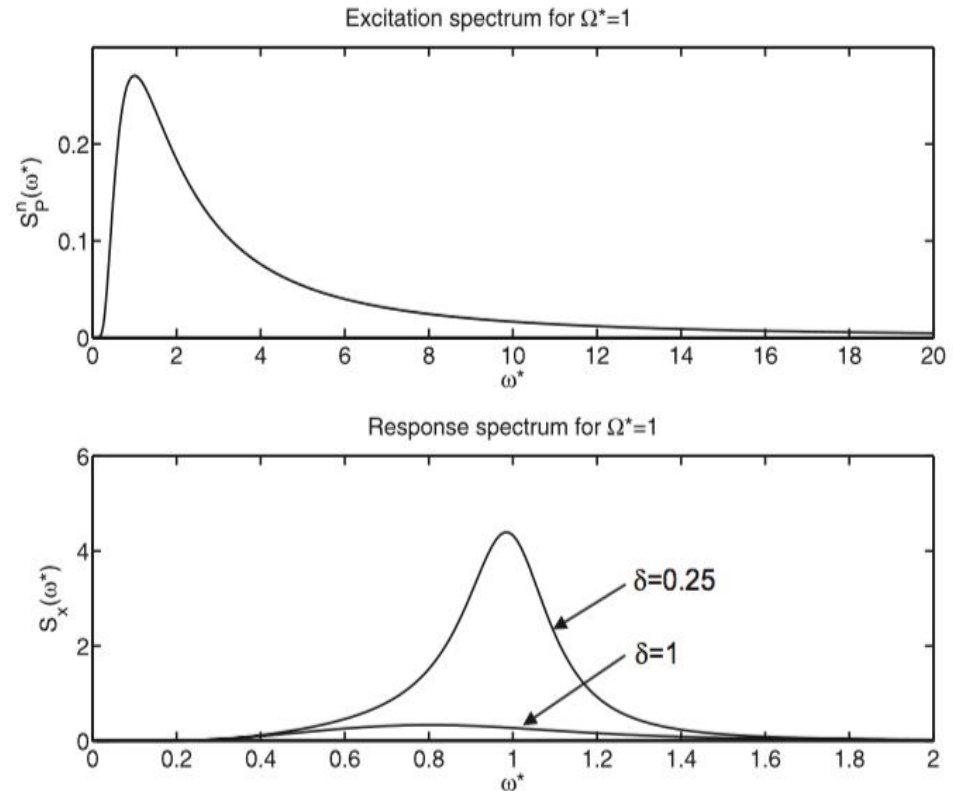Response spectrum for $\Omega^*=1$

$\delta=0.25$

$\delta=1$
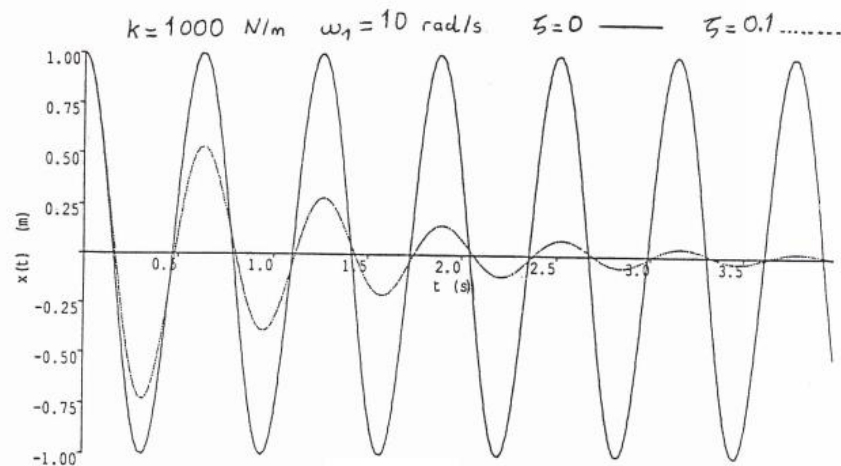
Figure 4.4. Resonant response.

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: $\delta = 2\pi\zeta$

Papers

https://mycourses.aalto.fi/mod/folder/view.php?id=985808&class=d-flex%20align-items-center

Pay attention to SD01 – SD04

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Good Luck !!!