Lecture 1 - Introduction to Ship Dynamics

1. Preamble

In the broadest sense, the subject of **ship dynamics** is concerned with all conditions where the inertia forces interplay a role in ship motions. Traditionally, the ship is assumed to behave as a rigid body that is static or slowly moving between positions of equilibrium. Thus, ship dynamic idealizations should account for all operational conditions that differ from the ideal still water condition. Waves, forward speed effects and the influence of elastic distortions on ship dynamic response may also play a role. Ship dynamic models comprise of sub-models encompassing the principles of *ocean wave mechanics*, *seakeeping, maneuvering, structural vibration, and dynamic stability.* Modelling each of the sub-models within the context of hydrodynamics is prone to simplifying assumptions that should be thoroughly evaluated before models are used for design or operational decision support. As an example, traditional seakeeping models are linear and understood within the context of potential flow analysis.

Naval architecture experience suggests that linear hydrodynamic models can be useful in concept or preliminary design stages provided that their limitations are well understood. This is because they are computationally economic and seakeeping methods (e.g. frequency domain boundary element and strip theory methods) have been validated over a long period of time. Of course, understanding nonlinear ship dynamics in time can help with improved quantification of the influence of realistic operational conditions on ship motions and loads (e.g. the influence of asymmetry of sagging and hogging on dynamic response), dynamic stability in waves (e.g. parametric rolling, broaching and ship capsizing) under large amplitude motions, medium to high forward speed or other extreme environmental conditions. In traditional naval architecture, the assessment of ship maneuvering and seakeeping dynamics is separate and the hydrodynamic methods used hybrid. Ship maneuvering is assessed in still water conditions and associated in plane ship motions (surge, sway and yaw) are evaluated in time.

Over the last twenty years advances in computer applications allowed for the emergence of non-linear seakeeping methods (Mortola et al., 2011), rapid unified seakeeping-maneuvering approaches (Taimuri et al.,2020) and the development of hydroelastic models (Hirdaris et al., 2010). Advanced fluid dynamic models also emerged although their proficient use for design development and assessment may be considered a medium to long term target (e.g. Lakshmynarayanana and Hirdaris, 2020; Jiao and Huang, 2020; Kim et al., 2021).

(a) A ship in stochastic seaways © national geographic – world of the wild

(b) Seakeeping simulations using CFD (Jiao and Huang, 2020)

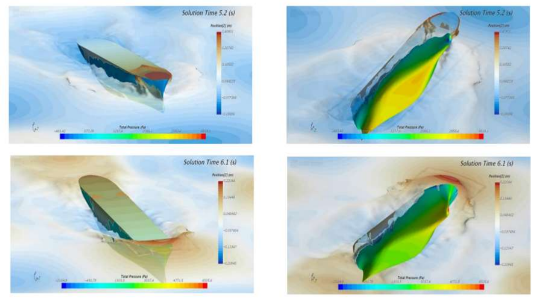


Figure 0-1 A ship in waves (reality vs simulation)

2. Some definitions

Seakeeping refers to a ship’s ability to remain at sea in all conditions and carry her intended mission. Topics such as dynamic stability in waves, strength, maneuvering, added resistance inevitably link with seakeeping dynamics and ship performance in waves. This is because excessive ship motions may have adverse effects on ship design and operations. They may lead to hull rupture or distortions, discomfort of the passengers and crew, result in less efficient working conditions and bad worker / customer experience. Added water resistance due to ship motions in waves and propellers exposed to heavy conditions may also result in reduced ship efficiency. This is because severe motions and heavy loading on propulsors may lead to voluntary ship speed loss. To control this problem computerized weather routing systems are now fitted on several ships allowing the master greater control of speed and seaworthiness in demanding or extreme conditions.

In traditional seakeeping analysis the ship is modelled as a rigid body moving in six degrees of freedom namely three translations (heave, surge, and sway), and three rotations (roll, pitch, and yaw). For a ship to maintain sound **dynamic stability** in waves the oscillatory degrees of freedom of roll, pitch and heave should be controlled. In heavy seas a ship’s bow may dig into waves and water may be driven over the ship’s forecastle deck. The phenomenon is known as **deck wetness** and may be linked with strongly coupled heave an pitch motions. In such conditions **slamming** loads may be evident. The main design factors affecting these operational scenarios are the relative motion of the bow, the sea surface and the ship freeboard.

When sailing in congested waterways such as canals or during navigation in harbors, ship control is essential to ensure accurate ship tracking relative to the berth points and safety in relation to other ships in harbor. A ship is said to be directionally stable if a deviation from a set course increases only while an external force or moment is acting to cause the deviation. Conversely, it is said to be unstable if a course deviation begins or continues even in the absence of an external cause. A directionally unstable ship is easy to maneuver, while a stable ship requires less energy to maintain a set course. A compromise between extremes is therefore desirable. Another example are dynamic positioning systems used in offshore vessels or drilling platforms. Such systems help maintain floatability and positioning relative to the seabed. Thus, propulsors producing ahead and astern thrust as well as turning moments and thrust have been developed. The latter (i.e., turning moments and lateral thrust) are provided using rudders directly positioned behind the main propulsors and in some cases additional lateral thrusters are used where higher maneuvering capability is required (e.g., ship bow/stern regions).

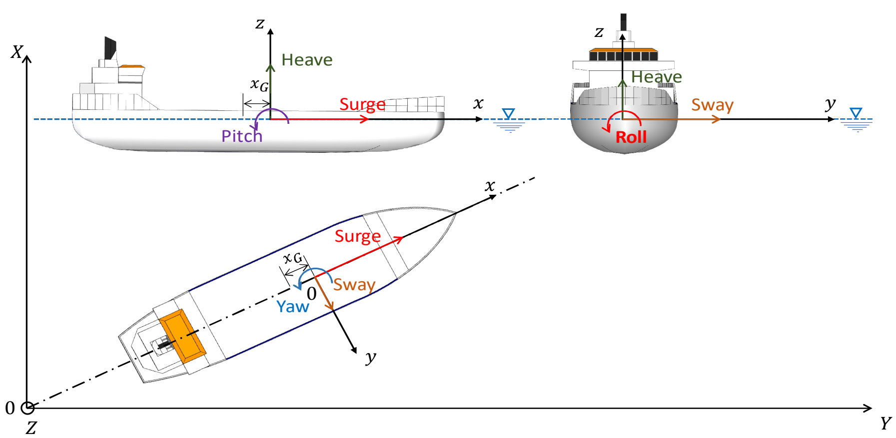
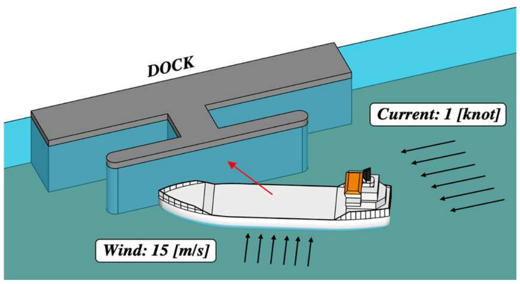


Figure 0-2 Coordinate model representing the 6 degrees of freedom of a rigid ship, x_G is the longitudinal position of the center of gravity relative to the body fixed coordinate system x, y and z (Taimuri et al., 2020)

Ship maneuvering and control (positional and directional stability) relate with controlling ship course and speed and may involve the investigation of motions due to disturbing forces from the environment (e.g., sway and yaw) and / or control mechanisms such as rudders. The maneuvering characteristics of a vessel are usually defined in still water conditions. Wind effects on maneuvering characteristics are of concern for ships with large superstructures such as cruise ships and ferries. When a ship operates close to banks or at close proximity to another ship, she may experience additional forces and turning moments with significant variations. Thus, the use of time domain hydrodynamic models are typical in manoeuvring but only an option in seakeeping. Manoeuvring is often studied in shallow waters but seakeeping in open seas. Finally, seakeeping is studied by an inertial coordinate system while manoeuvring by a ship fixed system. The simulation of viscous fluid flows implies mathematical difficulties and computational costs (Kim et al., 2021).

The primary purpose of computing motions and loads of ships in a seaway is to assure the safety of persons on board, the integrity of the ship and the cargo. They also aim to improve performance and efficiency (Hirdaris et al., 2014). Excessive motions may cause shift of cargo, damage from loosened deck containers or equipment and dangerously large heel angles and capsizing (Acanfora et al., 2017). Furthermore, ship motions affect the comfort of persons on board, leading to sea sickness or, in extreme cases, to render it impossible for the crew to accomplish a ship's mission. Knowledge of wave-induced loads is necessary to assess the integrity of the ship's structure. Most important for this are vertical and horizontal bending moments, torsional moments, and sometimes shear forces in transverse sections of the hull girder (Hirdaris et al., 2010). Wave-induced local pressure acting on the hull determines the necessary strength of plates, stiffeners, and web frames. Furthermore, steady wave- and wind-induced forces and moments should not prevent the ship from arbitrary course changes nor from making adjustments to the speed ahead.

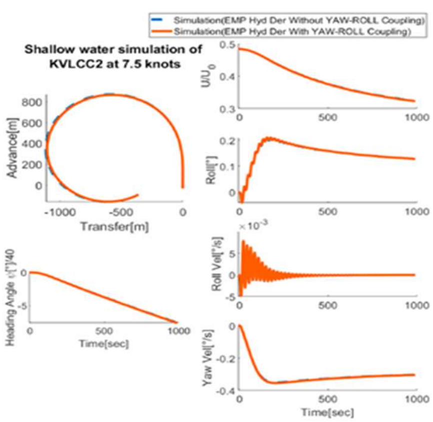
(a) Idealization of a ship maneuvering at close proximity to harbor under wind and current forces



(b) Littoral combat ship in turning circle manouvre

Figure 0-3 Ship maneuvers at harbor and during sea trials

(a) shallow water slow maneuver



(b) deep water fast maneuver

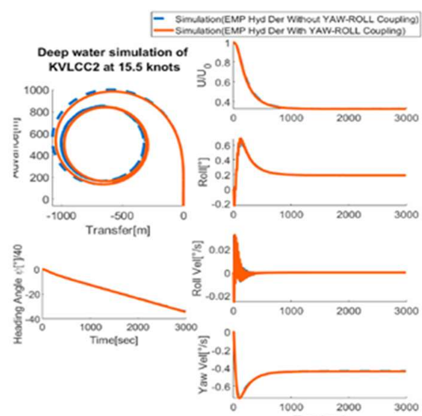
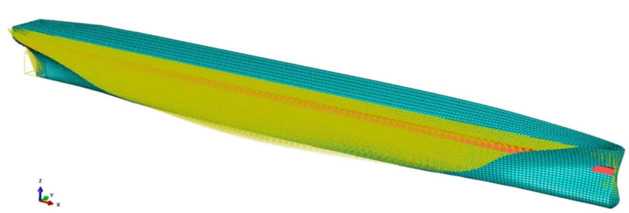


Figure 0-4 Ship maneuvering idealization using a potential flow solver (Taimuri et al., 2020)

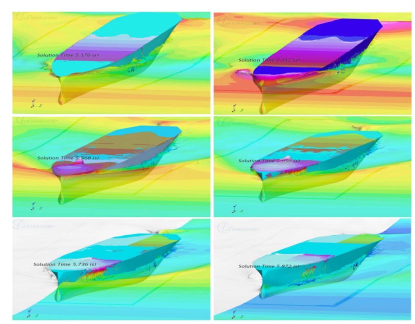
3. Specialist topics

Hydroelasticity of ships is concerned with the interaction of the ship modelled as an elastic body with her surrounding fluid (Hirdaris et al., 2010). Theoretically, flexible ship dynamics recognize the significant differences in the hydrodynamic, inertia, and elastic forces that may lead to the amplification of **wave loads** and excessive strains and stresses possibly leading to hull rupture or high fatigue loads. The importance of flexible ship dynamics increased over the last few years as sea transportation and ship sizes increased. Modern ocean carriers are more flexible, and their structural natural frequencies can fall into the range of the encounter frequencies of the sea spectrum. It is now recognized that hydroelastic effects associated with ship slamming or the antisymmetric (i.e. coupled horizontal bending and torsion) dynamics of ships with large openings may influence wave load predictions.

(a) FE model showing the beam (blue) and hull surface connected by the kinematic coupling constraints (yellow) as presented in Lakshmynarayanana and Hirdaris (2020)



(b) Time instance of coupled CFD simulations showing bow emerging in and out of the water surface (Lakshmynarayanana and Hirdaris, 2020)



(c) Illustration of in vacuo flexible dynamics of a modern container ship (Hirdaris et al., 2010)

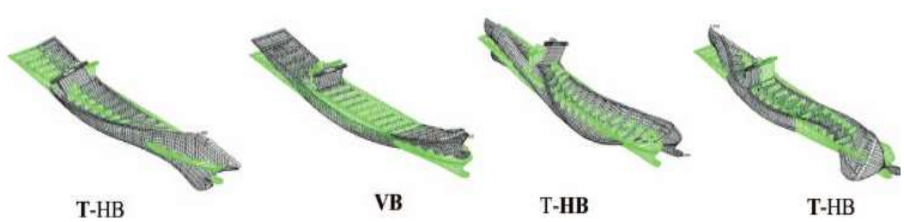
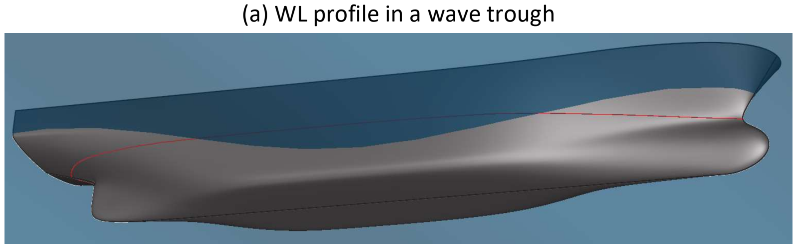


Figure 0-5 Hydroelasticity modelling combines principles of marine hydrodynamics and structural dynamics

Ship dynamic stability in waves attempts to investigate roll motions which are subject to heeling moments in the irregular seaway. Investigations therefore include nonlinearities (e.g. roll damping) and provide variation of roll angle in time with the ultimate purpose to investigate whether the ship will capsize. There are also some investigations dealing with the coupled sway-roll-yaw motions; thus, bringing together the subjects of directional and dynamic stability. **Ship survivability against capsizing** in heavy seas has become one of the areas of primary concern among ship researchers, designers and regulators in recent years. When a ship is subjected to the effect of large waves it may capsize according to several different scenarios, which further depends on the magnitude and direction of the wave excitation and the ship's own capability to resist such excitations. **Resonant or breaking waves** approaching a ship from the ship side (beam seas) have a potential to excite large rolling which could result in capsizing, especially if the intensive oscillation of the ship causes a shift of cargo or a considerable quantity of green water is seen on the deck. More dangerous still can be a group of steep and relatively long waves approaching a ship from the stern (following-seas). Waves of this kind are known to incur significant reductions in roll restoring capability (i.e. the tendency to return to the upright position) for many types of vessels and they may also instigate dangerous coupled motions.

(a) WL profile in a wave trough



(b) WL profile in a wave crest

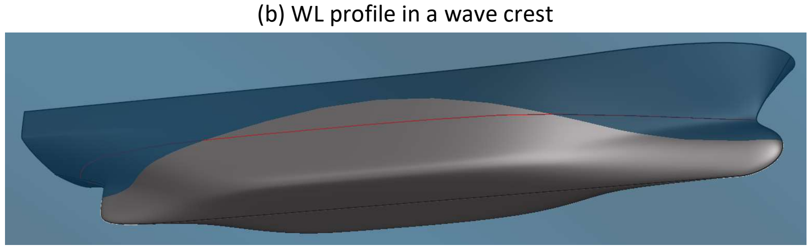


Figure 0-6 Ship stability in longitudinal waves (calm water line – WL is denoted in red)

In following-seas a ship may capsize in at least two ways known as **pure loss of stability** and **parametric instability**. The former is a sudden, non-oscillatory type capsize taking place around a wave crest due to slow passage from a region of the wave where roll restoring has become negative. Parametric instability is the gradual build-up of excessively large rolling created by a mechanism of internal forces, the result of a fluctuating restoring movement that depends on where the ship lies in relation to the wave (ABS, 2004). This phenomenon is related to the periodic change of stability as the ship moves in longitudinal waves at a speed when the ship's wave encounter frequency is approximately twice the rolling natural frequency and the damping of the ship to dissipate the parametric roll energy is insufficient to avoid the onset of a resonant condition. If a ship is in a wave trough, the average waterplane width is significantly greater than in calm water. The flared parts of the bow and stern are more deeply immersed than in calm water and the wall-sided midship is less deep. This makes the mean, instantaneous waterplane wider than in calm water with the result that the metacentric height increases over the calm water value. When the wave crest is located amidships, the waterplane at the immersed portions of the bow and stern are narrower than in calm water. Consequently, the average waterplane is narrower and the metacentric height decreases in comparison to calm water. As a result, the roll restoring moment of the ship changes as a function of the wave's longitudinal position along the ship. **Broaching to** relates to an unintentional change in the horizontal-plane kinematics of a ship. Broadly, it may be described as the *"loss of heading"* by an actively steered ship. It is accompanied by an uncontrollable build-up of a large deviation from the desired course. Broaching to is more commonly occurring in waves which come from behind and propagate in a direction forming a small angle, say 10-30 deg., with the longitudinal axis of the ship (Spyrou, 2011).

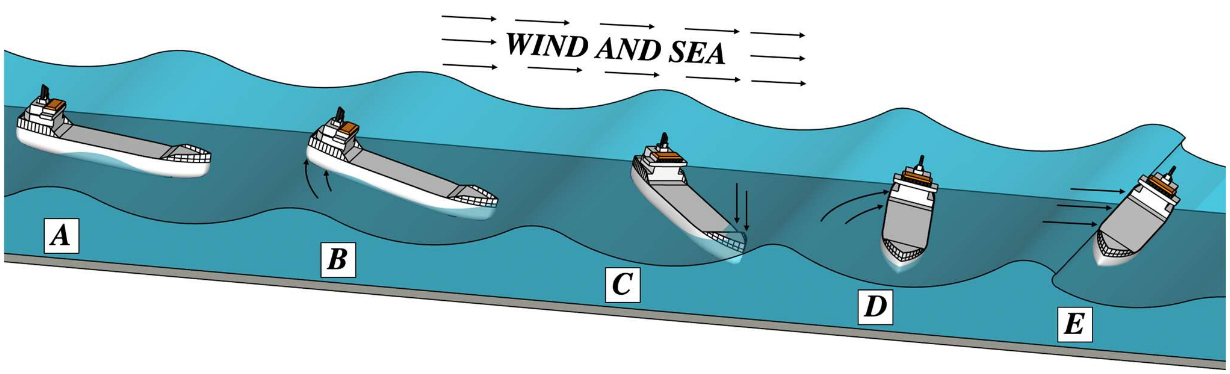


Figure 0-7 Stages of a Broaching to scenario: (a) The ship may run on crest; (b) ship stern gets too high and thus the rudder losses effect; (c) the bow pitches into trough and buries; (d) stern swings round bringing ship abeam to elements; (e) next wave will possibly break over the ship and cause severe damage.

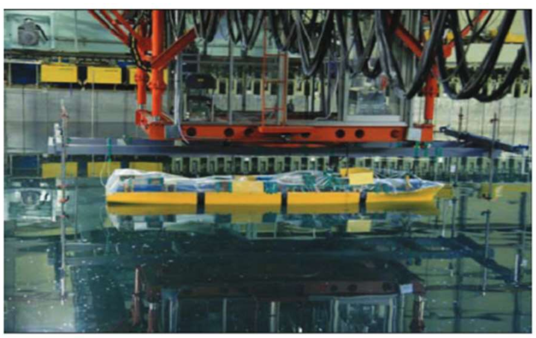
4. The influence of ship dynamics on ship design development

Ship safety in design is assured by the IMO and Classification Societies. The Class Societies develop rules regarding ship loads (e.g. https://www.lr.org/en/rules-regulations/). Traditional Classification rules are based on accident records and experiences with ships in operations, as well as theoretical and experimental studies leading to closed form / empirical criteria. Ship safety criteria that relate with maritime operations (e.g. maneuvering and stability requirements) are introduced by the International Maritime Organization (IMO) and developed in association with Flag Administrations, Classification Societies, academia and industry including non-governmental organizations (IMO,2017). In the last 20 years, computational methods have been used to improve and extend the rules related to wave loads and seakeeping and to investigate wave responses for newbuild ships that differ substantially from those for which the rules were prepared. For reliable load predictions, it may be advantageous to apply advanced and possibly costly computations to reduce a ship's scantlings or the probability of structural failures. Numerical simulations may help to estimate the probability of excessive motions and accelerations with respect to ship motions. This may help to extend the safe limits of metacentric height (e.g., Lloyd's Register, 2018).

Ship dynamics can be assessed by using full-scale measurements, model tests, and numerical methods. Despite advances in theoretical ship hydrodynamics the design of novel hull forms at preliminary design stage makes use of **model scale experiments**. Development of wave basin models are cut from a plan re-drawn from the hull lines and may be costly unless 3D printing methods are employed. From naval architecture perspective it is imperative to realize that ship models used in model tests should be as large as possible to minimize viscosity scale effects. Yet, increased model size should not influence ship dynamics in restricted waters and the size of a stock propeller is to be taken into consideration when the scale for a ship model is selected. The material of which the model is made is not important provided the model is sufficiently rigid. Wood, wax, high density closed cell foam and fiber reinforced plastic are commonly used. Model test results can be converted to full-scale data except for the influence of viscosity, which is small in most cases. More important is the limited size of the model basin, the degree of sophistication of the equipment of the test facility, and cost and time to perform such experiments. In irregular seaways, long test runs are required to obtain representative results. Thus, for seakeeping models today, experiments are used mainly to validate numerical methods. An exception is the sloshing of fluids in tanks, where small-scale effects like wave breaking and the collapse of bubbles may be important for practical questions but are difficult or impossible to simulate accurately.

The range of model tests carried out depend on the type of the analysis or the sub-model by which the ship behavior is investigated. As an example, model tests that aim to predict powering performance of a ship comprises the resistance test, the self-propulsion test and the propeller open-water test. **Seakeeping model tests** usually employ self-propelled models in narrow towing tanks or broad, rectangular seakeeping basins. The models are sometimes completely free, being kept on course by a rudder operated in remote control or by an autopilot. In other cases, some degrees of freedom are suppressed e.g., by wires. If internal forces and moments are to be determined, the model is divided into sections. The individual watertight sections are coupled to each other by gauges consisting of two rigid frames connected by stiff flat springs with strain gauges. Model motions are then determined either directly or by measuring the accelerations and integrating them twice in time. Waves and relative motions of ships and waves are measured using two parallel wires penetrating the water surface. The change in the voltage between the wires is then correlated to the depth of submergence in water. The accuracy of ultrasonic devices is slightly worse. The model position in the tank can be determined from the angles between the ship and two or more cameras at the tank side. Either lights or reflectors on the ship give the necessary clear signal.

(a) Hydroelastic ship model (Lee et al., 2011)



(b) Ship resistance model © MARIN, Netherlands

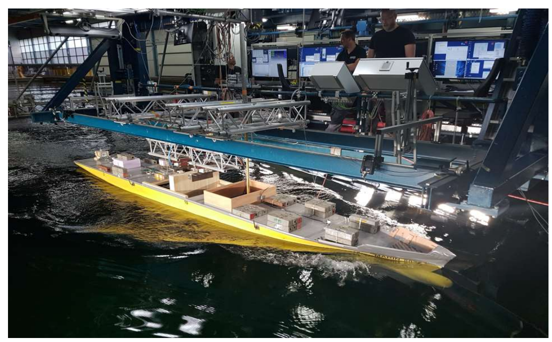


Figure 0-8 Model testing remains key part for the validation of ship dynamics of novel hull forms

Full-scale measurements (FSMs) are possible only if a ship, or her sister to this vessel, are build. FSMs may be expensive, the wave conditions cannot be controlled and assessing the wave conditions during the measurements with the required accuracy may be difficult. During FSMs ship motions are measured by accelerometers and gyros., Global and local loads are measures by strain gauges andloss of speed, propeller rpm and torque are all monitored. Recording the seaway can be done either by recording measurements over many years of operation, or by deducing the maximum values during the lifetime of the ship and then by extrapolating the recorded distribution of long-term measurements.

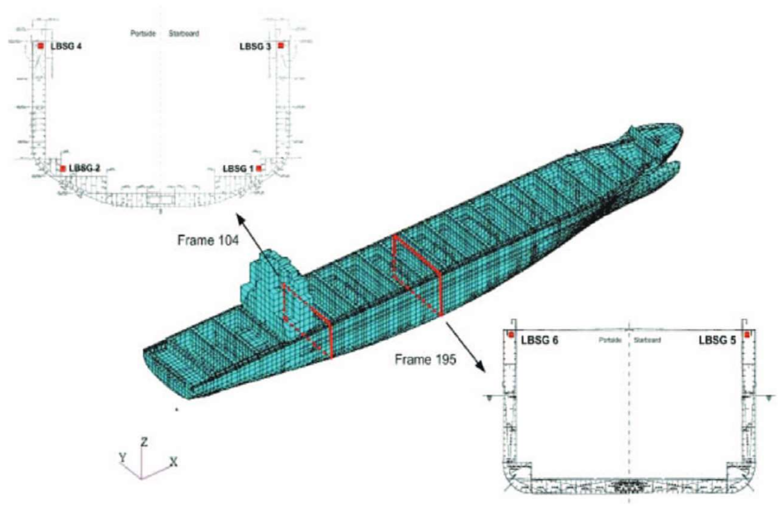


Figure 0-9 Wiring of a containership with strain gauges (Hirdaris et al., 2010)

The random variation of the actual sea states encountered by a ship may introduce considerable inaccuracies for the predicted extreme values even if several years of measurements are available. Although model tests and FSMs can provide useful information of a ship's performance, designs and operational conditions may differ. Hence it is not certain whether the elaborated ship hull form together with the designed propeller and appendages will ensure efficient performance of any ship in all conditions. Such possibilities are offered by numerical methods such as computational fluid dynamics and finite element analysis. **Linear hydrodynamic models** are used to determine motions and structural hull girder loads for ships advancing at constant forward speed in small amplitude regular waves under various combinations of wave frequency and heading. For any seaway described by a wave spectrum, the results are combined to obtain root mean square values of loads extrapolated linearly over wave amplitude. Results for different seaway conditions are then combined to a long-term probability distribution of loads. For suitably selected design conditions, nonlinear corrections to the linear loads can be applied. If more accuracy is required, solvers for Navier-Stokes or Euler equations may be applied, which consider the water/air interface. Full understanding and an accurate prediction of hydrodynamic wave body interactions is challenging. The associated nonlinear effects become critical when large-amplitude body motions and/or high surface waves are involved.

(a) 3D potential flow model (b) Topology of hydrodynamic models

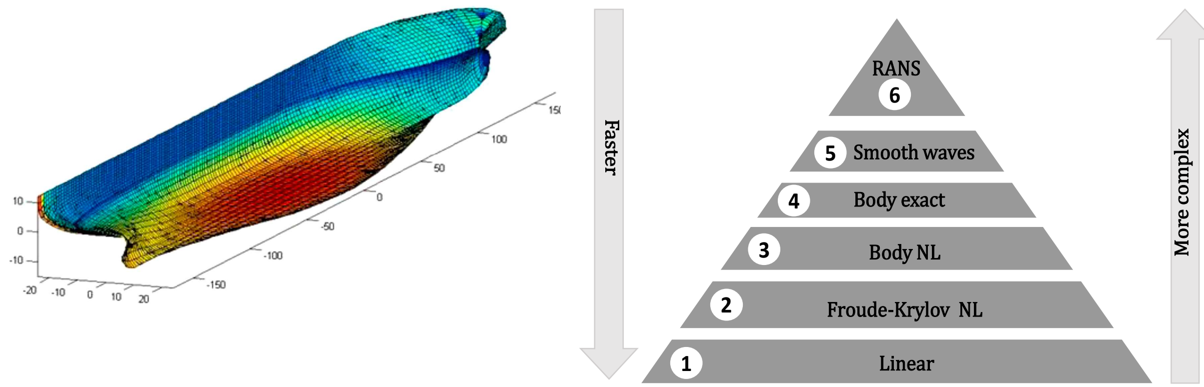


Figure 0-10 Overview of seakeeping methods (Hirdaris et al., 2016)

Recent research advances in the area of **ship damage stability** suggest that implementation of marine hydrodynamics and structural dynamics in ship crashworthiness assessment will influence ship design development and assessment (Kim et al., 2022). The use of big data analytics may also prove useful in terms of defining direct assessment methods accounting for the influence of hydro-meteorological conditions on the probability of ship collision and grounding (Zhang et al. 2021). It is envisaged that these developments will impact upon future IMO ship damage stability standards.

5. Questions

1. What are the key terms for ship dynamics and which ones affect the design of the ship?
2. What is the difference between seaworthiness and seakeeping?
3. Which phenomena are frequently simplified when creating model simulations of ship dynamics problems?
4. Why would shipyards and shipowners have different maneuvering requirements for vessels?
5. What are the main categories of wave loads and which methods are used to model them?
6. Which organizations are responsible for ship safety in terms of structure and design and how do they develop the rules?
7. Which organizations are responsible for ship safety in terms of maritime operation and how do they develop the rules?
8. What types of engineering tools are used to generate and collect data regarding ship dynamics topics?

9. What are the advantages and disadvantages to full-scale measurements? Briefly describe how data is collected.
10. Which non-linear effects important to the operation of a ship and why?

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