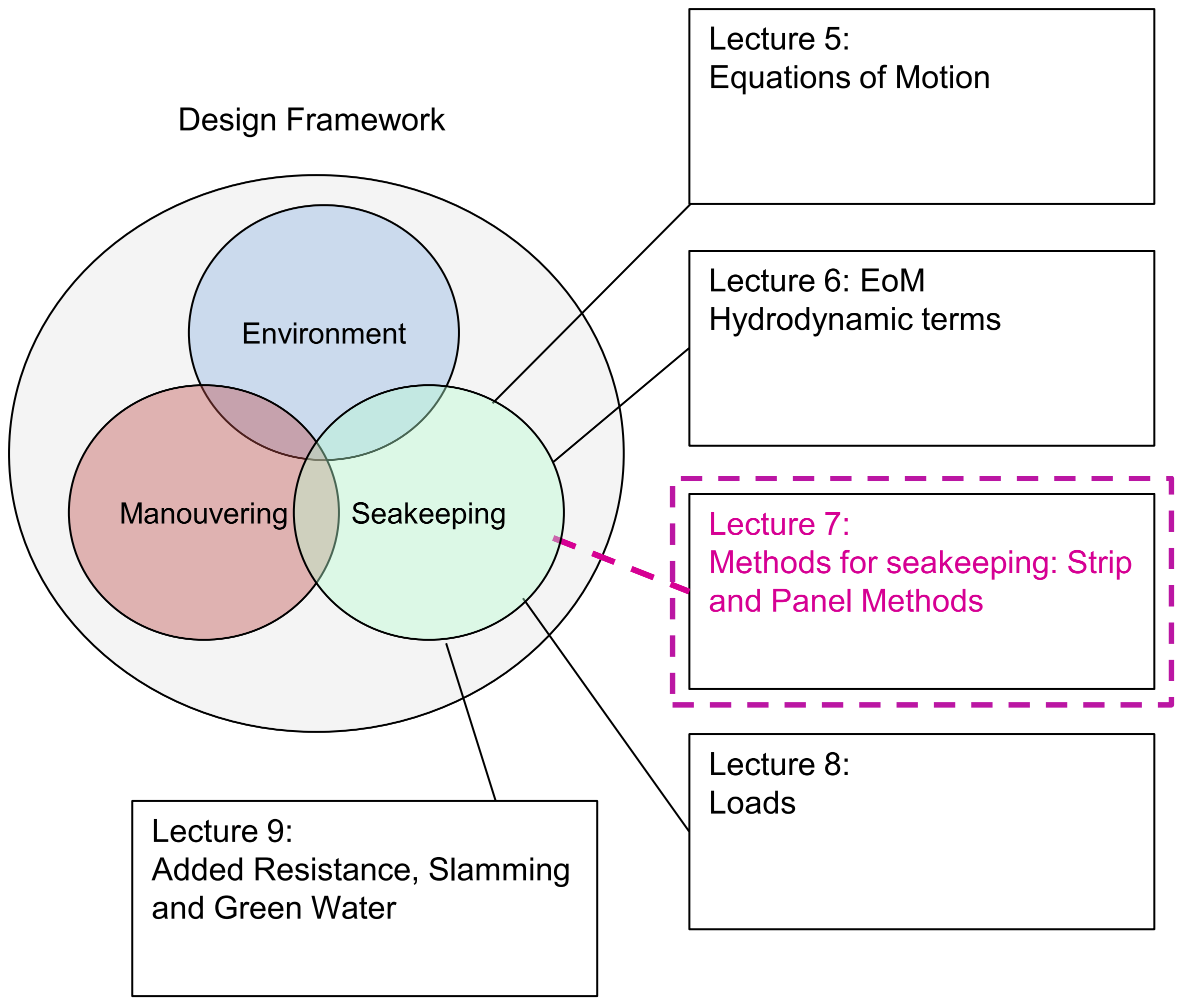
Aalto University
School of Engineering

MEC-E2004 Ship Dynamics (L)

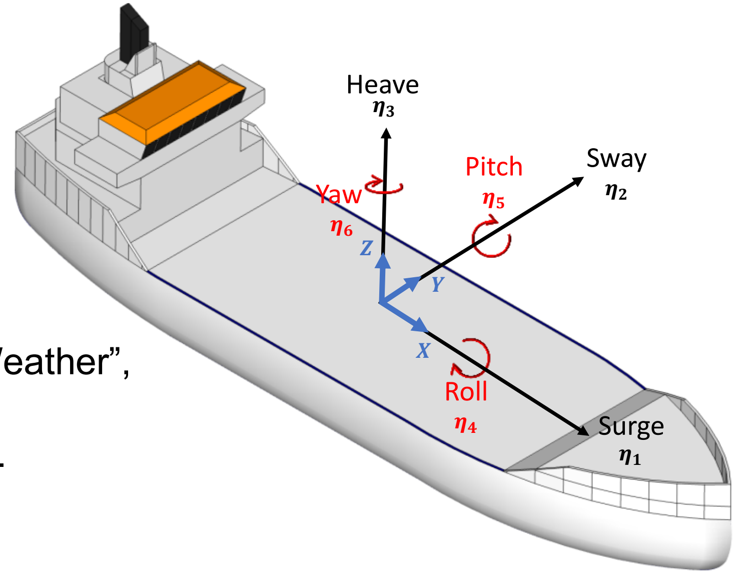
Lecture 7 –Seakeeping methods

Where is this lecture on the course?



Contents

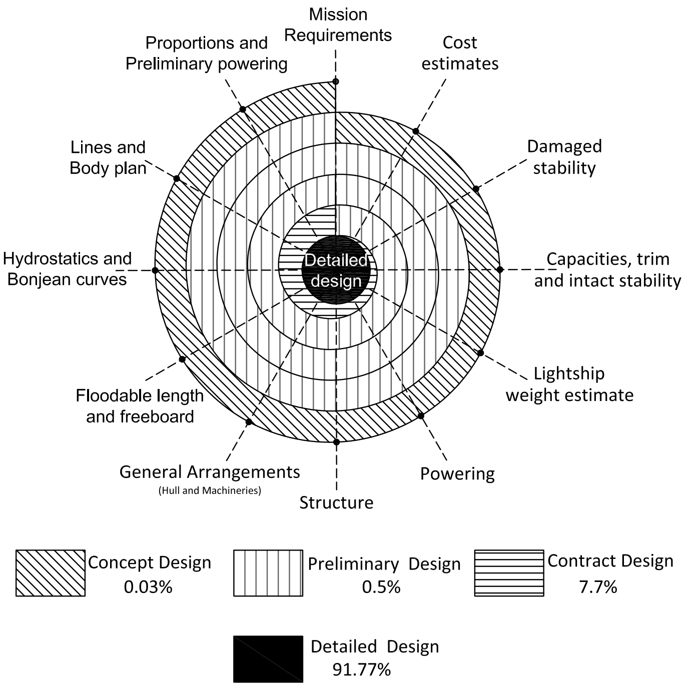
- **Aim :** Solution of the equations of motion by potential flow methods
  - Overview of existing methods
  - Focus on Strip theory
  - Simple reference to 3D panel methods
  - Overview on the importance of non linearities



- Literature
  - Journee, J.M.J., "Introduction to Ship Hydromechanics"
  - Lloyd, A.R.J.M, "Seakeeping – Ship Behavior in Rough Weather", John Wiley & Sons
  - Bertram, V., "Practical Ship Hydrodynamics", Butterworth-Heinemann, Ch. 4.
  - Matusiak, J., "Ship Dynamics", Aalto University
  - Lewis, E. V. Principles of Naval Architecture. Vol. 3, "Motions in waves and controllability"
  - Rawson, K. J., "Basic Ship Theory. Volume 2, Ship dynamics and design - ch.12 Seakeeping"

Motivation

- The analysis of ship motions is complex engineering task. We need to have appreciation of the key characteristics and limitations of alternative methods and their use in design.
- 2D and 3D linear approaches are useful at the preliminary ship design stage to help us reduce risks associated with seakeeping performance.
- Today seakeeping theory is implemented in various computer programmes and allows for the computation of various sea states, motion components etc. in 2D or 3D.
- There are several codes available with extensions to include non-linear corrections (e.g. strip theory, panel methods). Appreciation of their advantages and limitations from a hydrodynamic modelling perspective is useful.
- The validation of computational methods is imperative especially in those cases that design innovation impacts upon rule and regulations (i.e. cases where credible and validated calculations are important).

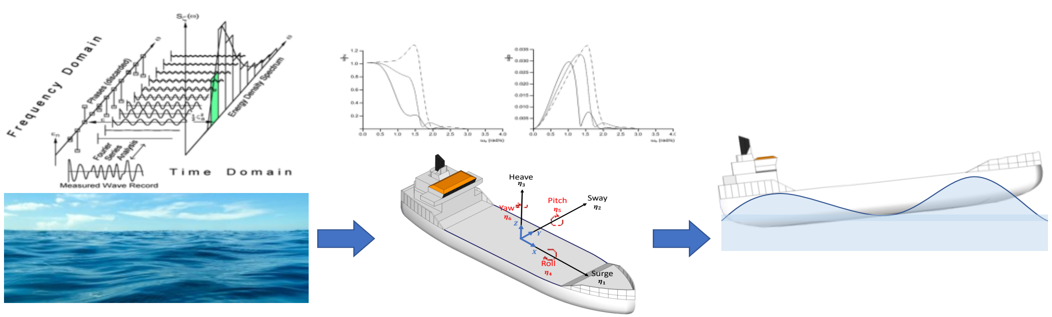


Assignment 4

- **Grades 1-3:**
  - Select a book-chapter related to determination of ship motions and loads and get acquainted with a tool to predict these
  - Form a seakeeping analysis model from your ship, discuss the simplifications made
  - Perform the computations for Response Amplitude Operators

- **Grades 4-5:**
  - Compute all motions (6) and global loads (bending moments and shear forces) for your ship for selected sea spectra (e.g. worst case spectra in North Atlantic). You can predict 3 hour maximums
  - Based on scientific literature, discuss the accuracy of your results

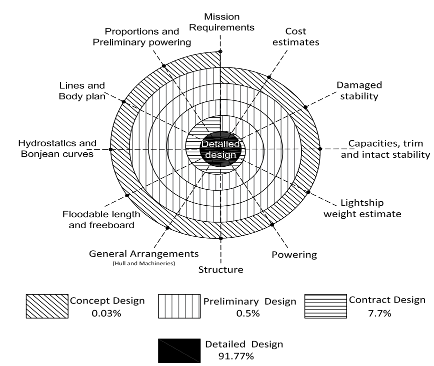
- **Report and discuss the work**



(a) Input
Waves and Winds

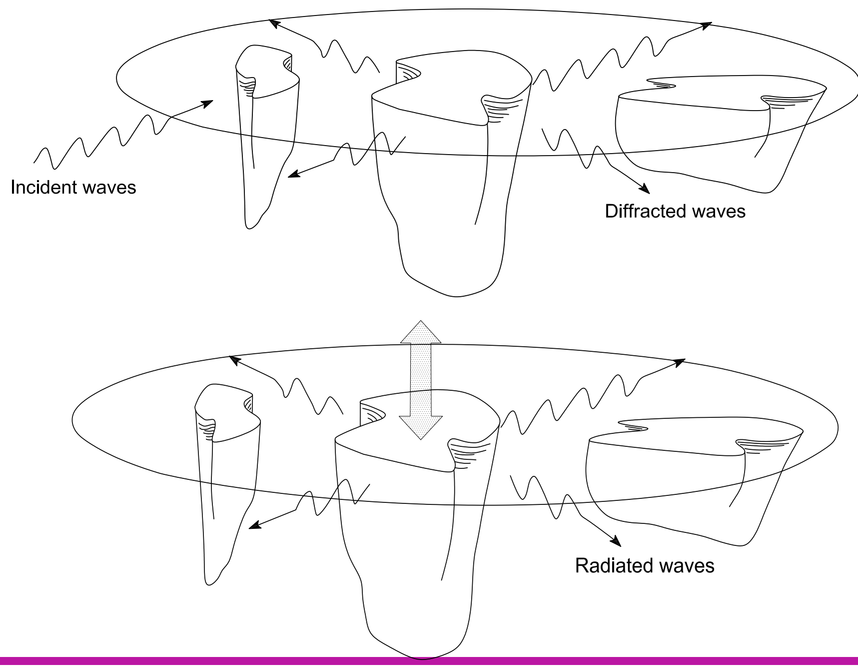
(b) System
RAOs

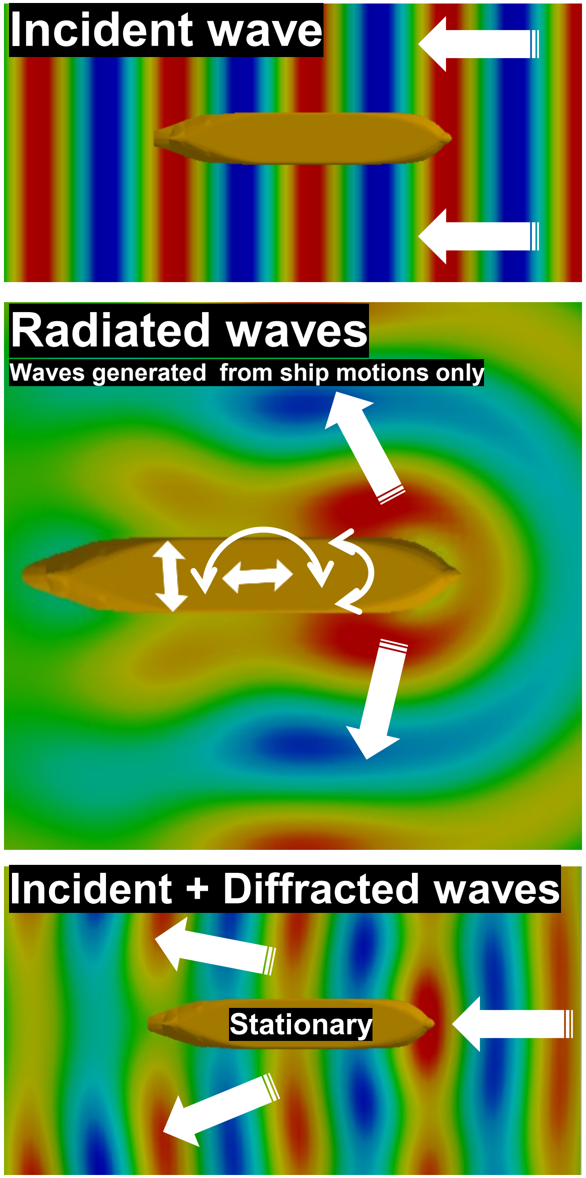
(c) Output
Motions and structural loads



Hydrodynamic Forces

- Three different types of forces, in addition to the restoring forces of hydrostatic origin:
  - **Incident wave or Froude-Krylov forces** (or moments)
  - **Diffraction forces** (or moments).
    - Excitation forces: $F_k^{excitation} = F_k^{Froude-Krylov} + F_k^{Diffraction}$
  - **Radiation forces** (or moments),





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

The perfectly linear seakeeping problem

- Waves are **progressive**: waves have translation speed (Celerity)
- Waves are **regular**: The spatial variation of the wave component is repetitive (constant wave length λ – wave number $k = \frac{2\pi}{\lambda}$)
- Waves are **harmonic**: The waveform repeats itself after a time interval T, and frequency $\omega = \frac{2\pi}{T}$
- Inviscid and incompressible fluid and irrotational flow.

Incompressible and irrotational flow	Undisturbed free surface $y = 0$	Impermeable seabed
$\nabla^2 \Phi = 0$	$\frac{\partial^2 \Phi}{\partial t^2} + \frac{\partial \Phi}{\partial y} = 0$	$\frac{\partial \Phi}{\partial \eta} = 0$

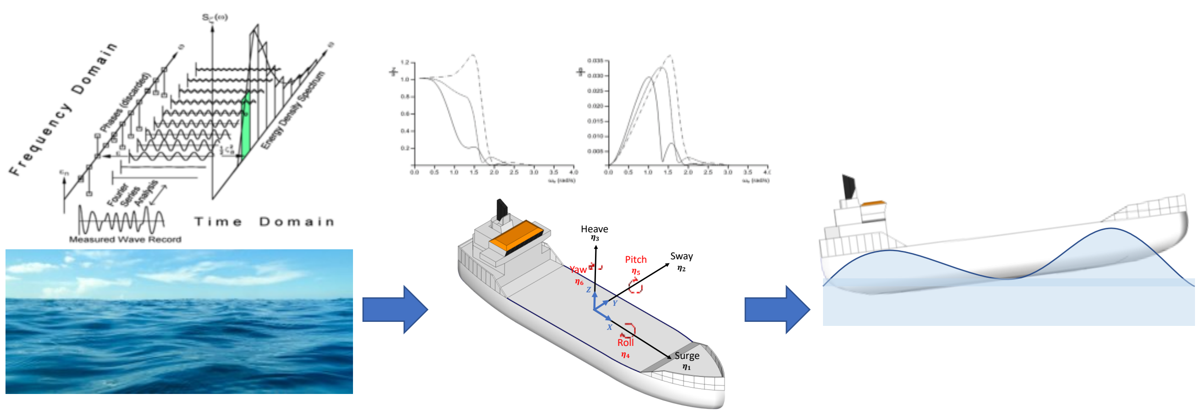
- $\Phi(x, y, z, t)$: Velocity potential function
- η: Normal to the free surface

The perfectly linear seakeeping problem

Assumptions

- 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

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



(a) Input
Waves and Winds

(b) System
RAOs

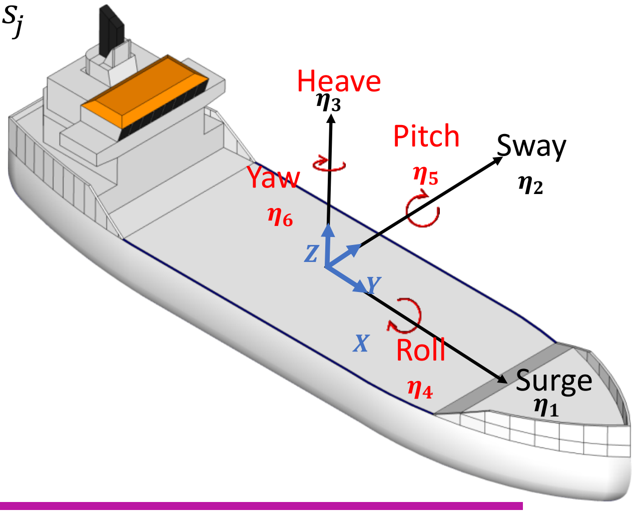
(c) Output
Motions and structural loads

Equations of Motion

- Rate of change of linear or angular momentum equal to the sum of the external forces and moments acting on the ship structure:
  - Translational : $\frac{dMS_j}{dt} = F_{excitation} + F_{radiation} + F_{hydrostatic} + F_{other}$
  - Rotational: $\frac{dI_{jj}S_j}{dt} = M_{excitation} + M_{radiation} + M_{hydrostatic} + M_{other}$

- Coupled motions
  - $\omega^2 M s_k = F_{kexcite} - \sum_{j=1}^{6}\left(-\omega^2 A_{kj} - i\omega B_{kj}\right)s_j - \sum_{j=3,4,5} C_{vj} s_j$

$k = 1$ surge, $k = 4$ roll
$k = 2$ sway, $k = 5$ pitch
$k = 3$ heave, $k = 6$ yaw



- J^{th} degree of freedom
- v correspond to roll, pitch and yaw.

Equation of Motions - genesis

- **Hydrostatic restoring** forces oblige to "Archimedes Principle" involve only the vertical plane motions:
  - Heave: $\omega^2 M s_3 = F_{3excite} - \sum_{j=1}^{6}(-\omega^2 A_{3j} - i\omega B_{3j})s_j - \sum_{j=3,4,5}^{6} C_{3j} s_j$
  - Roll : $\omega^2 I_{44} s_4 = F_{4excite} - \sum_{j=1}^{6}(-\omega^2 A_{4j} - i\omega B_{4j})s_j - \sum_{j=3,4,5}^{6} C_{4j} s_j$
  - Pitch: $\omega^2 I_{55} s_5 = F_{5excite} - \sum_{j=1}^{6}(-\omega^2 A_{5j} - i\omega B_{5j})s_j - \sum_{j=3,4,5}^{6} C_{5j} s_j$
- Other motions:
  - Surge: $\omega^2 M s_1 = F_{1excite} - \sum_{j=1}^{6}(-\omega^2 A_{1j} - i\omega B_{1j})s_j$
  - Sway: $\omega^2 M s_2 = F_{2excite} - \sum_{j=1}^{6}(-\omega^2 A_{2j} - i\omega B_{2j})s_j$
  - Yaw: $\omega^2 I_{66} s_6 = F_{6excite} - \sum_{j=1}^{6}(-\omega^2 A_{6j} - i\omega B_{6j})s_j$

- Solving these equations requires evaluation of the coefficients and the excitation amplitudes and phases.

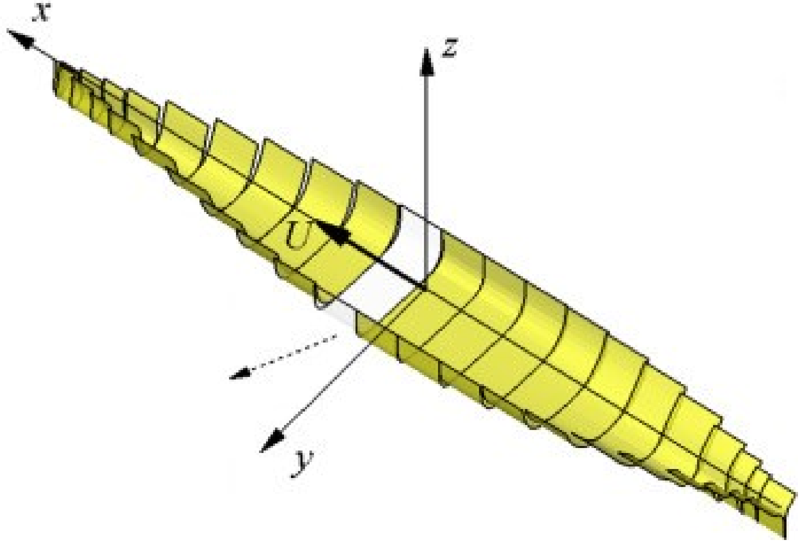
- In linear seakeeping analysis, two theories are used……

- J^{th} degree of freedom

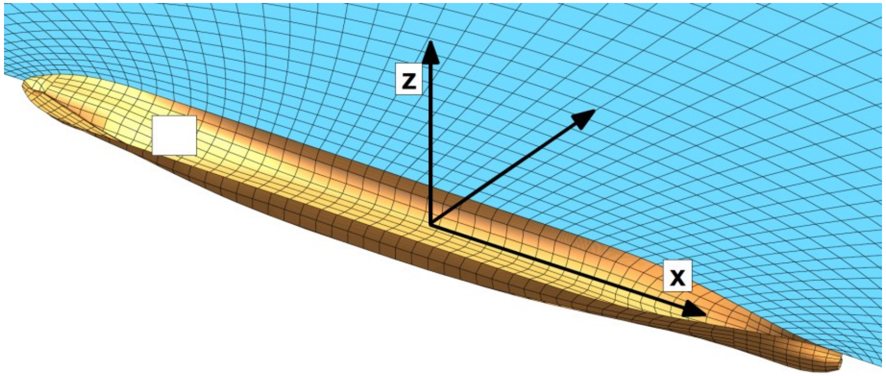
The evaluation of hydrodynamic forces

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

Strip theory



Panel method



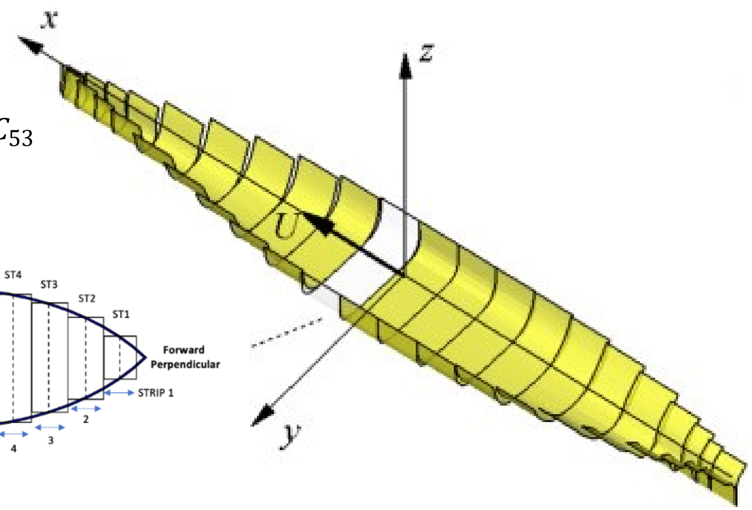
Reference : Tuck & Faltisen, Ship Motions and Sea Loads, Trans SNAME, 1970, 78:250-287

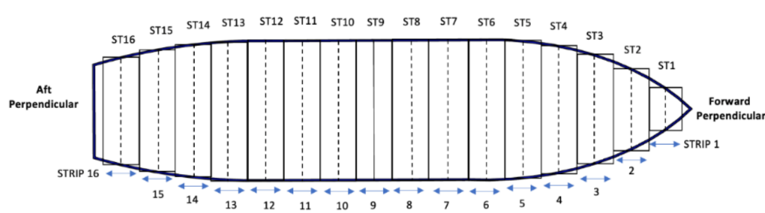
Strip theory – 2D analysis basics

- The rigid 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.
  - The sectional added inertia and damping coefficients are obtained for **heaving and coupled swaying - rolling slices**. Each strip has its local hydrodynamic properties (Added mass, Damping and Stiffness).
  - To obtain the added inertia and damping coefficients for the entire hull the sectional properties are integrated along the hull.
  - Summing the inertia force, the hydrodynamic force, and the hydrostatic resorting force, the equation of motion in the frequency domain can be re-written as:

$$\Sigma_{k=1}^{6}[-\omega_e^2(M_{jk}+A_{jk})+i\omega_e B_{jk}+C_{jk}]\zeta_k = F_{j,excite}$$

$F_{j,excite}$: Excitation force at each degree of freedom
M_{jk}: Generalized mass matrix
C_{jk} correspond to the restoring terms C_{33},C_{44},C_{55}, and C_{35}= C_{53}
A_{jk}/B_{jk}: Added mass and damping matrix





Strip Theory – assumptions (I)

- Potential flow analysis (irrotational, inviscid assumptions – velocity potential idealisation)

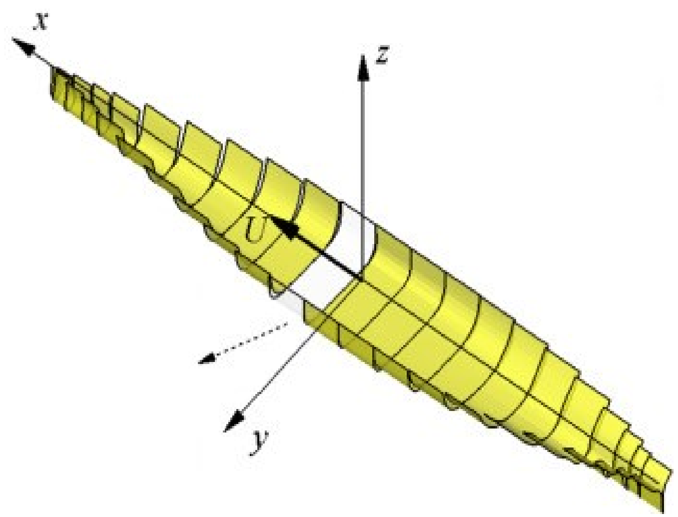
- Ship modelled as an infinitely long uniform rigid cylinder of arbitrary cross section.

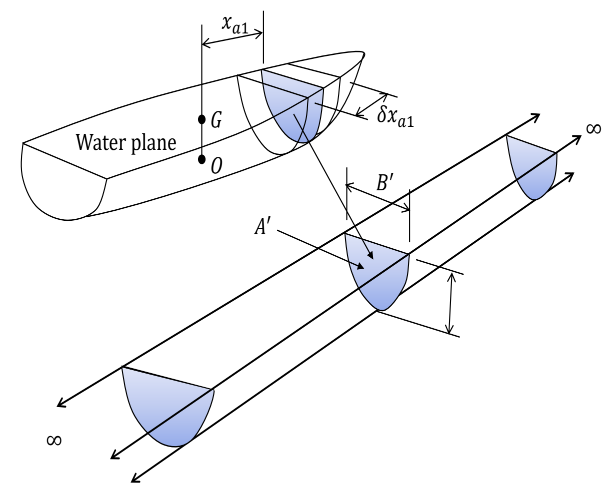
- Variation of the flow in the cross-directional plane >> Variation ship longitudinal direction

- No 3D effects and no 2D or 3D flow in hull proximities and no flow interactions between strips

- 2D coefficients for added mass are computed for each strip and then summed over the length following integration

- Longitudinal effects on the flow around the ship are ignored. Thus the theory is limited to small to moderate Froude numbers.





Strip theory – formulation of velocity potential

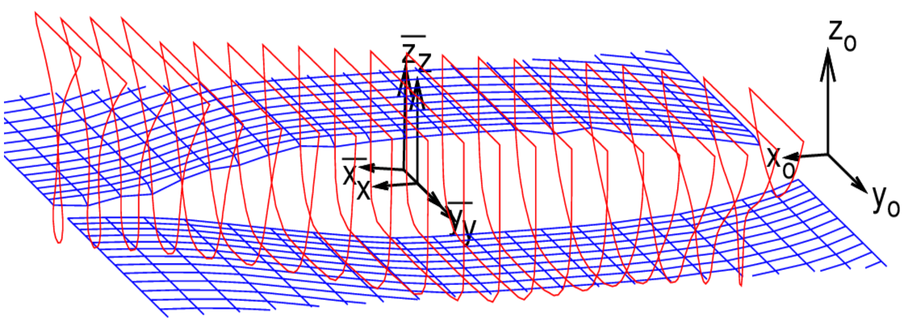
- Source or dipole distributions are used on the section contour. This method is preferred due to irregular frequencies leading to added mass and damping coefficients tending to infinite values

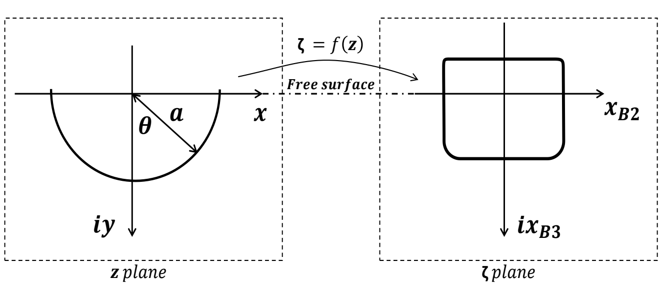
- A source + a dipole (in the case of roll) representing the oscillations of a **semi circular cross section**

- It is necessary to transform the idealised semi circle into a contour shape form that represents more realistically the hull form. Two basic methods :

  - ✓ Conformal mapping to Lewis hull form sections
  - ✓ Multiparameter mapping
  - ✓ Independently to the method used we always assume that the resultant section is perpendicular at free surface and centre line

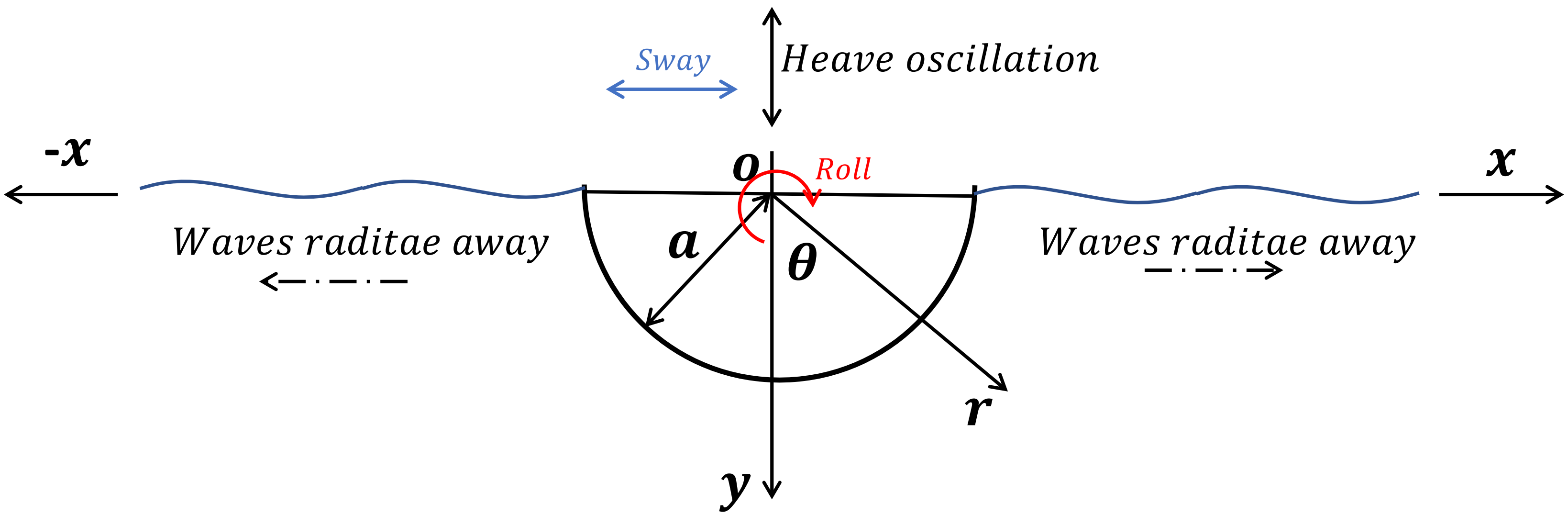
Conformal mapping idealisation



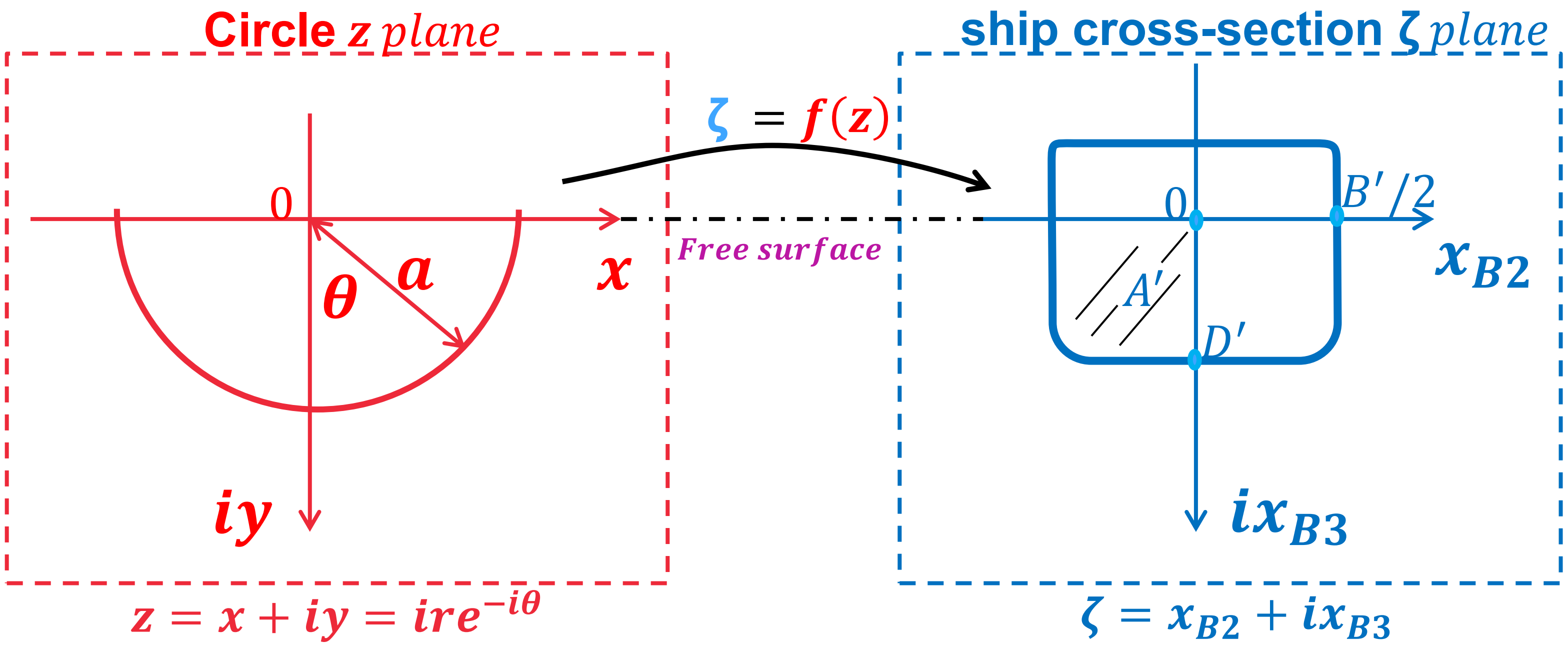


Conformal mapping basics

- Conformal mapping is used to define the local hydrodynamic coefficients
- The method is mathematically challenging and typically computers are used
- It begins by defining the properties of an infinitely long semicircular cylinder with radius a.
- The cylinder is assumed oscillating with small motion amplitudes and a transformation equation is used to extend the results into solution for realistic hull shapes.
- The cross-section must be symmetric, semi-submerged, and the hull needs to intersect the water surface perpendicularly



The principle of conformal transformation



Lewis forms equations

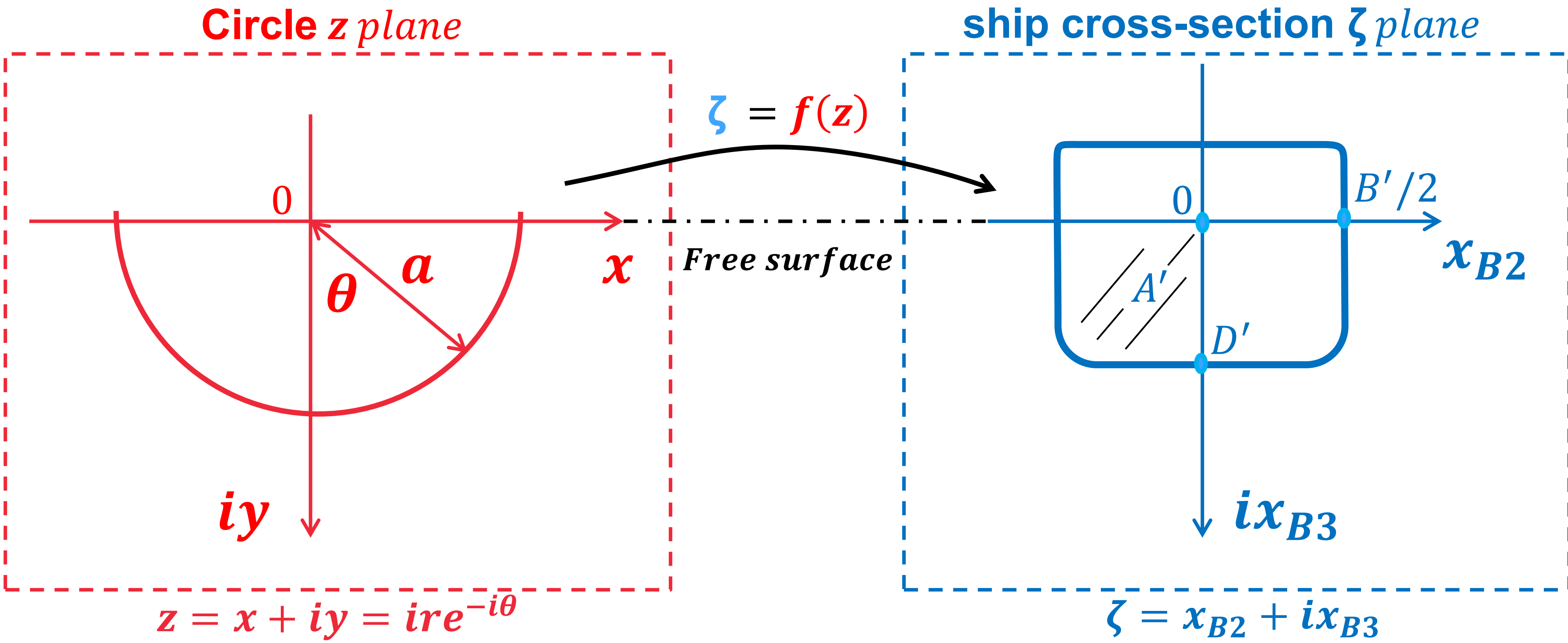
$$x_{B2} = a_0 a[(1 + a_1)\sin\theta - a_3 \sin(3\theta)]$$
$$x_{B3} = a_0 a[(1 - a_1)\cos\theta + a_3 \cos(3\theta)]$$

When $\theta = 0$ we obtain the bottom of the semicircle and the keel of the Lewis form:

$$x_{B2} = 0 \quad x_{B3} = D'$$

When $\theta = \pi/2$ → $x_{B2} = B'/2$ → $x_{B3} = 0$

Conformal transformation



Lewis transformation assumes symmetric cross-section around CL

$$\zeta = f(z) = a_0 a\left(\frac{z}{a} + \frac{a a_1}{z} + \frac{a^3 a_3}{z^3}\right)$$

$$H = \frac{B'}{D'}$$

$$\sigma = \frac{A'}{B'D'}$$

$$a_1 = (1 + a_3)\left(\frac{H-2}{H+2}\right)$$

$$a_3 = \frac{3 - C + \sqrt{9 - 2C}}{C}$$

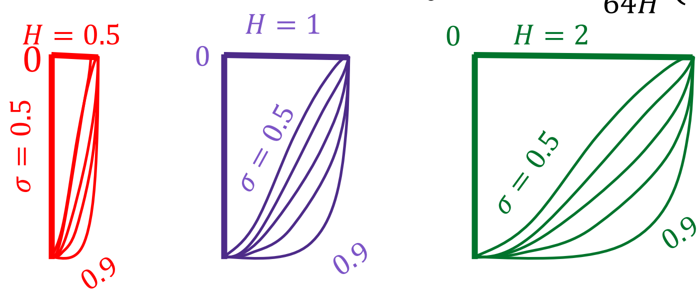
$$C = 3 + \frac{4\sigma}{\pi} + \left(1 - \frac{4\sigma}{\pi}\right)\left(\frac{H-2}{H+2}\right)^2$$

a_0 is a scale factor

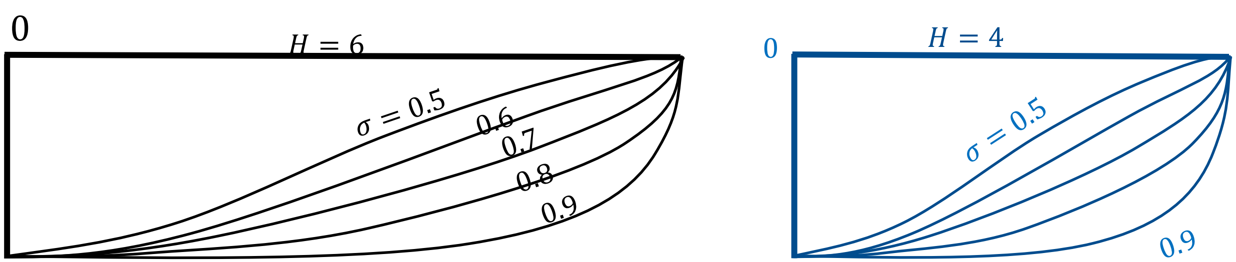
$a_1, a_3, a_5, \dots$ coefficients describe one side of the ship

Lewis hull section - limitations

- ❑ No limits for the H ratios
- ❑ Section area coefficient σ is valid only for $\sigma \leq \frac{\pi}{64H}\left(H^2 + 20H + 4\right)$

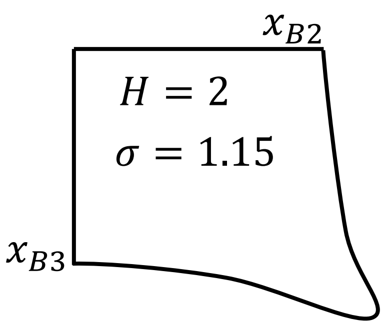


Realistic ship sections of different H ratios and section area coefficients σ

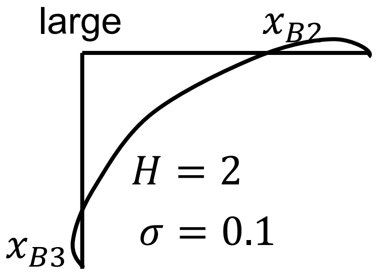


- ❑ Large σ will have unconventional shapes (flow separation will be dominant)
- ❑ Very small σ will render physically impossible shapes of Lewis forms

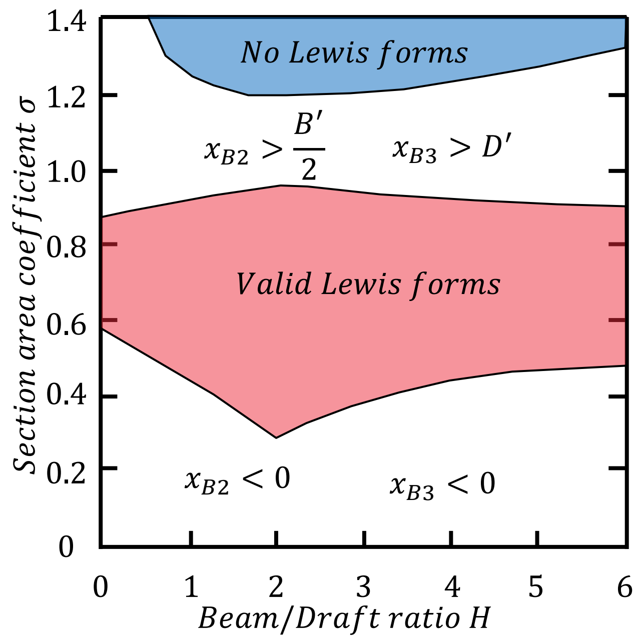
Lewis hull section – limitations

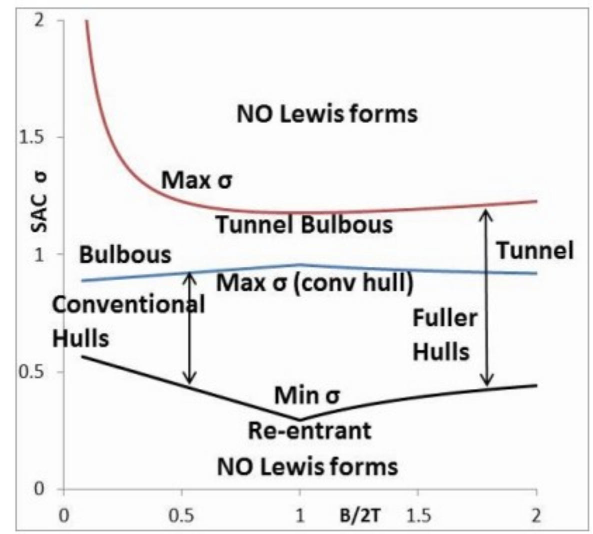


Area coefficient too large



Area coefficient too small





SAC $\sigma = S/BT$:	Sectional Area Coefficient
$\Lambda = B/2T$	Half breadth/ Draught ratio
S	Wetted area for half section

Multi-parameter mapping as alternative

- The cross section of most of the barges, the floating breakwaters and the floating pontoons is rectangular. Because of hard chine in the corners, the mapping of these sections has more difficulty than the common sections. In other words, the mapped section and the real section will not agree with each other.

- In such case instead of using conformal mapping on Lewis hull sections multi parameter transformation can be used. The method considers the 2nd moment of area based on defining points along section contours and can be used to obtain hull parameters using a least squares approximation.

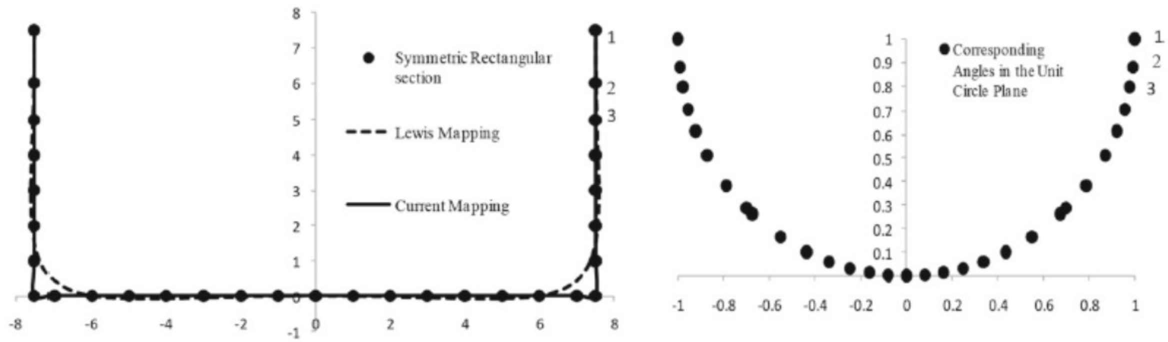
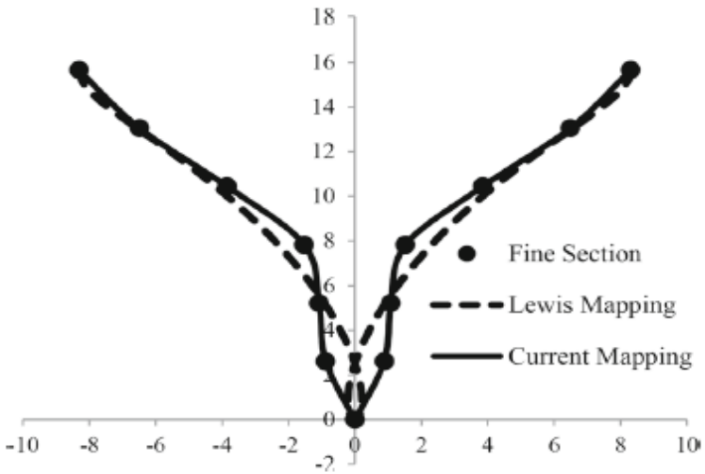
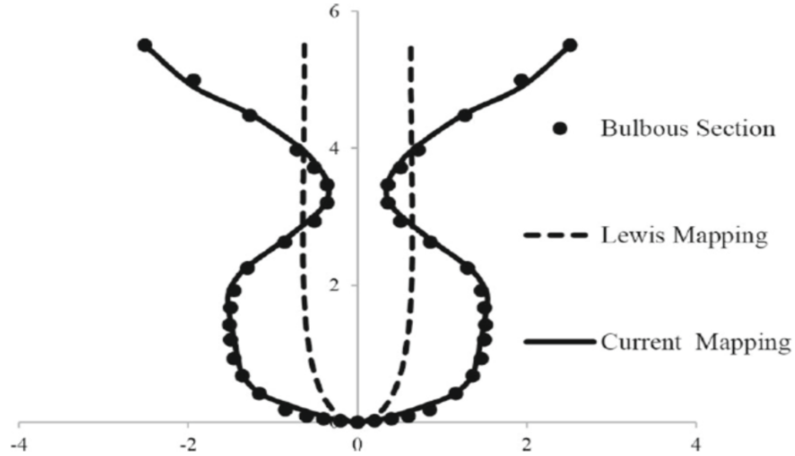


Illustration of a Symmetric rectangular section (left) and its corresponding angles in the transformed unit circle plane (right).

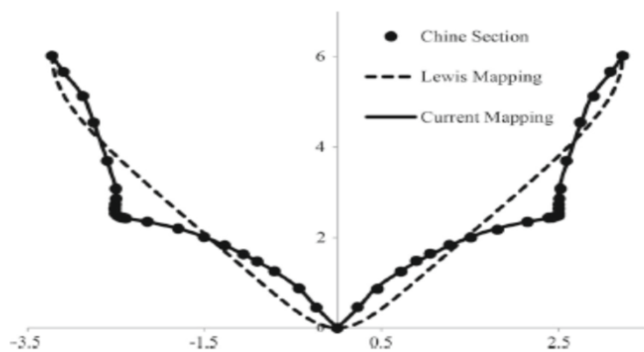
Lewis vs multiparameter mapping



Results of conformal mappings for the symmetric fine section.

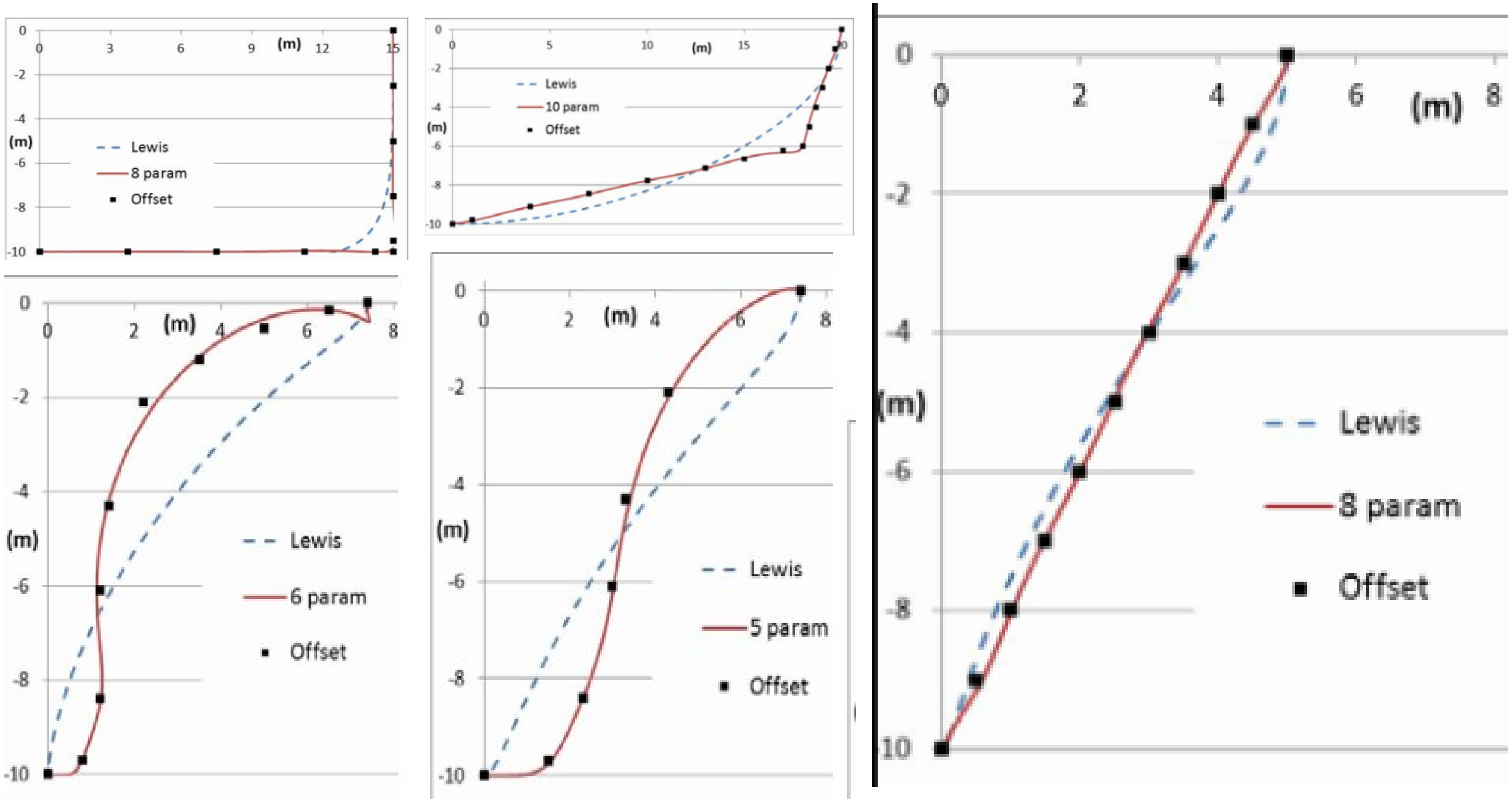


Results of conformal mappings for symmetric bulbous.



Results of conformal mappings for symmetric chine.

Lewis vs multiparameter mapping



Strip Theory – definition of added mass

Based on the Lewis method the sectional added mass coefficient:

$$a_{33} = K_2 K_4 A(x)$$

- ❑ K_2 is a non-dimensional coefficient to determine the mapping of the geometry into the flow around the cylinder ignoring the free surface:

$$K_2 = \frac{(1 + C_1)^2 + 3C_2^2}{1 - C_1^2 - 3C_2^2}$$

- ❑ K_4 is a non-dimensional frequency correction coefficient for the free surface:

$$K_4 = \begin{cases} \frac{-8}{\pi^2} ln(0.795(1 + \frac{2T}{B})\xi_0) & \text{for } \xi_0 < -\frac{1.3503}{\frac{T^{-0.9846}}{B} + 2.3567} + 0.5497 \\ 0.2367\xi_0^2 - 0.4944\xi_0 + 0.8547 + \frac{0.01}{\xi_0 + 0.0001} & \text{for } -\frac{1.3503}{\frac{T^{-0.9846}}{B} + 2.3567} + 0.5497 < \xi_0 < 1.388 \\ 0.4835 + \sqrt{-0.0484 + 0.0504\xi_0 - 0.001\xi_0^2} & \text{for } 1.388 < \xi_0 \leq 7.31 \\ 1 \quad \text{for } \xi_0 > 7.31 \end{cases}$$

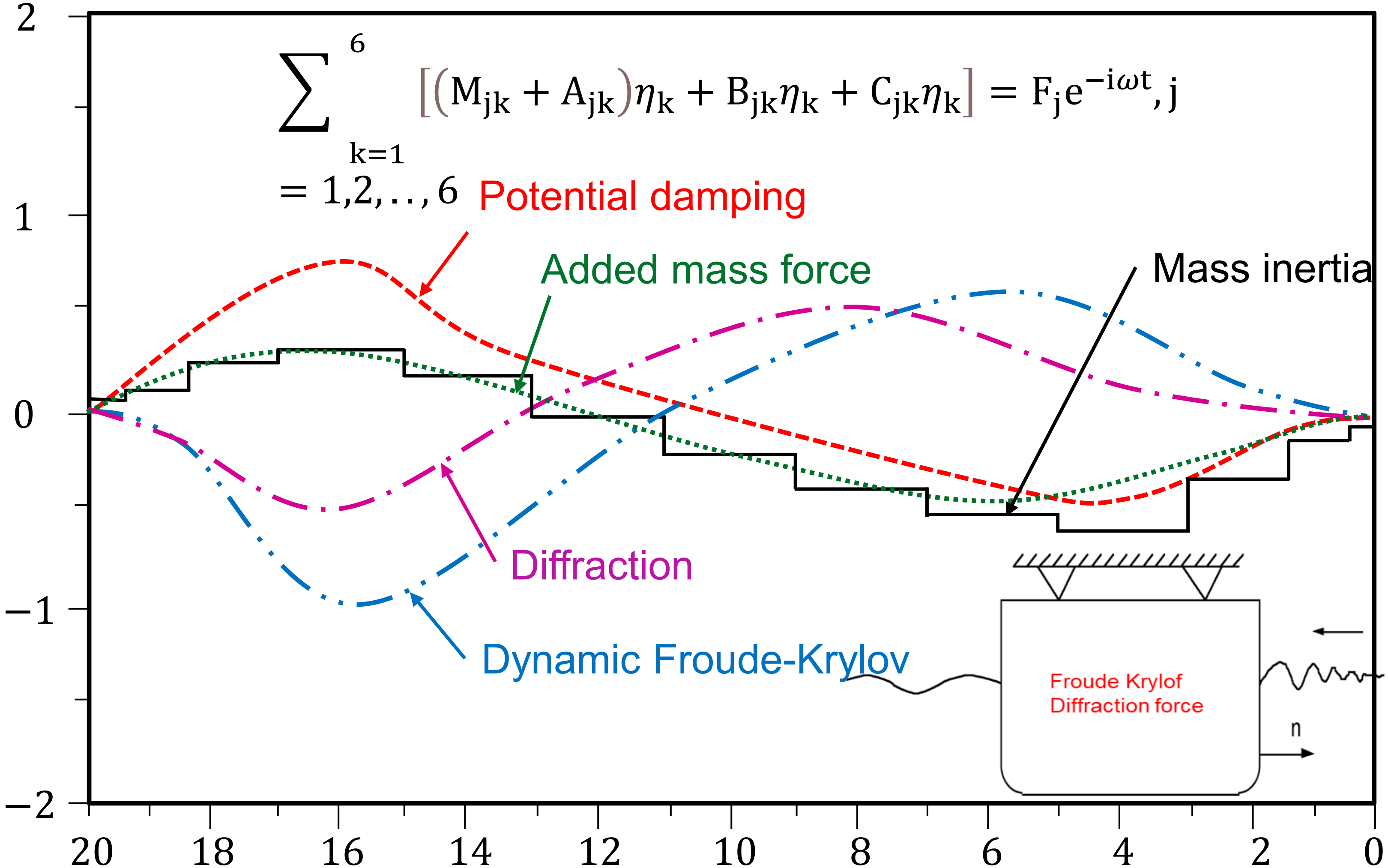
- ❑ $A(x)$ is the immersed cross-sectional area

$C_{1,2}$ Lewis' mapping coefficients

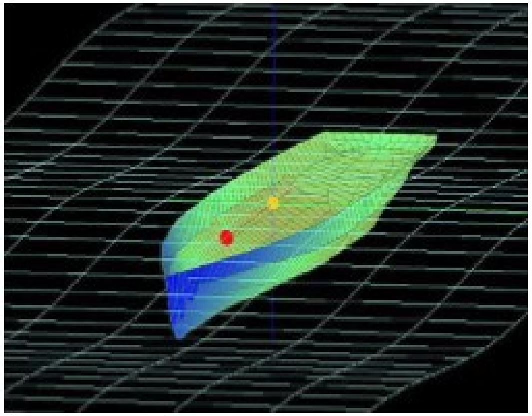
$\xi_0 = \frac{\omega_e^2 B}{2g}$ non-dimensional frequency

Strip Theory – Basic EoM

$$\sum_{k=1}^{6} \left[(M_{jk} + A_{jk})\eta_k + B_{jk}\eta_k + C_{jk}\eta_k \right] = F_j e^{-i\omega t}, j = 1,2,..,6$$



Introduction to panel methods

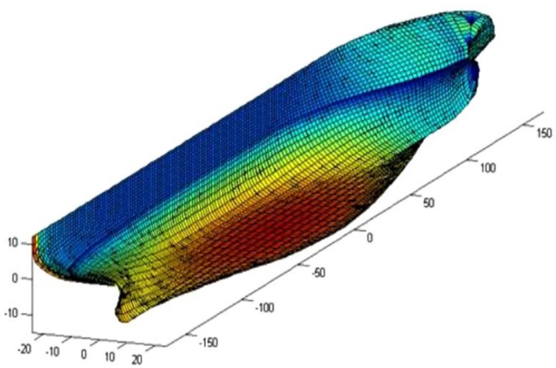


- To overcome the restrictions imposed by strip theory the **3D potential flow analysis** was developed.
- The method discretises the mean or still water wet surface of the hull by panels and places a pulsating (or translating and pulsating source) in each panel.
- After the evaluation of the strength 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 BEM**
- 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.

Engineering tools

- Numerous fast potential flow analysis codes (strip theory or panel methods) are available and well validated for linear seakeeping analysis.
- The codes handle different assumptions and there are numerous extensions. So they should be used with intelligence !
- In irregular seas, it is possible to analyze the response of each wave component separately (i.e., in the frequency domain) and then combine them together using Fourier analysis (i.e., in the time domain).
- Alternatively, it is possible to obtain the spectrum of the response directly from the sea spectrum by pure time domain (panel or strip theory) methods.

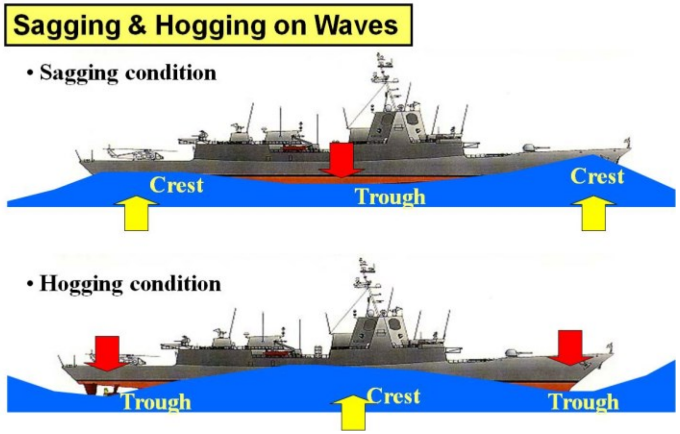


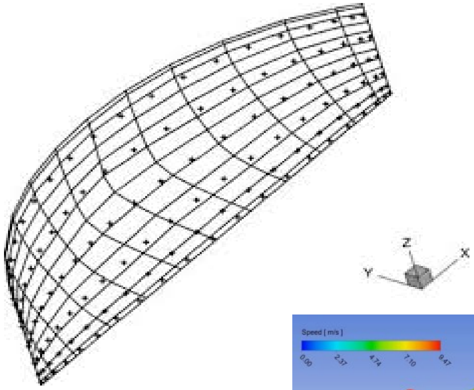
Why use non-linear models ?

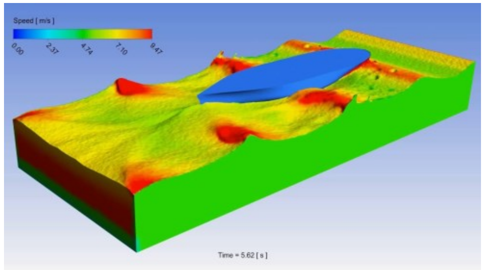
- ❑ Linear seakeeping methods may become invalid due to NL effects such as :
  - ✓ Changes of wetted surface
  - ✓ Variations in true draught and beam of ship sections
  - ✓ Flow interactions between sections
  - ✓ Forward speed effects
  - ✓ Large amplitude motions

- ❑ In such cases we can use nonlinear strip theories or panel methods (e.g. Rankine panel) to solve the problem

- ❑ RANS CFD is an emerging method that may be used to solve the problem as computational capabilities increase. There is need for further research and validation in this area.



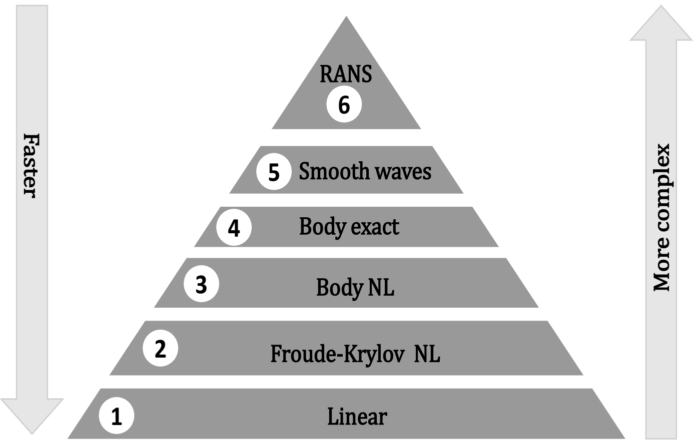




Options for NL simulations

- ❑ Methods: Levels 1 – 6
- ❑ To identify the significance of non-linearity often we need two types of analyses:
  - ✓ Screening in frequency domain: what are the worst conditions for our ship?
  - ✓ Simulations in time domain: when wave-amplitude dependency is violated, what is the impact?
- ❑ Methods contain different assumptions on
  - ✓ Stochastics of the problem
  - ✓ Fluid mechanics idealisations:
    1. Navier-Stokes, i.e. full CFD
    2. Reynolds-Averaged Navier-Stokes (little turbulence fluctuations omitted in boundary layer, averaged)
    3. Euler equations (viscosity neglected, coarser meshes, faster simulations)
    4. Potential flow solvers (irrotational flow, 1 non-linear Eq. instead of 4, cannot model breaking waves or splashes)

- Most applications use potential flow
- Ad-hoc codes use partly NL methods
- Fully NL & RANS solvers not mature
- Modelling & use in design not verified



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.

Example 1 : Linear vs NL models

Linear model disadvantages

- Large amplitude effects 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.

Example 2 : NL restoring forces

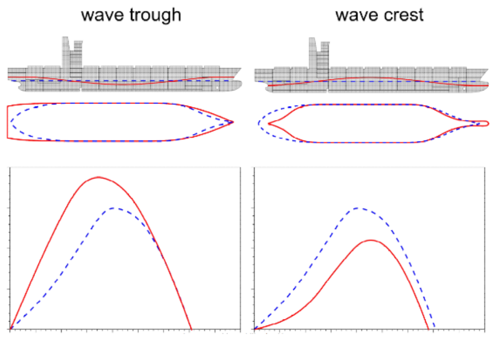
- Restoring and Froude-Krylov actions evaluated on the effective immersed hull in wave at each time step :

$$p_t = p - p_a = \rho g \zeta e^{k(Z_0 - \zeta)} - \rho g Z_0 = p_d + p_h$$

p_d: dynamic pressure due to the wave

p_h: hydrostatic pressure

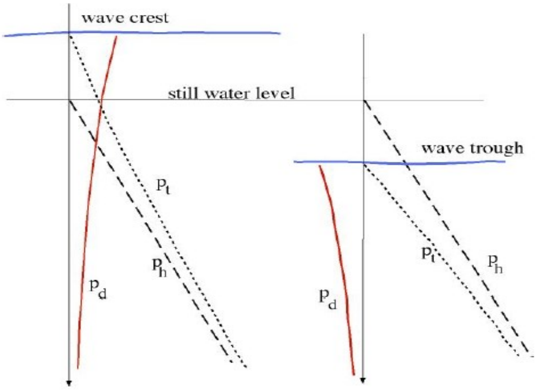
p_t : total pressure



- The knowledge of the dynamic pressure allows calculating the Froude-Krylov forces and moments; while hydrostatic pressure allows restoring force and moment calculation

$$\mathbf{F}_{\mathrm{F.K}}^{\mathrm{total}} = \sum_{i}^{N} \mathbf{F}_{\mathrm{F.}K;\mathrm{i}}^{\mathrm{total}} = \sum_{i}^{N} p_{\mathrm{i}} \Delta S_{\mathrm{i}} \mathbf{n}_{\mathrm{i}}$$

$$\mathbf{M}_{\mathrm{F.K}}^{\mathrm{tatal}} = \sum_{i}^{N} \mathbf{r}_{\mathrm{i}} \times \mathbf{F}_{\mathrm{F.}K;i}^{\mathrm{toal}},$$



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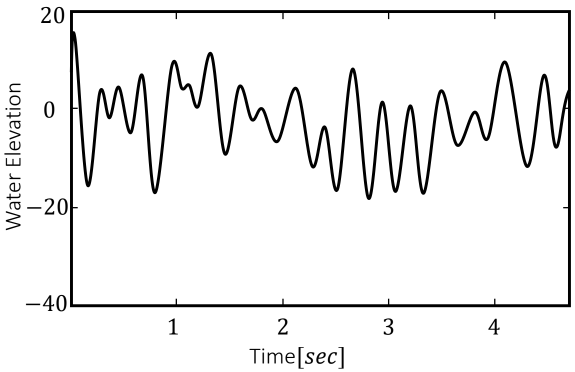
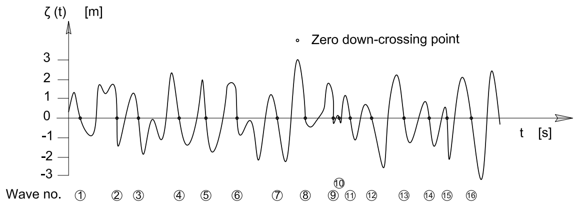
Example 3 : Fluid memory effects

- The non-linear assumption does not allow to use spectral analysis
- This means that the irregular sea cannot be described anymore as the sum of several regular waves of different frequencies.
- We cannot work in frequency domain, we have to work in time domain!
- We need to rearrange in time domain the added mass and the damping actions (i.e. radiation force and moment) evaluated in frequency domain (evaluated according to the linear method). This is done by means of the memory functions

$$\mathbf{X}_{rad}(t) = -\mathbf{a}_{\infty}\ddot{\mathbf{x}}(t) - \int_{-\infty}^{t} \mathbf{k}(t-\tau)\dot{\mathbf{x}}(\tau)d\tau$$

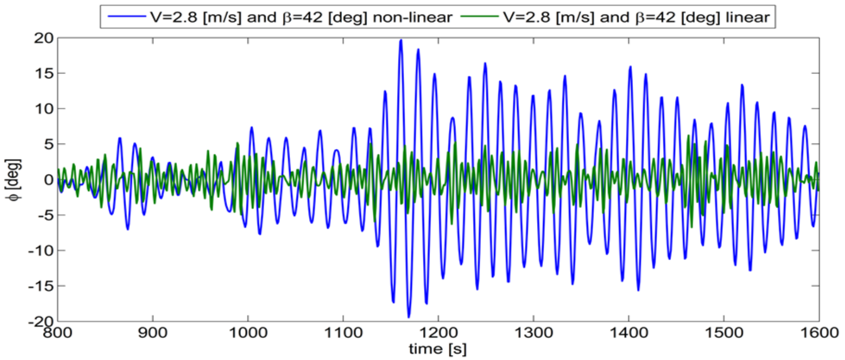
Time Domain



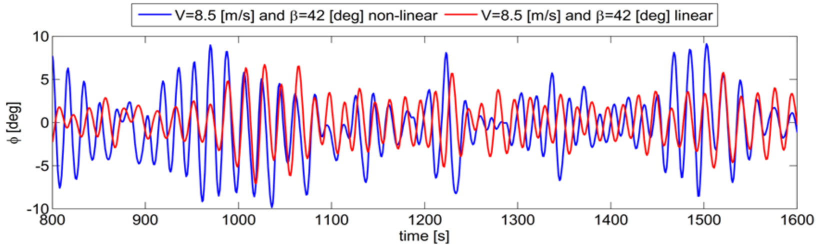


Example 4 : NL hydrodynamic tools

- **LaiDyn** is a non-linear numerical simulation model in time domain, that is capable of evaluating ship motions in regular and irregular seas. It is meant for research purposes.
- **ShipX Vessel Responces (VERES)** by *Marintek*, also includes the possibility to perform linear and non-linear numerical simulation.



Synchronous Roll Resonance in stern quartering irregular sea



$H_S = 4.6\ m$

$T_1 = 6.5\ s$

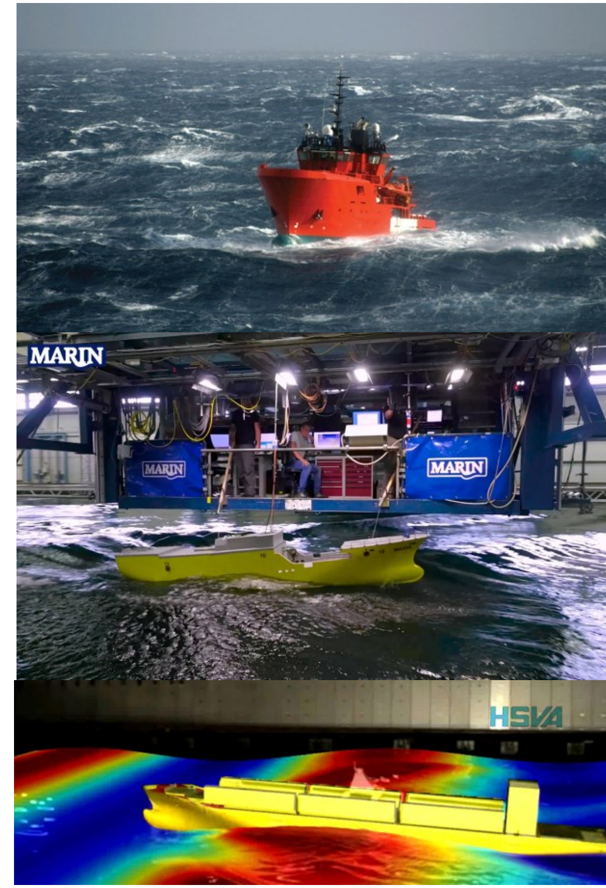
Summary

- The analysis of ship motions is demanding task and for this reason we should select always rational approach that may be suitable for design

- Linear approaches (Strip theory and BEM) allow us to use spectral techniques and use theory of linear systems

- Linear seakeeping theory is fast to use with modern computers and allows computation of various sea states, motion components etc. Extensions to those include non-linearities and various corrections to made assumptions

- If the motions are excessive linear theories may become invalid due to various non-linearities such as those emerging from waves, hull form and changes of weight distribution, cargo movement etc.



Thank you !!