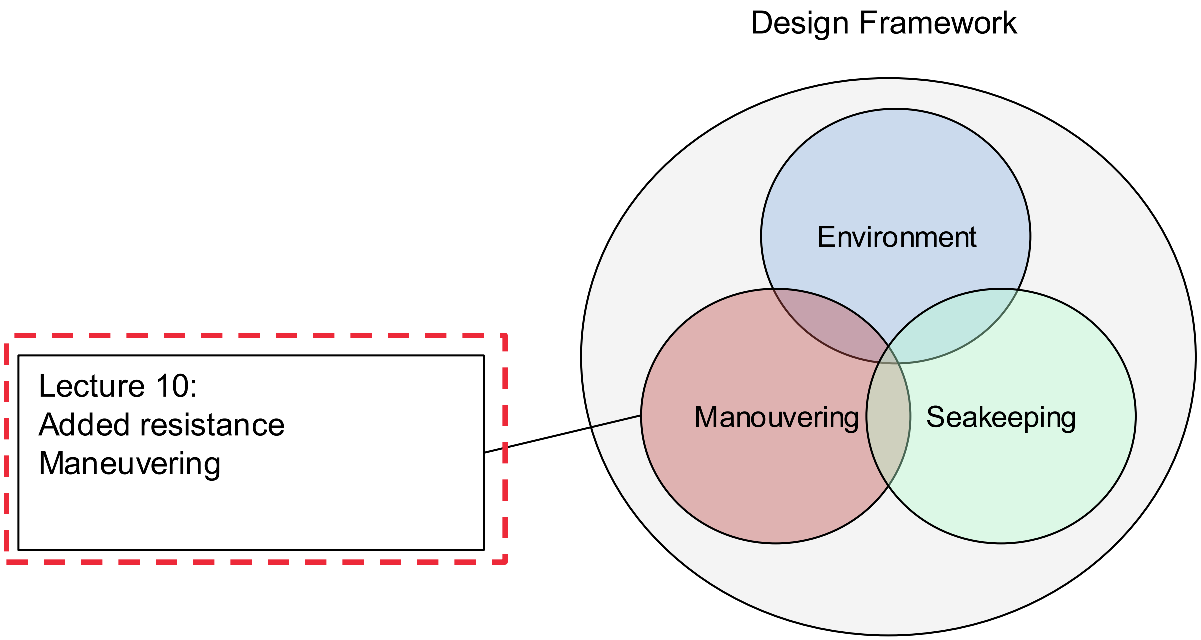
# Aalto University
# *School of Engineering*

MEC-E2004 Ship Dynamics (L)

## Lecture 10

## Manouvering & Added Resistance

# Where is this lecture on the course?



# Contents

**Aims :**

- How the added resistance due to waves and wind can be analysed ?
- How motions of the ship in the plane of sea-surface can be assessed ?

**Key topics :**

- Added resistance in regular & irregular head long and short waves
- Principles of aerodynamic resistance
- Maneuvering: motion stability, simulation, course-keeping, stability & control

**Literature:**

1. Lloyd, A.R.J.M, Seakeeping – Ship Behavior in Rough Weather, Ch. 19
2. Liu, S. and Papanikolau, A., On the Prediction of the Added Resistance of Large Ships in Representative Seaways, *Ships and Offshore Structures*, 2016.

1. Matusiak, J., ”Ship Dynamics”, Aalto University
2. Bertram, V., ”Practical Ship Hydrodynamics”, Ch. 5
3. Lewis, E. V. Principles of Naval Architecture. Vol. 3, Motions in waves and controllability, Ch.9
4. Rawson, K. J., Basic Ship Theory. Volume 2, Ship dynamics and design - Ch.13
5. Molland and Turnock, Marine Rudders and Control surfaces

# Weekly Exercise

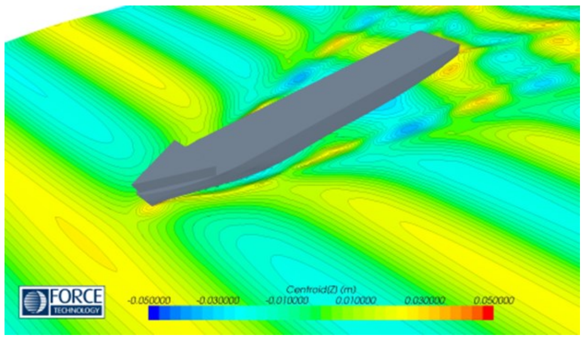
## Exercise 5

- **Grades 1-3:**
  - Select book-chapters related with (1) seakeeping design criteria (2) added resistance (3) maneuvering and reflect to your ship
  - Assess seakeeping criteria with some software and assess the performance of the initial design with respect to those
  - Discuss the simplifications made in added resistance/maneuvering modelling and analysis of your ship
  - Select the maneuvering tests to be simulated and justify the selections

- **Grades 4-5:**
  - Based on scientific literature, discuss the accuracy of the obtained results
  - Compute the part of added resistance in selected wave conditions in relation to still water resistance & discuss results
  - Discuss what issues you can still improve for you ship in the follow-up courses

- **Report and discuss the work**

# Part I : Added Resistance in waves




# Added Resistance - Introduction

- The speed of a ship in calm water is defined by : propeller efficiency, resistance (wave and friction), power of engines. In rough weather the resistance may be changed by the action of waves, current, wind, ice. Loads may also affect performance leading to involuntary loss of speed. A ship can experience a 15-30% resistance increase in a seaway and an effect of this is higher OPEX.

- Added resistance in waves is the part of a ship's total resistance that is caused by encountering waves. Calculations of added resistance can be used as an addition to the calm water resistance to predict the total resistance of a ship in a seaway.

- Being able to predict added resistance due to waves is therefore a vital part of the prediction of a ships resistance.

- Prediction of added resistance can be used in the following problems:

  - **Weather margin** where the max. resistance increase due to weather can be predicted, to decide engine installations and so on.

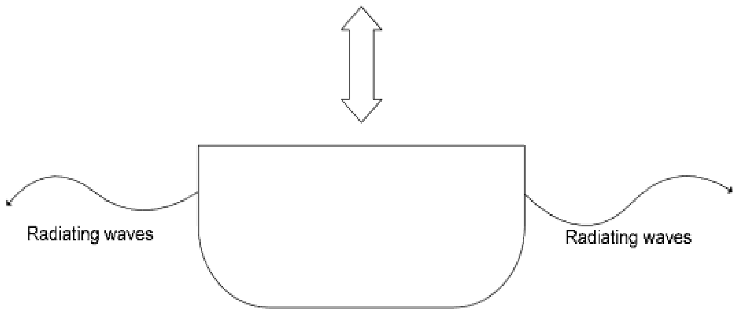
  - **Weather routing** which is important due to its economical effect on ship exploitation. It is for instance very important to make good estimations of the time it will take for a ship to travel a route, so the cargo owners know when the ship will arrive in port, minimizing the costs of storage. It is also very important to be able to optimize routes in order to reduce the fuel consumption and emission.

  - **Performance analysis** – solving the inverse problem : By excluding the influence of stochastic waves in a seaway, we can evaluate a ship's "real" calm water resistance. This "real" calm water resistance can be used as a measurement of the ships performance over time. The ship owners could use this information to determine the value of a ship, and how often it should be docked for antifouling and so on.

# Added Resistance in Regular Waves

- A ship operated in regular head waves has changing resistance. The mean value of the resistance will be always larger than that of calm water resistance.

- When a ship is oscillating due to waves, it supplies energy to the surrounding water, energy that will increase the resistance. This energy is primarily transmitted **with the waves radiating from the ship**.



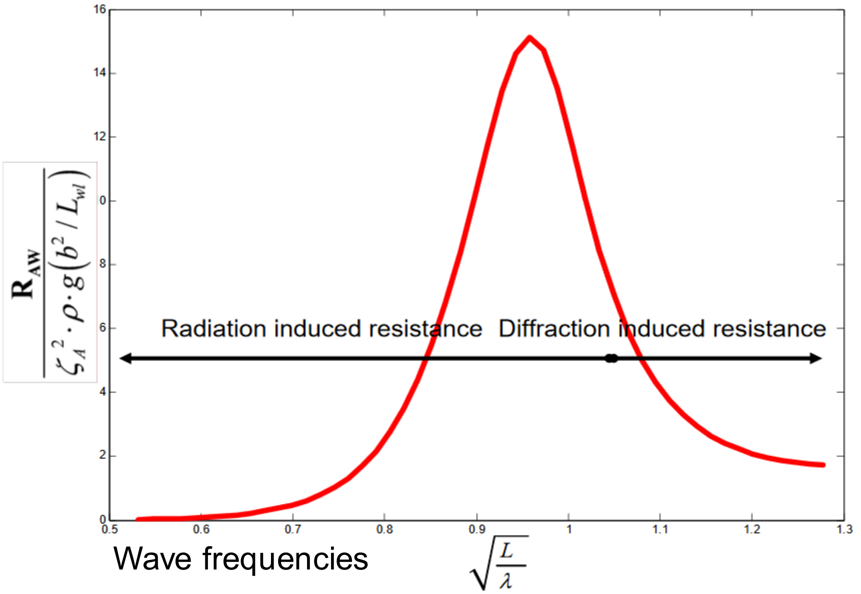

Radiating waves due to oscillation.

- Energy is also transmitted to the surrounding water by waves generated by the forward speed of the ship. This is referred to as the **calm water resistance**

# Added Resistance in Regular Waves

- The supplied energy is due to damping of the oscillatory motions. Hydrodynamic damping is dominating for heave- and pitch motions, which are the biggest contributors to added resistance. The viscous damping can therefore be neglected, which means that added resistance can be considered as a non viscous phenomenon.

- This means that potential theory can be used. The radiation induced resistance is dominating when the ship motions are big. This happens in the region of the resonance frequency of heave and pitch motions. The reflection of incident waves is also causing added resistance. The so called diffraction induced resistance is dominating for high wave frequencies, where the ship motions are small.



# Key methods for the evaluation of added resistance in regular waves

Three key methods exist. Those were introduced by **(1)** Gerritsma and Beukelman, **(2)** Boese and **(3)** Faltinsen.

- Methods (1) and (2) deal with radiation induced resistance only
- **Method (1) is a so called radiated energy method.** This problem starts out by trying to describe the energy that the oscillating ship transmits to the surrounding water. It is assumed that to maintain a constant forward ship speed, this energy should be delivered by the ship's propulsion plant.
- Method (2) is a pressure integration method, which basically means that the linear pressure in the undisturbed wave is integrated over the ship hull, to obtain a mean force in the heading direction of the ship. It may seem strange that the linear pressure would give a mean force, but it does in this case since the ship hull, where the integration is performed, is moving.
- Method (3) only deals with diffraction induced resistance, and neglects the ship motions.

# Geritsma and Beukelman method

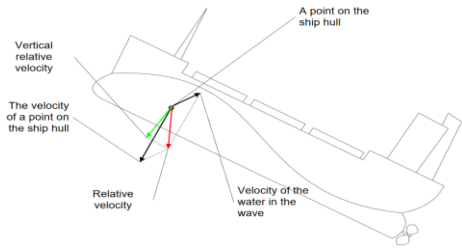
- **Basic idea :** Calculate the **radiated wave energy** during one period of oscillation, in regular waves. This is the energy required to create waves, when the ship is oscillating ; and it is assumed that to maintain a constant forward ship speed, this energy should be delivered by the ship's propulsion plant.

- The **relative velocity** is the vertical velocity of the water related to a point on the ship. It is evaluated by the expression :

$$V_{z_b} = \left[ -V \cdot \eta_5 + i \cdot \omega_e \left( x_b \cdot \eta_5 - \eta_3 \right) + i \cdot \omega \cdot \zeta_a \cdot e^{-k \cdot \bar{D}} \cdot e^{-i \cdot k \cdot x_b \cdot \cos(\beta)} \right] \cdot e^{i \cdot \omega_e \cdot t}$$

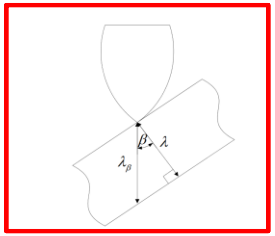
…and the amplitude:

$$\left| V_{z_b} \right| = \left| -V \cdot \eta_5 + i \cdot \omega_e \left( x_b \cdot \eta_5 - \eta_3 \right) + i \cdot \omega \cdot \zeta_a \cdot e^{-k \cdot \bar{D}} \cdot e^{-i \cdot k \cdot x_b \cdot \cos(\beta)} \right|$$




- The radiated energy can be calculated $E = \int_0^{T_e} \int_0^{L} b' \cdot V_{z_b}{}^2 \cdot \partial x_b \cdot \partial t$

assuming the ship progresses diagonally in waves



- The added resistance is $R_{aw} = \frac{-k \cdot \cos(\beta)}{2 \cdot \omega_e} \int_0^{L} b' \cdot \left| V_{z_b} \right|^2 \cdot \partial x_b$ this method is very much related to the Strip theory; *b'* is the sectional damping coefficient for speed, for the different strips.

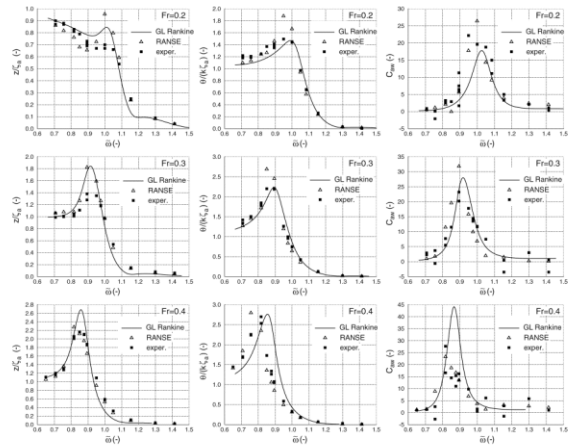
# Added Resistance in Irregular Head Waves

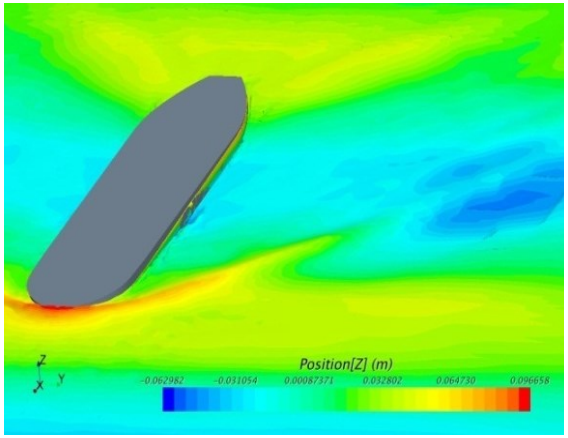
- Typically the ways to assess added resistance are:
  - ➢ Towing tank tests
  - ➢ CFD tools

- The range of wave to ship length is around 0.5-2, for large ships we need to go below this range, e.g. 0.15

- The problem in model scale testing is the low force values to be measured

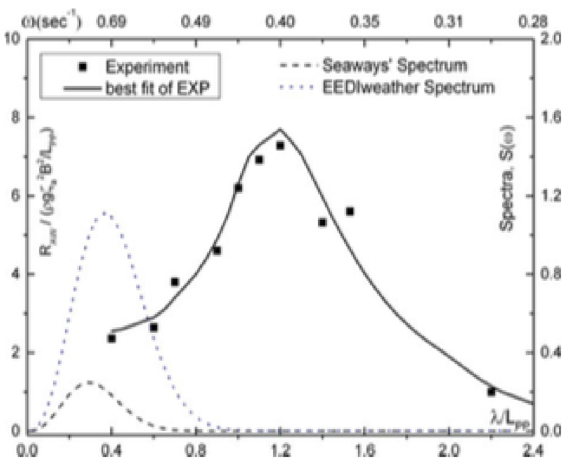
- The problem in CFD is that it requires very dense computational mesh

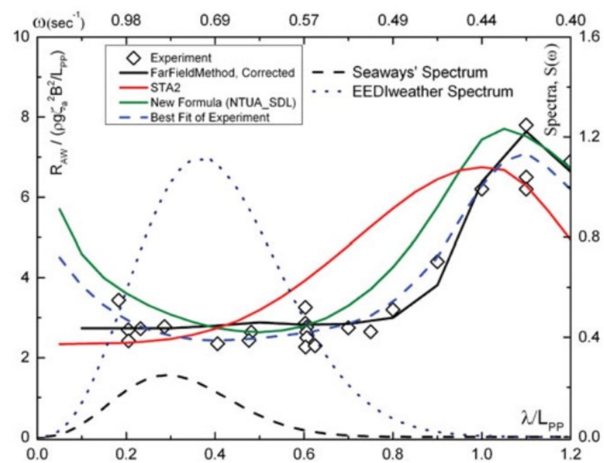


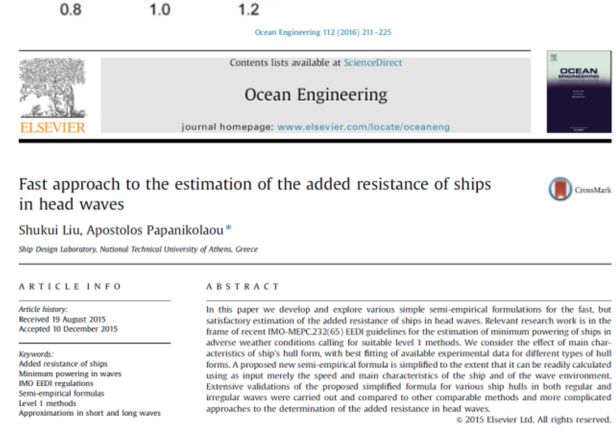



# Added Resistance in Irregular Head Waves

- The added resistance in short waves is due to diffraction and reflection effects
- The added resistance in long waves is due to motions
- Both of the cases have been discussed in Liu and Papanikolaou (10.1016/j.oceaneng.2015.12.022)



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Fast approach to the estimation of the added resistance of ships in head waves


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ABSTRACT

In this paper we develop and explore various simple semi-empirical formulations for the fast, but satisfactory estimation of the added resistance of ships in head waves. Relevant research work is in the frame of recent IMO-MEPC.232(65) EEDI guidelines for the estimation of minimum powering of ships in adverse weather conditions calling for suitable level 1 methods. We consider the effect of main characteristics of ship's hull form, with best fitting of available experimental data for different types of hull forms. A proposed new semi-empirical formula is simplified to the extent that it can be readily calculated using as input merely the speed and main characteristics of the ship and of the wave environment. Extensive validations of the proposed simplified formula for various ship hulls in both regular and irregular waves were carried out and compared to other comparable methods and more complicated approaches to the determination of the added resistance in head waves.




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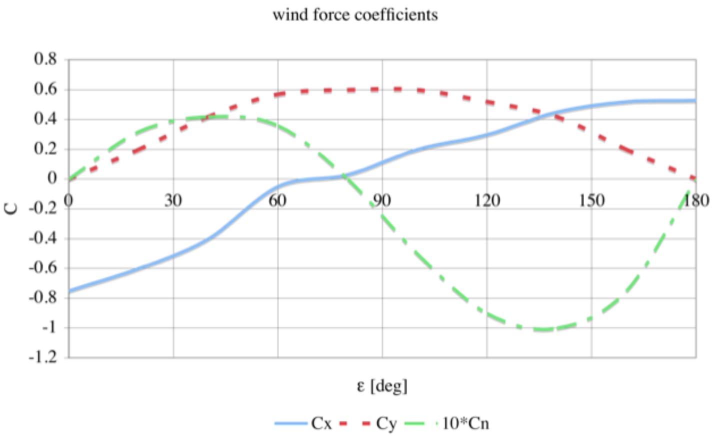
# Aerodynamic Forces

- For ship dynamics the hydrodynamic forces are not enough
- Aerodynamic loads may also play an important role
  - Strong side wind may disturb ship berthing
  - gusty side wind may cause large dynamic heeling
  - Strong head wind may increase resistance
  - maneuvering qualities of ship
  - + aerodynamics can cause funnel fumes to land on sundeck of a passenger ship
- Evaluation of the loads requires of the aerodynamic force coefficients
- These are given in the body- fixed co-ordinate system.
- If in-plane horizontal motion of ship is considered only, then two force components (x- and y-directional ones) and yawing moment coefficient are required
- The total resistance is

$$D_c = C_D \tfrac{1}{2} \rho_A U^2 A_s$$

where $A_s$ is the cross-sectional area of influence, U and $\rho_A$ the wind speed and air density and $C_D$ the drag coefficient to be determined by CFD or wind-tunnel tests



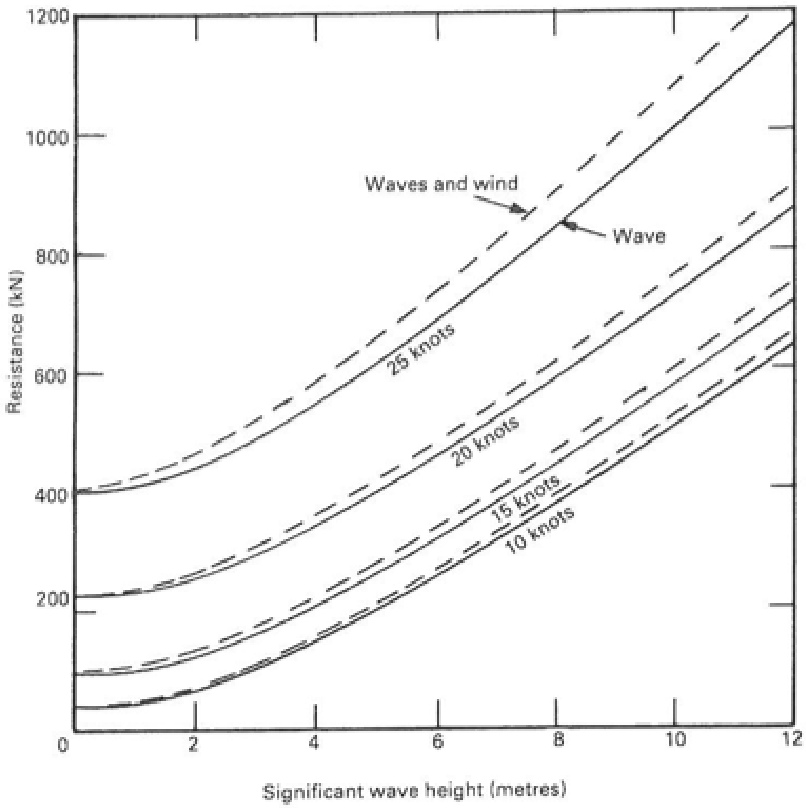
# Aerodynamic Forces

- The waves are typically present with the wind which increases the aerodynamic drag to

$$D_w = C_D \tfrac{1}{2} \rho_A (U + U_w)^2 A_s$$

- And the total drag is then

$$D_{aw} = C_D \tfrac{1}{2} \rho_A (U_w^2 + 2UU_w) A_s$$

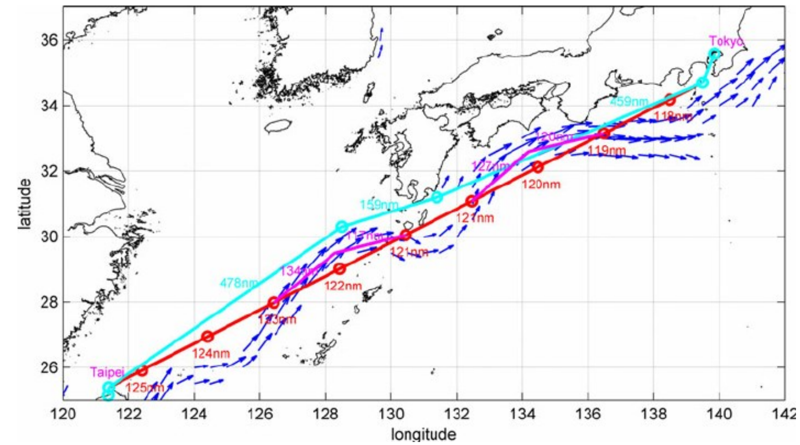


# Weather Routing

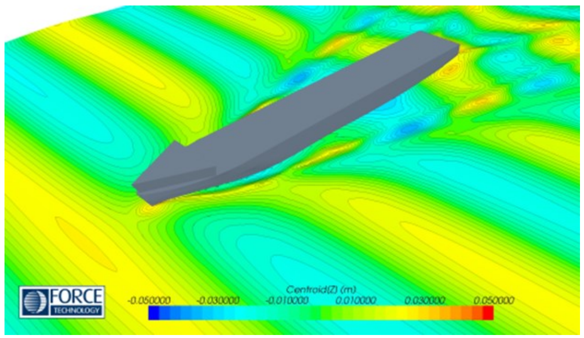
- When the added resistance can be predicted for various sea states, we can start to optimize the route for individual journeys
- We need to know the wave environment
  - Scatter diagram
  - Weather forecasts
- We need to know the RAO for added resistance
  - Measured from the ship
  - Simulations
  - Model scale experiments
- The RAO x sea state considers, as short time of 0.5-3hours
- The entire journey is set of short term responses
  - Several simulations are needed to assess the probabilities
  - Course can be changed based on weather forecasts to save fuel (EEDI)

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

| Wave height, m | Wave Period $T_1$, sec 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 |



# Part II : Ship Maneuvering




# Motivation

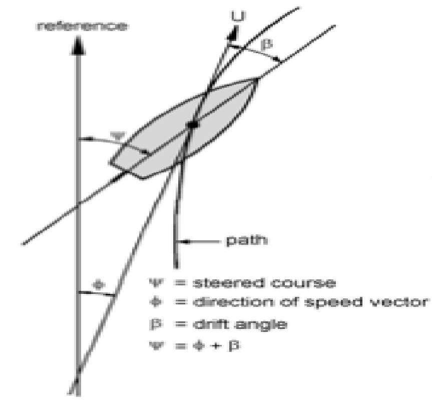
- Ship is a large moving mass that should be carefully controlled

- Motions are extremely slow
  - Response time not comparable to cars etc.
  - Stopping a ship might take kilometres

- Three aspects for good controllability:
  - Realistic specification and criteria for course keeping, manoeuvring and speed change
  - Design of hull and control equipment to meet these requirements
  - Validation with full-scale sea-trials to compare with specification and predictions

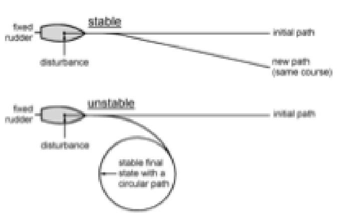
# Controllability & Motion Stability

- Controllability covers all aspects related to ship's:
  - Trajectory
  - Speed
  - Orientation
  - Positioning and station keeping

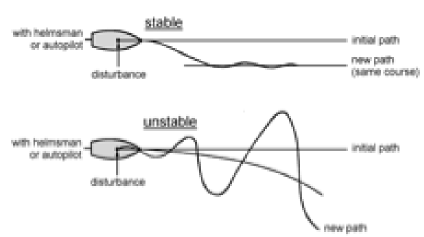



- Controllability is typically divided to three areas:
  - Course keeping and steering, i.e. maintaining steady mean course
  - Manoeuvring, i.e. changing the direction of the course
  - Speed changing, i.e. controlled speed change including stopping and backing

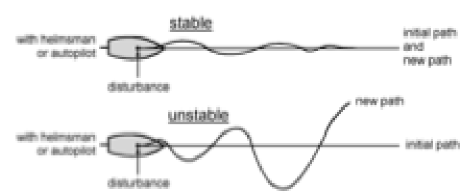
- Ship performance varies with water, depth, channel restrictions and hydrodynamics among other vessels and obstacles. The stability/instability of ship to in-plane motions can occur in (3) modes :




**Straight line dynamic stability**



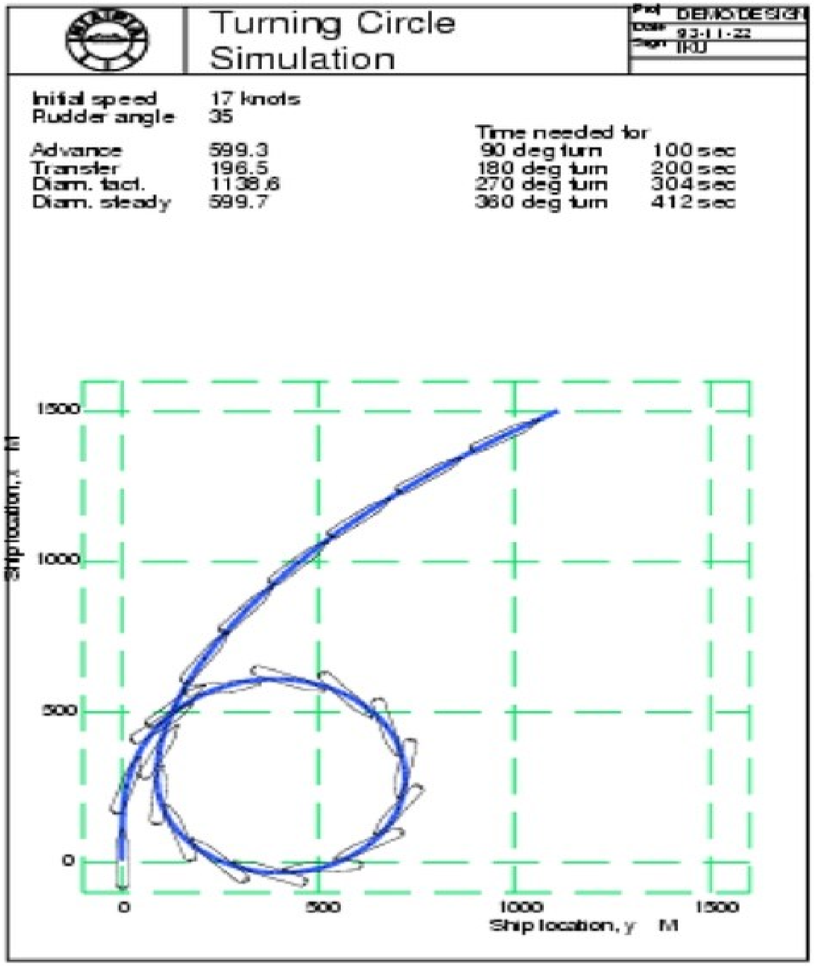

**Directional course stability**




**Path stability**

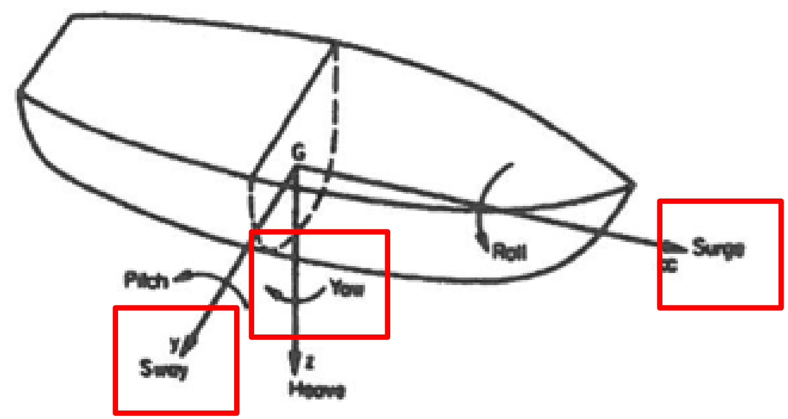
# Maneuvering models

- Mathematical maneuvering models are used mainly to
  - assess with the aid of ship maneuvering simulator the ship behavior, to train navigating officers and to develop a ship auto-pilot dedicated
  - the model can be complicated, consisting of three non-linear, coupled first order differential equations
- For directional stability and maneuverability the only purpose is to describe yaw and sway as accurately as necessary only for this purpose
- These models are coded to several design software



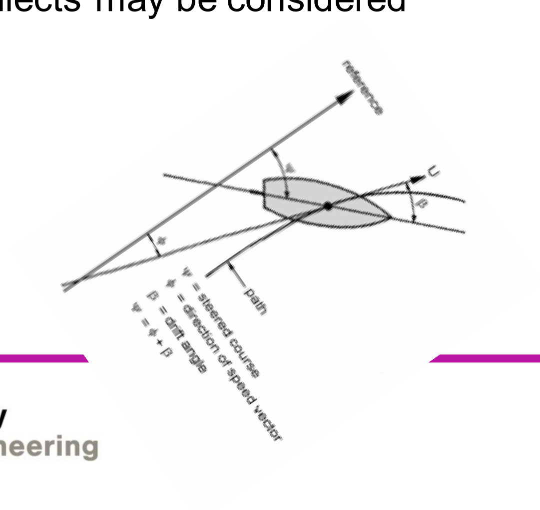
# Simple kinematic model assumptions

- 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

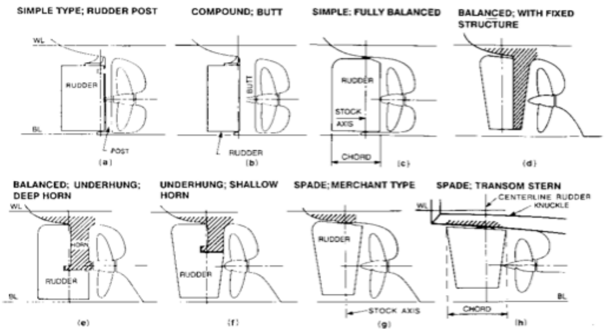



| Translation or rotation | Axis | Description | Positive sense |
|---|---|---|---|
| Translation | Along x | Surge | Forwards |
| | Along y | Sway | To starboard |
| | Along z | Heave | Downwards |
| Rotation | About x | Roll | Starboard side down |
| | About y | Pitch | Bow up |
| | About z | Yaw |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

*Fig. 12.1 Ship motions*



# Rudder Forces



[Source: PNA, 1989]

- Rudder is a fin that produces lift and drag

- Rudders produce large turning forces in comparison to their size. These forces give rise to the rudder moment which is influenced by the choice of the balance ratio of Rudder Area forward of the rudder stock and the Total Rudder Area. This ratio usually varies between 0.25-0.27 for most ships.

- Structural considerations, costs, the need for additional stabilizing side forces provided by a horn and the considerations may require use of other types of rudders such as the semi-suspended (or horn) rudder.

- The horn type is also favored for operations in ice

- This force causes further turning of a ship with causes additional attack of angle to the flow and turns the ship

# Rudder Forces

- All-movable rudders are desirable
  - ability to produce large turning forces for their size
  - required rudder moment is strongly influenced by a choice of the balance ratio
    - rudder area forward of the rudder stock divided by the total rudder area
    - Usually, this varies between 0.25-0.27 for ships

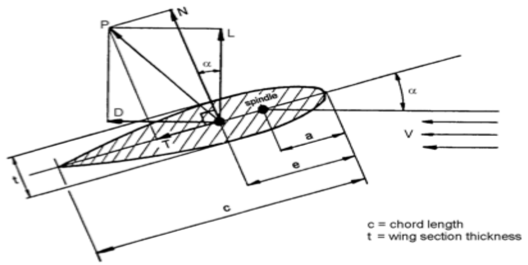



Figure 4.3: Forces on a Rudder Section

$$
\begin{aligned}
P &= \sqrt{L^2+D^2} = \sqrt{N^2+T^2} \\
N &= L\cos\alpha + D\sin\alpha \quad \text{and} \quad C_N = C_L\cos\alpha + C_D\sin\alpha \\
T &= D\cos\alpha - L\sin\alpha \quad \text{and} \quad C_T = C_D\cos\alpha - C_L\sin\alpha
\end{aligned}
$$

- Structural considerations, costs, the need for additional stabilizing side forces provided by a horn and the considerations may require use of other types of rudders such as the semi-suspended (or horn) rudder.

$$L = \frac{1}{2}\rho C_L A_R V_R^2,\ D = \frac{1}{2}\rho C_D A_R V_R^2,$$

- The horn type is also favored for operations in ice

$$C_L = \frac{2\pi\Lambda(\Lambda+1)}{(\Lambda+2)^2}\sin(\delta+\gamma), \qquad C_D = 1.1\frac{C_L^2}{\pi\Lambda} + C_{D0},$$

- Rudder is a fin that produces lift and drag

$$C_{D0} = 2.5 C_F = 2.5\frac{0.075}{(\log Rn - 2)^2},$$

- This force causes further turning of a ship with causes additional attack of angle to the flow and turns the ship

# IMO Requirements

*“The IMO Sub-Committee agreed that it would be permissible to demonstrate compliance with the standards by predicting trial performance through model tests and/or computer simulation. Moreover, when acceptable methods of prediction have demonstrated compliance with the standards, the results of full scale trials would not disqualify a ship.”*

## 4.4 Maneuverability Activities of IMO

During the last three decades, the IMO (International Maritime Organization) has been active in dealing with the following aspects on ship maneuverability, which are vital to achieve its objectives of safer shipping and cleaner oceans:

1. Maneuvering information aboard ships in order to enhance the safety of navigation.
2. Impaired maneuverability of tankers to reduce the risk of marine pollution.
3. Maneuvering standards for ship designers to ensure that no ships have maneuvering properties that may constitute a safety risk.

Many resolutions with respect to maneuverability of ships were initiated by the IMO Sub-Committee on Ship Design and Equipment and by the IMO Marine Safety Committee, which were adopted by the IMO Assembly; for detailed information see a paper of [Srivastava, 1993] and references given there. However, the IMO gives recommendations and guidelines only; they can not make international laws, the final decision has to be made by the individual Governments.

### 4.4.1 Maneuverability Information On-Board Ships

The value of readily available maneuvering information on the ship's bridge can not be overemphasized as it is of crucial importance to the master, navigating officers and pilots for discharging their duties efficiently and enhancing the safety of navigation.
Having regard to the variety of circumstances that a ship may encounter and the ship's characteristic maneuvering capabilities, the IMO Assembly adopted in 1968 in Resolution A.160 on "Recommendation on Data Concerning Maneuvering Capabilities and Stopping Distances of Ships". The Governments were urged to ensure that the master and the

# Mathematical background

- The forces and velocities are often scaled so that we can handle both model and full-scale with same parameters ($q=\rho u^2/2$, speed is initial speed)

$$\begin{Bmatrix} X' \\ Y' \\ K' \\ N' \end{Bmatrix} = \frac{1}{q \cdot L^2} \begin{Bmatrix} X \\ Y \\ K/L \\ N/L \end{Bmatrix} \quad \text{or} \quad \begin{Bmatrix} C_X \\ C_Y \\ C_K \\ C_N \end{Bmatrix} = \frac{1}{q \cdot L \cdot T} \begin{Bmatrix} X \\ Y \\ K/L \\ N/L \end{Bmatrix}$$

- Then the force coefficients can be determined with testing of CFD simulations in still water, resulting in e.g.

$$v' = v/u; \quad r' = r \cdot L/u; \quad \dot{u}' = \dot{u} \cdot L/u^2; \quad \dot{v}' = \dot{v} \cdot L/u^2; \quad \dot{r}' = \dot{r} \cdot L^2/u^2$$

$$Y' = Y'_{\dot{v}} \cdot \dot{v}' + Y'_{\dot{r}} \cdot \dot{r}' + Y'_{v} \cdot v' + Y'_{v^3} \cdot (v')^3 + Y'_{vr^2} \cdot v'(r')^2 + Y'_{v\delta^2} \cdot v'\delta^2 + Y'_{r} \cdot r' + Y'_{r^3} \cdot (r')^3 + \cdots$$

**Table 5.2** Non-dimensional hydrodynamic coefficient of four ship models (Wolff (1981)); values to be multiplied by $10^{-6}$

| Model of Initial $F_n$ | Tanker 0.145 | Series 60 0.200 | Container 0.159 | Ferry 0.278 |
|---|---|---|---|---|
| $m'$ | 14 622 | 11 432 | 6 399 | 6 765 |
| $x'_G m'$ | 365 | 57 | −127 | −116 |
| $I'_{zz}$ | 766 | 573 | 329 | 319 |
| $X'_{\dot{u}}$ | −1 077 | −1 064 | 0 | 0 |
| $X'_{\dot{u}u^2}$ | −5 284 | 0 | 0 | 0 |
| $X'_{u}$ | −2 217 | −2 559 | −1 320 | −4 336 |
| $X'_{u^2}$ | 1 510 | 0 | 1 179 | −2 355 |
| $X'_{u^3}$ | 0 | −2 851 | 0 | −2 594 |
| $X'_{v^2}$ | −889 | −3 908 | −1 355 | −3 279 |
| $X'_{r^2}$ | 237 | −838 | −151 | −571 |
| $X'_{\delta^2}$ | −1 598 | −1 346 | −696 | −2 879 |
| $X'_{v^2u}$ | 0 | −1 833 | −2 463 | −2 559 |
| $X'_{\delta^2u}$ | 2 001 | 2 536 | 0 | 3 425 |
| $X'_{r^2u}$ | 0 | 0 | −470 | −734 |
| $X'_{vr}$ | 9 478 | 7 170 | 3 175 | 4 627 |
| $X'_{v\delta}$ | 1 017 | 942 | 611 | 877 |
| $X'_{r\delta}$ | −482 | −372 | −340 | −351 |
| $X'_{vu}$ | 745 | 0 | 0 | 0 |
| $X'_{vu^2}$ | 0 | 0 | −207 | 0 |
| $X'_{ru}$ | 0 | −270 | 0 | 0 |
| $X'_{r}$ | 48 | 0 | 0 | −19 |
| $X'_{\delta}$ | 166 | 0 | 0 | 0 |
| $X'_{\delta u^2}$ | 0 | 150 | 0 | 0 |
| $X'_{v^2\delta}$ | −4 717 | 0 | 0 | 0 |
| $X'_{r^2\delta}$ | −365 | 0 | 0 | 0 |
| $X'_{v^3}$ | 1 164 | 2 143 | 0 | 0 |
| $X'_{r^3}$ | −118 | 0 | 0 | 0 |
| $X'_{\delta^3u}$ | −278 | 0 | 0 | 0 |
| $X'_{\delta^4}$ | 0 | 621 | 213 | 2 185 |
| $X'_{v^3u}$ | 0 | 0 | −3 865 | 0 |
| $X'_{r^3u}$ | 0 | 0 | −447 | 0 |

**Longitudinal forces *X***

| Model of | Tanker | Series 60 | Container | Ferry |
|---|---|---|---|---|
| $Y'_{\dot{v}}$ | −11 420 | −12 608 | −6 755 | −7 396 |
| $Y'_{\dot{v}v^2}$ | −21 560 | −34 899 | −10 301 | 0 |
| $Y'_{\dot{r}}$ | −714 | −771 | −222 | −600 |
| $Y'_{\dot{r}r^2}$ | −468 | 166 | −63 | 0 |
| $Y'_{0}$ | −244 | 26 | 0 | 0 |
| $Y'_{u}$ | 263 | −69 | −33 | 57 |
| $Y'_{v}$ | −15 338 | −16 630 | −8 470 | −12 095 |
| $Y'_{v^3}$ | −36 832 | −45 034 | 0 | −137 302 |
| $Y'_{vr^2}$ | −19 040 | −37 169 | −31 214 | −44 365 |
| $Y'_{v\delta^2}$ | 0 | 0 | −4 668 | 2 199 |
| $Y'_{r}$ | 4 842 | 4 330 | 2 840 | 1 901 |
| $Y'_{r^2}$ | 0 | 152 | 85 | 0 |
| $Y'_{r^3}$ | 1 989 | 2 423 | −1 945 | −1 361 |
| $Y'_{ru}$ | 0 | −1 305 | 2 430 | −1 297 |
| $Y'_{ru^2}$ | 0 | 0 | 4 769 | 0 |
| $Y'_{rv^2}$ | 22 878 | 10 230 | −33 237 | −36 490 |
| $Y'_{r\delta^2}$ | 1 492 | 0 | 0 | −2 752 |
| $Y'_{\delta}$ | 3 168 | 2 959 | 1 660 | 3 587 |
| $Y'_{\delta^2}$ | 0 | 0 | 0 | 98 |
| $Y'_{\delta^3}$ | 3 621 | −7 494 | 0 | 0 |
| $Y'_{\delta^4}$ | 1 552 | 613 | −99 | 0 |
| $Y'_{\delta^5}$ | −5 526 | 4 344 | −1 277 | −6 262 |
| $Y'_{\delta v^2}$ | 0 | 0 | 13 962 | 0 |
| $Y'_{\delta r^2}$ | 1 637 | 0 | 2 438 | 0 |
| $Y'_{\delta u}$ | −4 562 | −4 096 | 0 | −5 096 |
| $Y'_{\delta u^2}$ | 0 | 974 | 0 | 0 |
| $Y'_{\delta^3u}$ | 2 640 | 4 001 | 0 | 3 192 |
| $Y'_{v\|v\|}$ | −11 513 | −19 989 | −47 566 | 0 |
| $Y'_{r\|r\|}$ | −351 | 0 | 1 731 | 0 |
| $Y'_{\delta\|\delta\|}$ | −889 | 2 029 | 0 | 0 |
| $Y'_{v^3r}$ | 12 398 | 0 | 0 | 0 |
| $Y'_{r^3u}$ | 0 | 2 070 | 0 | 0 |

**Transverse forces *Y***

| Model of | Tanker | Series 60 | Container | Ferry |
|---|---|---|---|---|
| $N'_{\dot{v}}$ | −523 | 326 | 239 | 426 |
| $N'_{\dot{v}v^2}$ | 2 311 | 1 945 | 5 025 | 10 049 |
| $N'_{\dot{r}}$ | −576 | −461 | −401 | −231 |
| $N'_{\dot{r}r^2}$ | −130 | −250 | 132 | 0 |
| $N'_{0}$ | 67 | 9 | 0 | 0 |
| $N'_{u}$ | −144 | 37 | 8 | −36 |
| $N'_{v}$ | −5 544 | −6 570 | −3 800 | −3 919 |
| $N'_{v^2}$ | −132 | 0 | 0 | 0 |
| $N'_{v^3}$ | −2 718 | −16 602 | −23 865 | −33 857 |
| $N'_{vu}$ | 0 | −1 146 | −2 179 | −3 666 |
| $N'_{vr^2}$ | 3 448 | 4 421 | −4 586 | 0 |
| $N'_{v\delta^2}$ | 2 317 | 0 | 1 418 | 570 |
| $N'_{r}$ | −3 074 | −2 900 | −1 960 | −2 579 |
| $N'_{r^2}$ | 0 | −45 | 0 | 0 |
| $N'_{r^3}$ | −865 | −1 919 | −729 | −2 253 |
| $N'_{ru}$ | 0 | 0 | −473 | 0 |
| $N'_{ru^2}$ | 913 | 0 | 0 | 0 |
| $N'_{rv^2}$ | −16 196 | −20 530 | −27 858 | −60 110 |

| Model of | Tanker | Series 60 | Container | Ferry |
|---|---|---|---|---|
| $N'_{r\delta^2}$ | −324 | 0 | −404 | 237 |
| $N'_{\delta}$ | −1 402 | −1 435 | −793 | −1 621 |
| $N'_{\delta^2}$ | 0 | −138 | 0 | −73 |
| $N'_{\delta^3}$ | −1 641 | 3 907 | 0 | 0 |
| $N'_{\delta^4}$ | −536 | 0 | 0 | 0 |
| $N'_{\delta^5}$ | 2 220 | −2 622 | 652 | 2 886 |
| $N'_{\delta v^2}$ | 0 | 0 | −6 918 | −2 950 |
| $N'_{\delta r^2}$ | −855 | 0 | −1 096 | −329 |
| $N'_{\delta u}$ | 2 321 | 1 856 | 0 | 2 259 |
| $N'_{\delta u^2}$ | 0 | −568 | 0 | 0 |
| $N'_{\delta^2u}$ | 316 | 0 | 0 | 0 |
| $N'_{\delta^3u}$ | −1 538 | −1 964 | 0 | −1 382 |
| $N'_{v\|v\|}$ | 0 | 5 328 | 8 103 | 0 |
| $N'_{r\|r\|}$ | 0 | 0 | −1 784 | 0 |
| $N'_{vr}$ | −394 | 0 | 0 | 0 |
| $N'_{\delta\|\delta\|}$ | 384 | −1 030 | 0 | 0 |
| $N'_{v^3u}$ | −27 133 | −13 452 | 0 | 0 |
| $N'_{r^3u}$ | 0 | −476 | 0 | −1 322 |

# Mathematical background

- For small deviations from initial, straight path, the motions can be approximated with

$$(X'_{\dot{u}} - m')\dot{u}' + X'_u \Delta u' + X'_n \Delta n' = 0$$
$$(Y'_{\dot{v}} - m')\dot{v}' + (Y'_{\dot{r}} - m'x'_G)\dot{r} + Y'_v v' + (Y'_r - m')r' = -Y'_\delta \delta$$
$$(N'_{\dot{v}} - m'x'_G)\dot{v}' + (N'_{\dot{r}} - I'_{xx})\dot{r} + N'_v v' + (N'_r - m'x'_G)r' = -N'_\delta \delta$$

where $m' = m/(1/2\rho L^2)$, $I'_{zz} = I_{zz}/(1/2\rho L^5)$ and

- For the linearized case, we get $I_{zz} = \int (x^2 + y^2)\,\mathrm{d}m$

$$M'\dot{\vec{u}}' + D'\vec{u}' = \vec{r}'\delta + \begin{Bmatrix} T' \\ T'x'_t \end{Bmatrix}$$

Mass

Motion

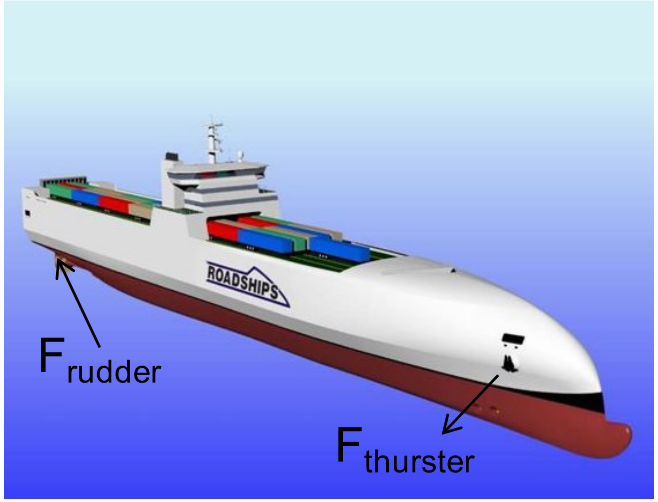
$$M' = \begin{bmatrix} -Y'_{\dot{v}} + m' & -Y'_{\dot{r}} + m'x_G \\ -N'_{\dot{v}} + m'x_G & -N'_{\dot{r}} + I_{zz} \end{bmatrix}; \quad \vec{u}' = \begin{Bmatrix} v' \\ r' \end{Bmatrix}$$

$$D' = \begin{bmatrix} -Y'_v & -Y'_r + m' \\ -N'_v & -N'_r + m'x'_G \end{bmatrix}; \quad \vec{r}' = \begin{Bmatrix} Y'_\delta \\ N'_\delta \end{Bmatrix} \qquad \begin{Bmatrix} T' \\ T'x'_t \end{Bmatrix}$$

Damping

Rudder

Thrusters



# Mathematical background

- Regression formulae for the coefficients

$$Y'_{\dot{v}} = -\pi (T/L)^2 \cdot (1 + 0.16 C_B \cdot B/T - 5.1 (B/L)^2)$$
$$Y'_{\dot{r}} = -\pi (T/L)^2 \cdot (0.67 B/L - 0.0033 (B/T)^2)$$
$$N'_{\dot{v}} = -\pi (T/L)^2 \cdot (1.1 B/L - 0.041 B/T)$$
$$N'_{\dot{r}} = -\pi (T/L)^2 \cdot (1/12 + 0.017 C_B \cdot B/T - 0.33 B/L)$$
$$Y'_{v} = -\pi (T/L)^2 \cdot (1 + 0.40 C_B \cdot B/T)$$
$$Y'_{r} = -\pi (T/L)^2 \cdot (-0.5 + 2.2 B/L - 0.08 B/T)$$
$$N'_{v} = -\pi (T/L)^2 \cdot (0.5 + 2.4 T/L)$$
$$N'_{r} = -\pi (T/L)^2 \cdot (0.25 + 0.039 B/T - 0.56 B/L)$$

- The non-linear model involves second order terms of the velocities and rudder angle, but also cross-products of the different components. The equations are (see for details Matusiak book)

$$\begin{aligned} X = {} & X_{\dot{u}}\dot{u} + X_u u + X_{uu}u^2 + X_{uuu}u^3 + X_{vv}v^2 + X_{rr}r^2 + X_{\delta\delta}\delta^2 \\ & + X_{vr}vr + X_{v\delta}v\delta + X_{r\delta}r\delta + X_{vvu}v^2u + X_{rru}r^2u + X_{\delta\delta u}\delta^2 u \\ & + X_{r\delta u}r\delta u + X_{rvu}rvu + X_{v\delta u}v\delta u + X_{r\delta v}r\delta v. \end{aligned}$$

$$\begin{aligned} Y = {} & Y_{uu}u^2 + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + Y_r r + Y_\delta \delta + Y_{\delta u}\delta u + Y_{vu}vu + Y_{ru}ru + Y_{vuu}vu^2 \\ & + Y_{ruu}ru^2 + Y_{\delta uu}\delta u^2 + Y_{vvv}v^3 + Y_{rrr}r^3 + Y_{\delta\delta\delta}\delta^3 + Y_{rr\delta}r^2\delta + Y_{vrr}vr^2 \\ & + Y_{rvv}rv^2 + Y_{\delta vv}\delta v^2 + Y_{vr\delta}vr\delta + Y_{\delta\delta r}\delta^2 r + Y_{\delta\delta v}\delta^2 v. \end{aligned}$$

$$\begin{aligned} N = {} & Y_{uu}u^2 + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v + N_r r + N_\delta \delta + N_{\delta u}\delta u + N_{vu}vu + N_{ru}ru + N_{vuu}vu^2 \\ & + N_{ruu}ru^2 + N_{\delta uu}\delta u^2 + N_{vvv}v^3 + N_{rrr}r^3 + N_{\delta\delta\delta}\delta^3 + N_{rr\delta}r^2\delta + N_{vrr}vr^2 \\ & + N_{rvv}rv^2 + N_{\delta vv}\delta v^2 + N_{vr\delta}vr\delta + N_{\delta\delta r}\delta^2 r + N_{\delta\delta v}\delta^2 v. \end{aligned}$$

# CFD & Model tests

- Linear system leads often to good results in terms of comparing different design alternatives, but unsatisfactory results when accuracy is concerned

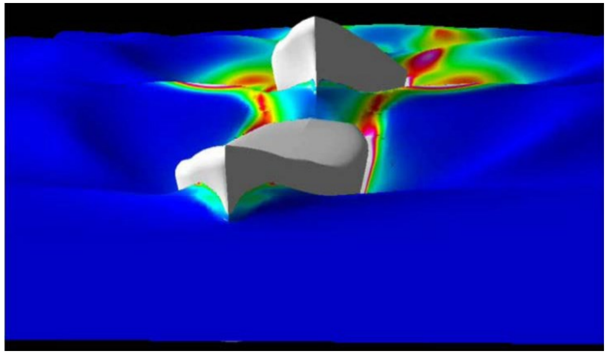
- CFD is the future of the maneuvering predictions as well
  - ➢ Lifting surface methods (inviscid flow about a plate)
  - ➢ Lifting body methods (source distributions to model body thickness)
  - ➢ Field methods (accounting also the viscous effects)

- These methods can be coupled to account free-surface effects

| | Type of Test | IMO A.601 | IMO A.751 | ITTC 1975 | SNAME 1989 | Norsk Standard | Japan RR |
|---|---|---|---|---|---|---|---|
| 1 | Turning Test | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 2 | Z-Maneuver Test (Kempf) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 3 | Modified Z-Maneuver Test | | | | | | ✓ |
| 4 | Direct Spiral Test (Dieudonné) | | | ✓ | ✓ | ✓ | ✓ |
| 5 | Reverse Spiral Test (Bech) | | | ✓ | ✓ | ✓ | ✓ |
| 6 | Pull-Out Test | ✓ | | ✓ | ✓ | | |
| 7 | Stopping Test | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 8 | Stopping Inertia Test | ✓ | | | | ✓ | ✓ |
| 9 | New Course Keeping Test | ✓ | | | | | ✓ |
| 10 | Man-Overboard Test | ✓ | | | | | |
| 11 | Parallel Course Maneuver Test | ✓ | | | | | |
| 12 | Initial Turning Test | | | | ✓ | | |
| 13 | Z-Maneuver Test at Low Speed | ✓ | | | ✓ | | ✓ |
| 14 | Accelerating Turning Test | ✓ | | ✓ | | | |
| 15 | Acceleration/Deceleration Test | ✓ | | | ✓ | | |
| 16 | Thruster Test | ✓ | | ✓ | ✓ | ✓ | |
| 17 | Minimum Revolution Test | ✓ | | | ✓ | ✓ | |
| 18 | Crash Ahead Test | ✓ | | | ✓ | ✓ | ✓ |

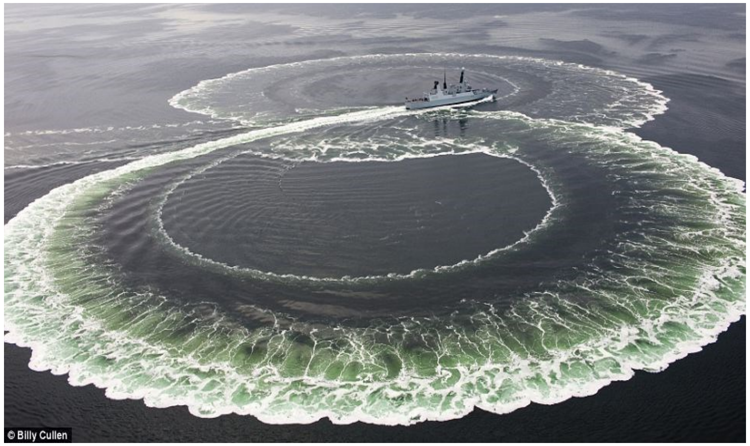
Table 4.1. Recommended Maneuvering Tests by Various Organizations

- Experiments should represent the load conditions ship has during its lifetime. The site of experiments should have
  - ➢ Adequate water depth
  - ➢ Enough distance to geographical flow disturbances
  - ➢ Mild wave and wind conditions
  - ➢ No currents



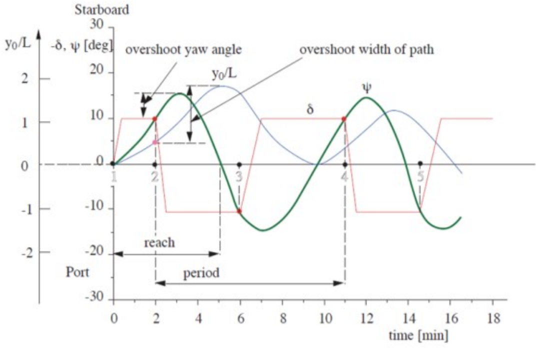
# Sea Trials

Sea trials are carried out after the dock tests to demonstrate proper operation of the main and auxiliary machinery, including monitoring, alarm and safety systems, under realistic conditions. The trials are also to demonstrate that any vibration which may occur within the operating speed range is acceptable.

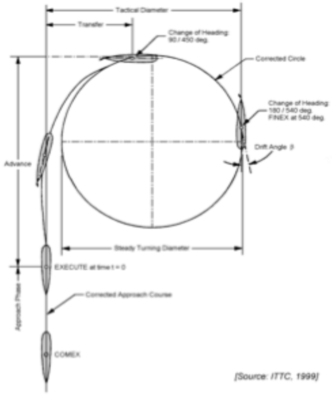


# Zig-Zag / Turning manouvering test

- **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

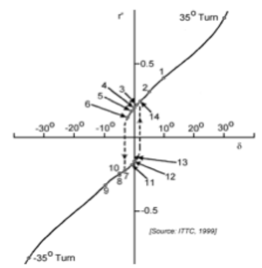



- **Turning :** to determine the turning characteristics of the ship at different speeds and rudder angles.
  Information obtained:
  - advance,
  - transfer,
  - tactical diameter,
  - steady turning diameter,
  - final ship speed
  - turning rate in the steady state



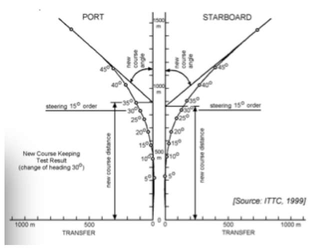
[Source: ITTC, 1999]

# Direct spiral, new course keeping, acceleration tests

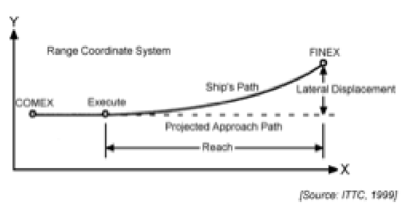



- **Direct Spiral :** The purpose is to find out if the ship is directionally stable or not. Important parameters are width and height of the loop for an unstable ship

- **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



# Summary

- The speed of a ship in calm water is defined by her **(1)** Resistance: wave + friction **(2)** Propeller efficiency **(3)** Power of engines

- In rough weather the resistance may be changed by the action of **(1)** Waves, **(2)** Wind, **(3)** Current **(4)** Ice

- Typically the change of load also affects the propeller efficiency and furthermore the speed we can obtain with certain main engine

- This is called involuntary loss of speed which can cause economically substantial losses

- Three key aspects for good controllability:
  - Realistic specification and criteria for course-keeping, manoeuvring and speed change
  - Design of hull and control equipment to meet these requirements
  - Validation with full-scale sea-trials to compare with specification and predictions

- Controllability covers all aspects related to ship's: **(1)** Trajectory **(2)** Speed **(3)** Orientation **(4)** Positioning and station keeping

- Performance varies with water, depth, channel restrictions and hydrodynamics among other vessels and obstacles