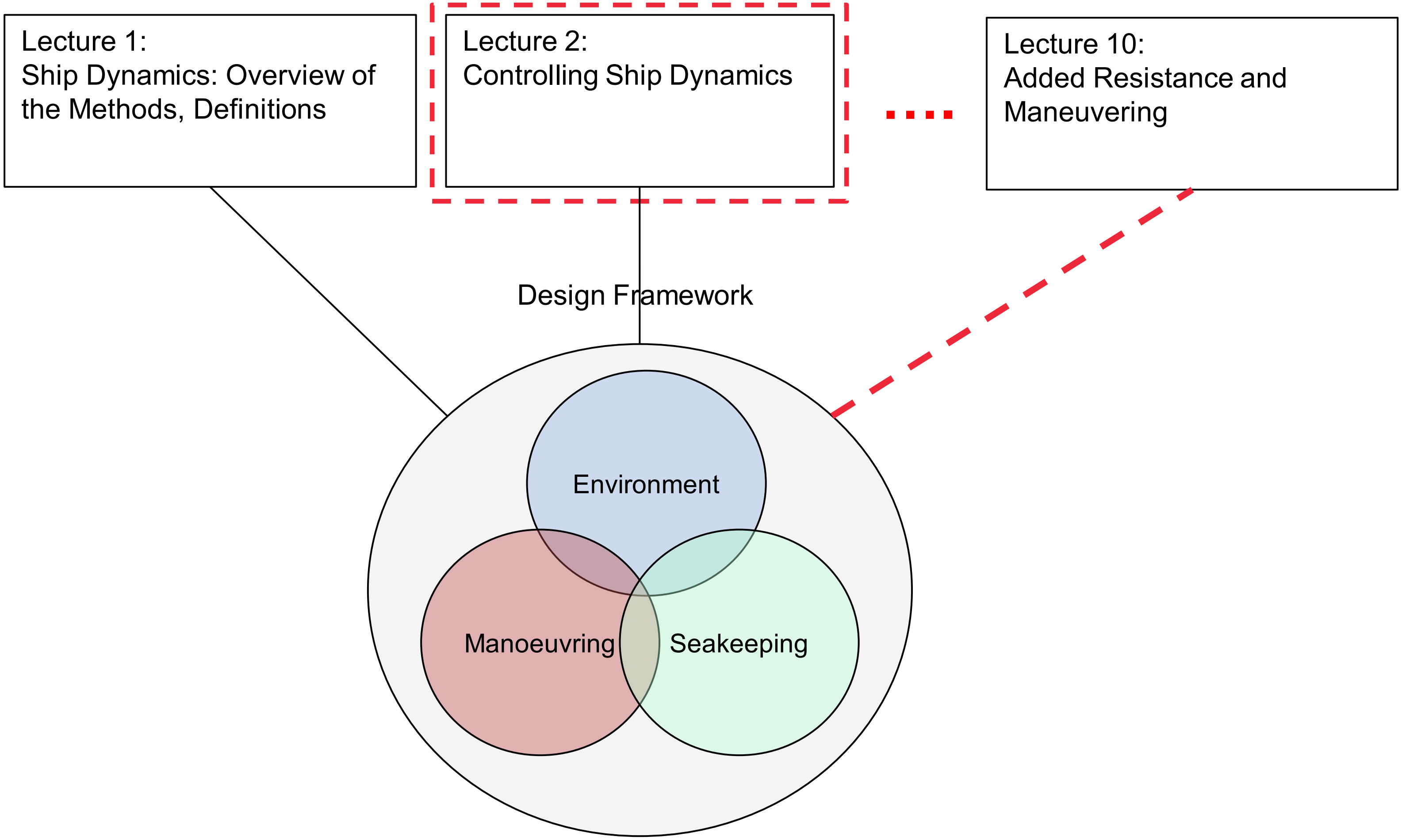
Aalto University
School of Engineering

MEC-E2004 Ship Dynamics (L)

Lecture 2

Controlling Ship Dynamics

Where is this lecture on the course?



Contents

Aims

- To understand how equipment and hull form affect ship dynamics.
- With reference to equipment : To appreciate the influence of propulsive control systems on ship dynamics and associated design choices.

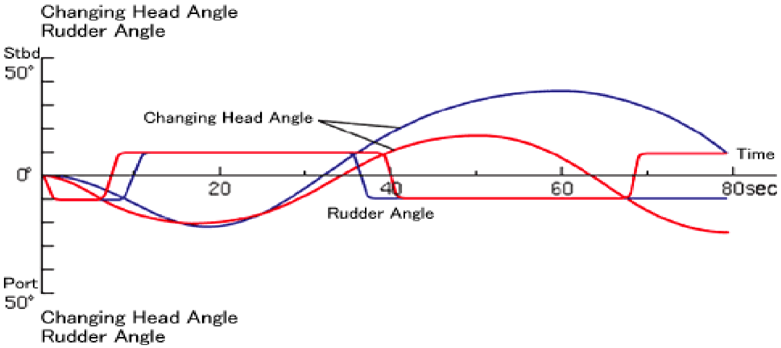
Keywords

- ***Propulsive control systems / Equipment:*** Rudder, Propeller, Pods, Thrusters,Bilge keels and stabilizer fins, Passive tanks
- ***Hull form dynamics, Controlability, Auto-pilot Systems***

Literature

- Bertram, V., ”Practical Ship Hydrodynamics”, Butterworth-Heinemann, Ch. 4, 5
- Lewis, E. V. “Principles of Naval Architecture - Motions in waves and controllability”, Vol. 3, Society of Naval Architects and Marine Engineers, Chapters 8 and 9
- Matusiak, J., ” Dynamics of a Rigid Ship”, Aalto University
- Journee, J., and Pinkster, J., ”Introduction in Ship Hydromechanics”, Delft University of Technology, April 2002.
- K.J. Rawson and E.C. Tupper, Basic Ship Theory, 5th Edition, Various Chapters, ISBN: 978-0-7506-5398-5



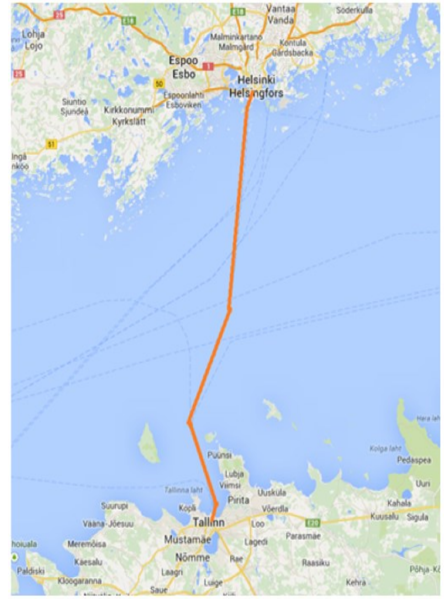



Assignment 1

- **Grades 1-3**
  - ✓ Select a book-chapter related to ship dynamics and read it
  - ✓ Define the operational profile for your ship, operations including seasonal effects and ship dynamics requirements
  - ✓ Define the shape, size, location and space reservation of the maneuvering devices of your ship and sketch them on top of your hull (Napa-input)
  - ✓ Describe the main features of your ship's hull form that affect the ship dynamics

- **Grades 4-5**
  - ✓ Read 1-2 scientific journal articles related to ship dynamics
  - ✓ Reflect these in relation to knowledge from books and lecture slides

- **Report and discuss the work**

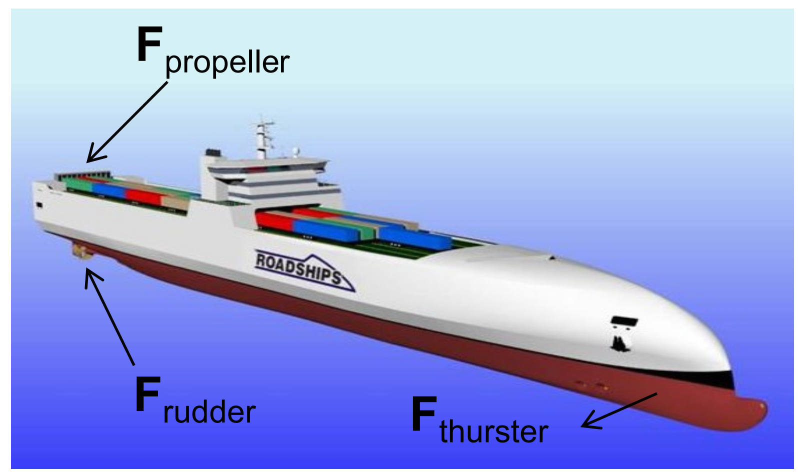


Baltic Sea
- 9 months in open water
- 3 months in ice

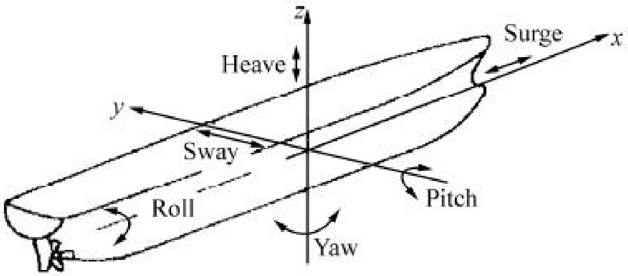
X trips per day/week
Y speed
Z cars and ZZ busses
…

Ice loads affect in-plane motions
Parametric rolling possible due to aft shape
Slamming due to bow shape
…

Any other relevant info for Ship dynamics, such as
- Moving cargo
- …



Motivation



- A ship should be able to operate according to her mission
- A ship is a dynamic system. The dynamics are affected by the environment, hull form and the appedanges (propulsive equipment)
- A ship is a body moving in 6 rigid dof (+ N distortions)
- The hull form interaction with water waves affects the seakeeping performance and loading / dynamics of the ship
- **Appendages (propeller, rudder, pods, thrusters, etc.) imply forces and moments on the hull and they interact with the wave environment. By altering the properties of this system we may affect dynamics and hence change (increase or reduce) motions, hull resistance and manoeuvrability leading to better or worse performance and increased or reduced safety**
- Moving cargo loads and onboard equipment (e.g. Heavy lift Cranes) may also affect motions and should be considered if/as applicable

Motivation

- Once we select the main dimensions and the mission of a vessel we have defined (to certain extend) the bounds of her seaworthiness

- Motions are in principle an undesirable feature and we need to reduce them

- **The use of "Motion stabilisation" methods, propulsors and auxiliary appendages / equipment can be very important and should be appreciated at concept design stage**

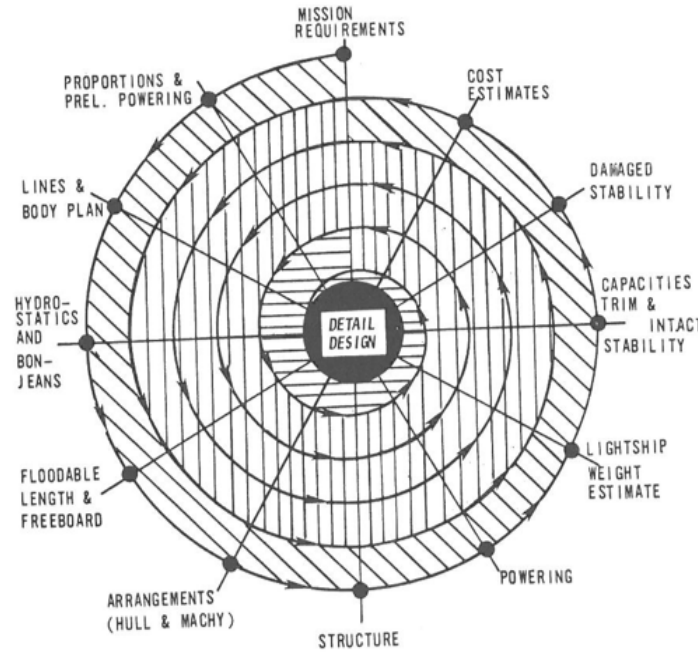
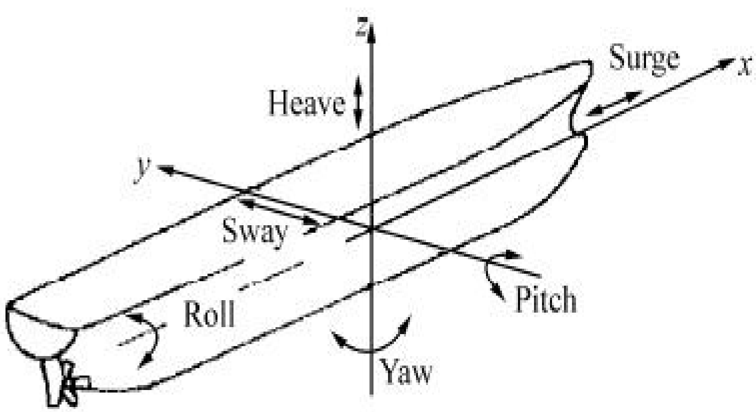


Fig. 1 Basic design spiral

Introduction to rigid body motions

- The dynamic behavior of ship can be defined by :
  - 6 degrees of freedom
  - 6 equations of motion
- The constants are determined based on
  - Hull form and weight distribution of ship
  - Added mass
  - Flows due to appendages and propulsion



The 6-DoF equation of motion in matrix format is

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

where for example the “mass” and “stiffness” matrixes are

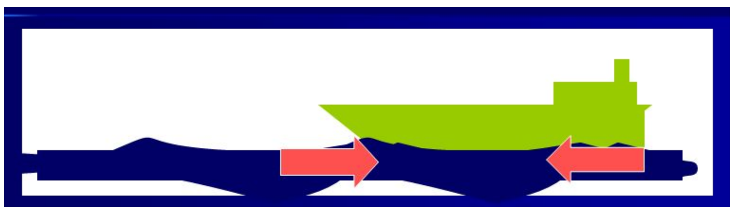
$$M = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & 0 \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & 0 & -mx_g & 0 \\ 0 & -mz_g & 0 & \theta_{xx} & 0 & -\theta_{xz} \\ mz_g & 0 & -mx_g & 0 & \theta_{yy} & 0 \\ 0 & mx_g & 0 & -\theta_{xz} & 0 & -\theta_{zz} \end{bmatrix}$$

$$S = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_w & 0 & -\rho g A_w x_w & 0 \\ 0 & 0 & 0 & gm\overline{GM} & 0 & 0 \\ 0 & 0 & -\rho g A_w x_w & 0 & gm\overline{GM}_L & 0 \\ 0 & 0 & 0 & 0 & 0 & \theta_{zz}\omega_g^2 \end{bmatrix}$$

V. Bertram – Practical Ship Hydrodynamics, Chapter 4, Ship Seakeeping (pp. 143-204), Butterworth - Heinemann, 2012, ISBN 9780080971506 ; https://doi.org/10.1016/B978-0-08-097150-6.10004-1.

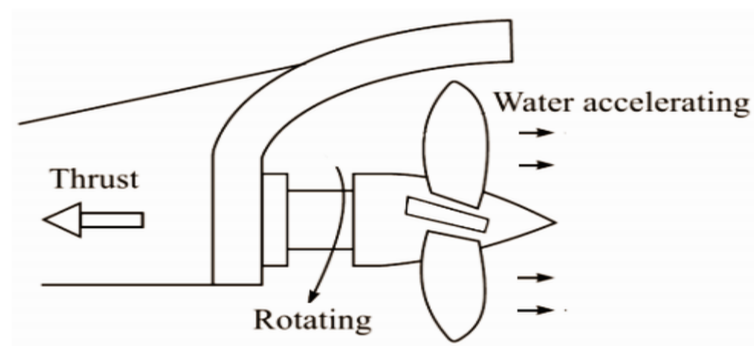
Ship Resistance & Propeller Trust (Method 1)

- The ideal world : Resistance magnitude = Thrust magnitude
- Resistance + Thrust magnitudes do not change.
- If there is a change of ship's speed during the maneuvers it is caused by cross-coupling between ship speed and angular inflow velocity (see vector derivatives ; *term r'v'* Ref.: J. Matusiek Book on Rigid body ship dynamics, page 37, section 5.7, paragraph 1)



THRUST > RESIST

- **Ship** ***accelerates***
- **Resistance** increases with speed
  - Until **Resistance = Thrust**
  - Ship at new, faster speed



Is Method 1 reallistic?

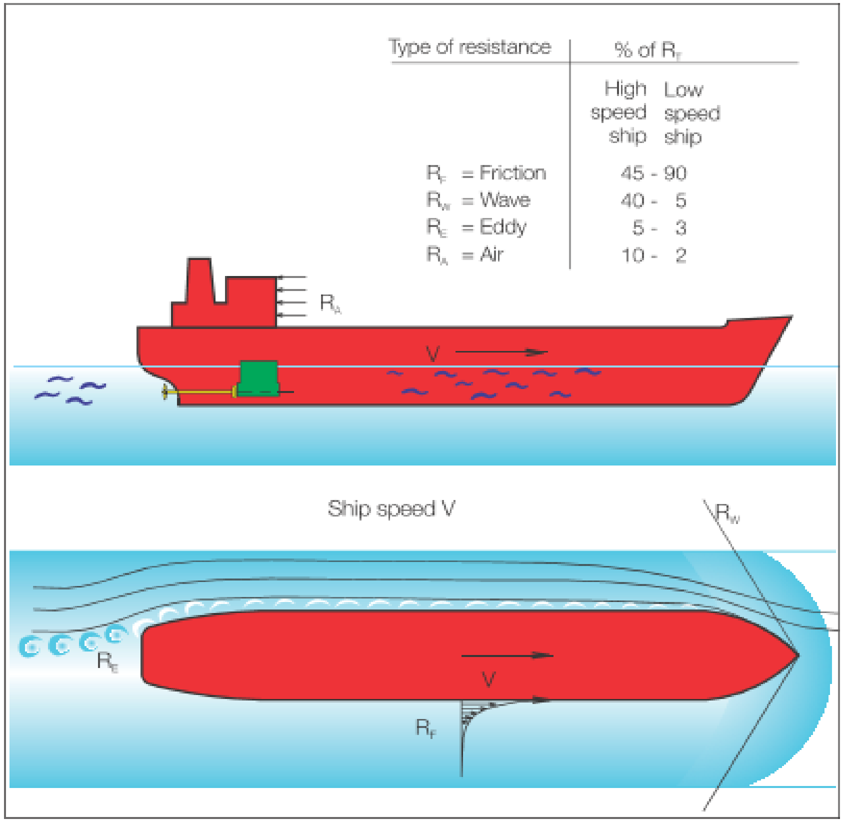
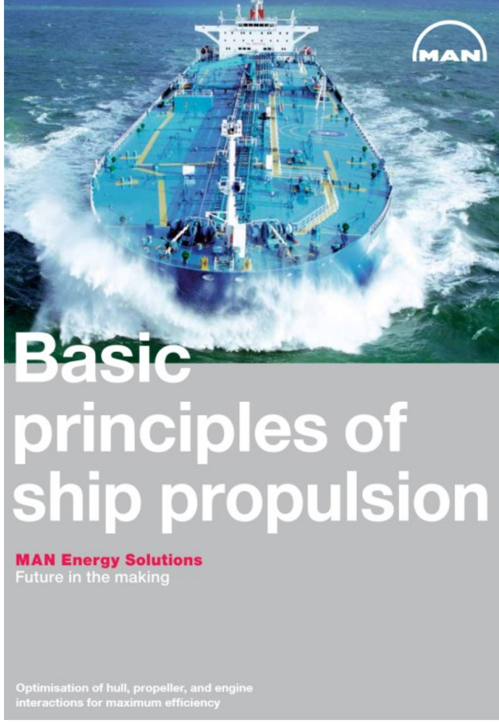
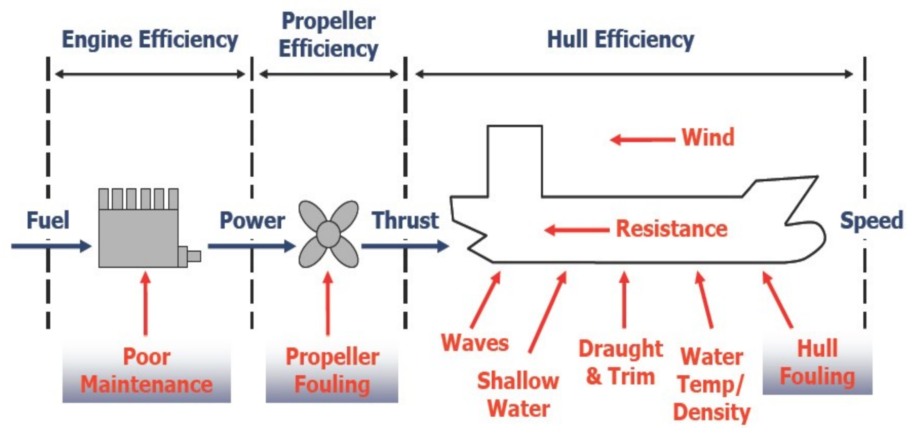


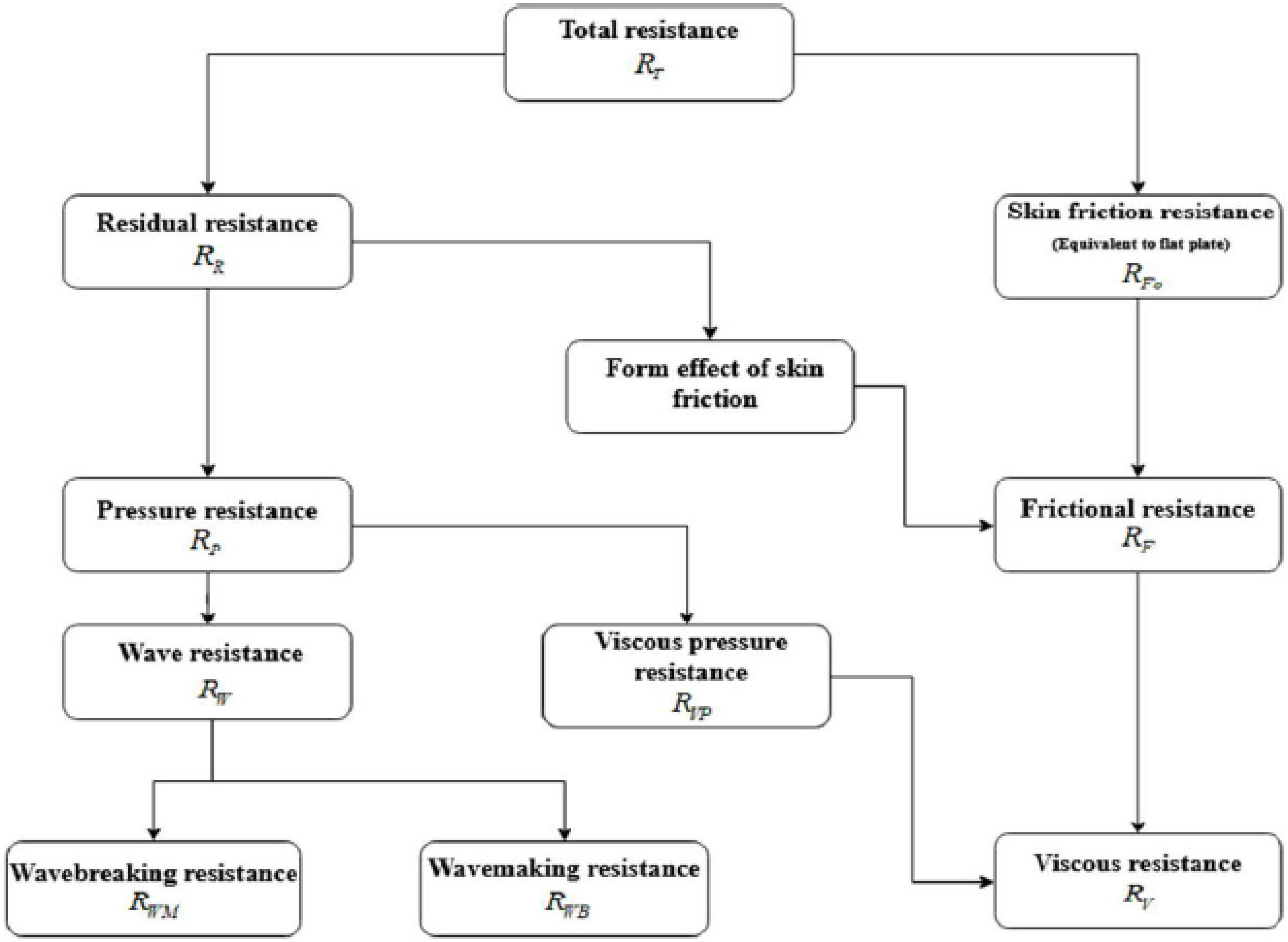
Fig. 4: Total ship towing resistance $R_T = R_F + R_W + R_E + R_A$





MAN, Basic principles of ship propulsion
[Basic Principles of Ship Propulsion - MAN Diesel SE - PDF Catalogs | Documentation | Boating Brochures (nauticexpo.com)]

Is Method 1 reallistic?

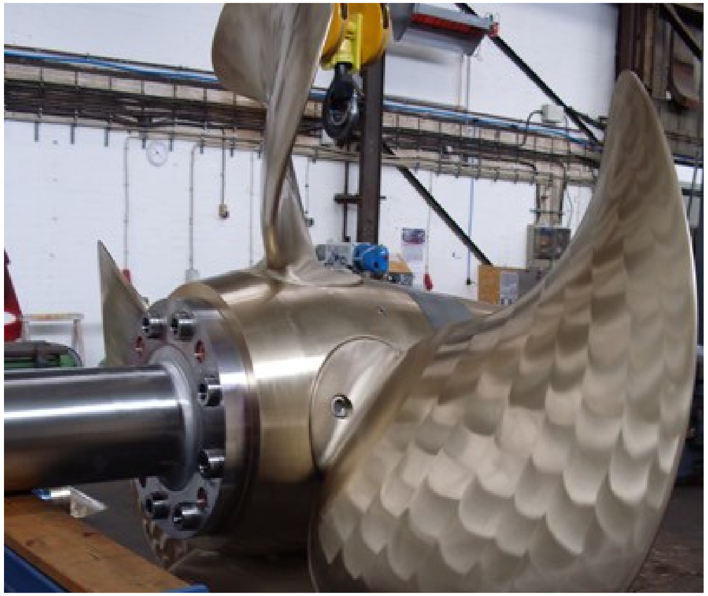


V. Bertram – Practical Ship Hydrodynamics, Chapter 3, Resistance and Propulsion (pp. 73-141), Butterworth - Heinemann, 2012, ISBN 9780080971506 ; https://doi.org/10.1016/B978-0-08-097150-6.10003-X

Ship Resistance & Propeller Thrust (Method 2 – The modular model)

- **Thrust deduction fraction principle**

The propeller increases the resistance of the ship by increasing the velocity along the hull (generally a small effect) and by decreasing the pressure around the stern. The increase of resistance due to the propeller action is expressed as the thrust deduction fraction $t = \frac{T - R_T}{T}$ where R_T is the total resistance as found by the resistance tests and T is the thrust required to maintain a certain speed.



- The relationship between resistance and thrust is

$$R_T = T(1 - t)$$

- So the resistance due to propeller dynamics will be :

$$X_{\text{resistance}} = -R_T/(1-t) = -0.5\rho u^2 S C_T/(1-t)$$

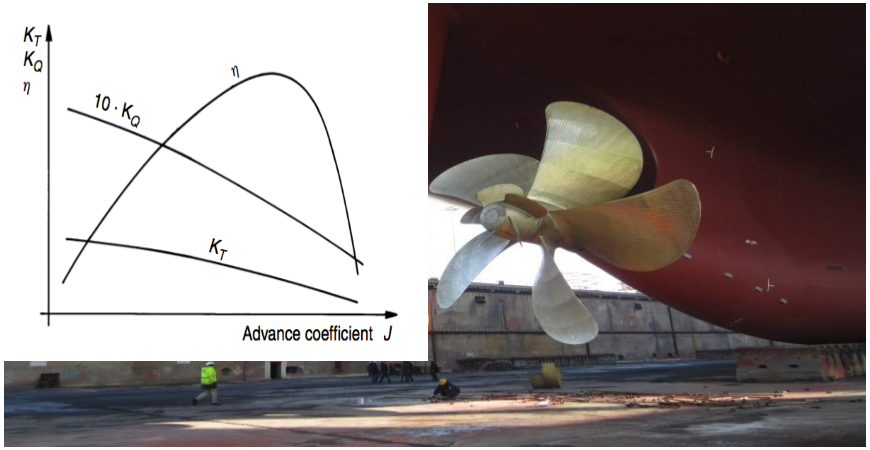
Where : R_T=total resistance, t=thrust deduction factor, ρ=density, u=x-direction velocity, S=wetted surface area, C_T=total resistance coefficient expressed as function of Froude no.

Thrust - Fixed pitch propeller

- The total thrust is evaluated from the open water characteristics (K_T - J curve) as :

$$X_{\text{prop}} = Z\rho n^2 D^4 K_T$$

Where Z is the no of propellers, *n* is the no. of propeller revolutions per second and D the propeller diameter.



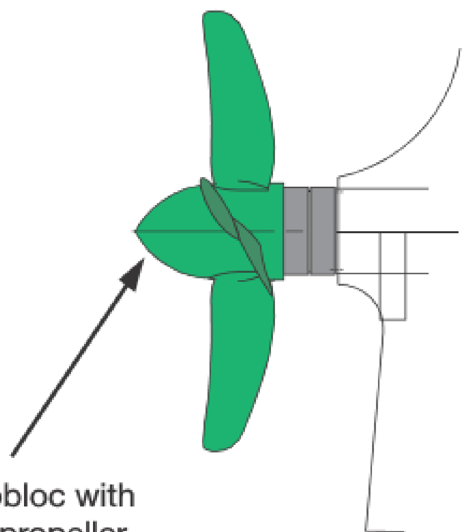
- The initial value of propeller revolutions should be adjusted so that a desired ship velocity is obtained for the still water, constant forward speed with no drift angle condition i.e. the propeller revs should be derived from the condition $\mathbf{X_{prop} = -X_{resistance}}$.

- Depending on the type of propulsion machinery, the revolutions are kept constant or adjusted to keep the propeller advance coefficient $J = \frac{V_A}{nD} = \frac{V(1-w)}{nD}$ constant. (NB : J expresses the obtainable propeller efficiency in dimensionless format)

- Keeping the revs constant is recommended as it results in a smaller deviation from the initial value of the forward speed.

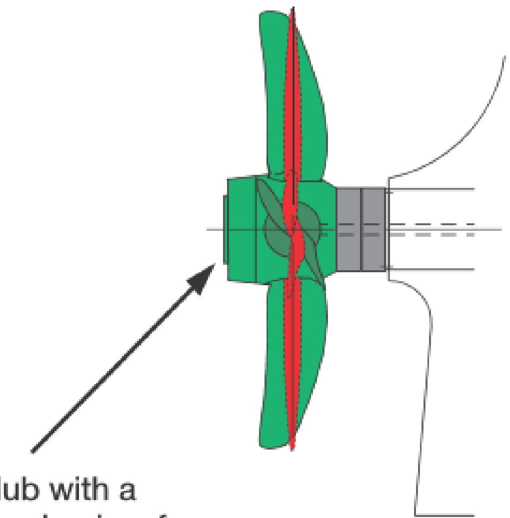
Fixed vs Controllable pitch propellers

Fixed pitch propeller
(FP-Propeller)



Monobloc with
fixed propeller
blades
(copper alloy)

Controllable pitch propeller
(CP-Propeller)



Hub with a
mechanism for
control of the
pitch of the blades
(hydraulically activated)

MAN, Basic principles of ship propulsion
https://marine.man-es.com/docs/librariesprovider6/propeller-aftship/5510-0004-04_18-1021-basic-principles-of-ship-propulsion_web.pdf?sfvrsn=c01858a2_8

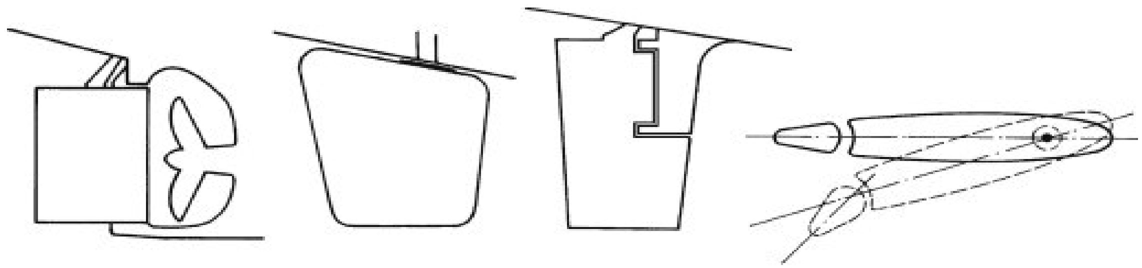
Thrust - Controllable pitch propeller

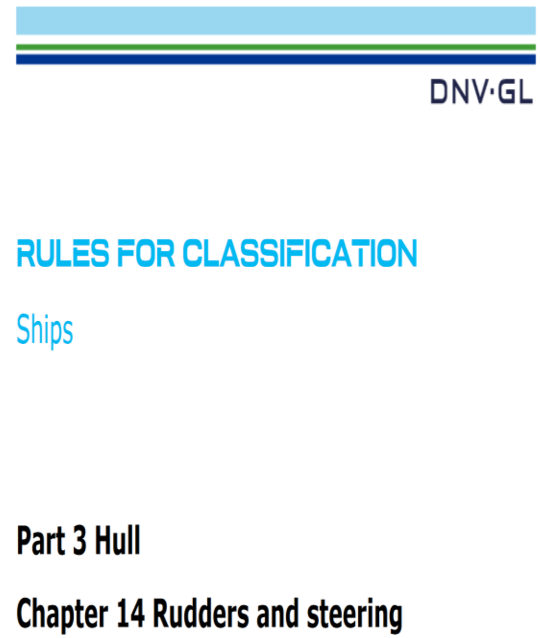
- If we assume that : *Constant delivered power = Constant propulsive efficiency*
  - Propeller pitch control is good and efficiency losses (aprox 10%) for the off-design operational conditions can be diregarded.
  - The above assumptions and resistance vs. power equations result in the following relation of thrust Xprop and ship's speed

$$X_{prop} = \frac{P_D \eta_0 \eta_R}{V(1-w)}.$$

Typically the thrust forward and backward is not equal which means that for example in ice rules you have to be able turn the direction of engine revs. Else you may end up with unreallistically high thrust.

Rudder & Steering (home review exercise)



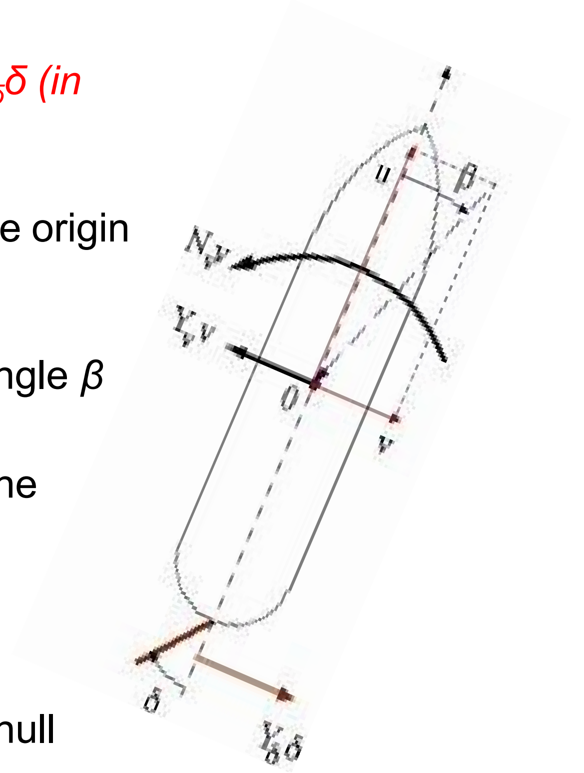


https://www.bing.com/videos/search?q=ship+Rudder+Types+&&view=detail&mid=0BD9ABF00E23E432F7D90BD9ABF00E23E432F7D9&&FORM=VDRVRV

V. Bertram – Practical Ship Hydrodynamics, Chapter 6, Ship maneuvering (pp. 241-298), Butterworth - Heinemann, 2012, ISBN 9780080971506 ; https://doi.org/10.1016/B978-0-08-097150-6.10006-5

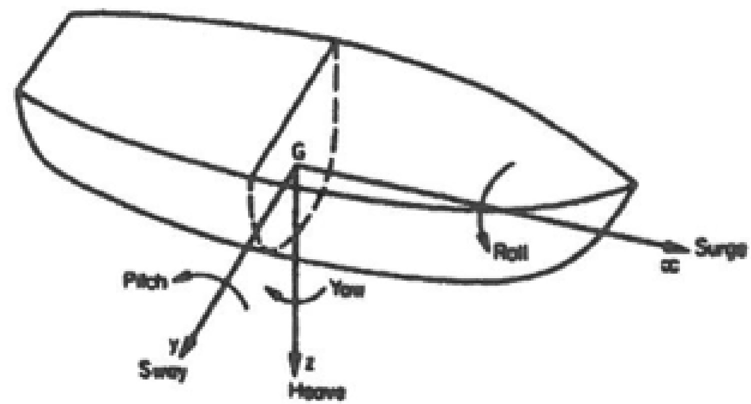
Rudder dynamics

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



Rudder kinematics

- The rudder angle and the angle at which the flow enters the rudder**, the angle of attack,** are not the same
- This is why the force $Y_\delta \times \delta$ is just a first approx.
- Both the inflow velocity and the angle of attack are affected by the **yaw** and **sway** motion of the ship
- If the rudder is located in the propeller slipstream this will also affect the inflow
- Inflow into the rudder may be also changed significantly due to the flow velocity in the surface wave



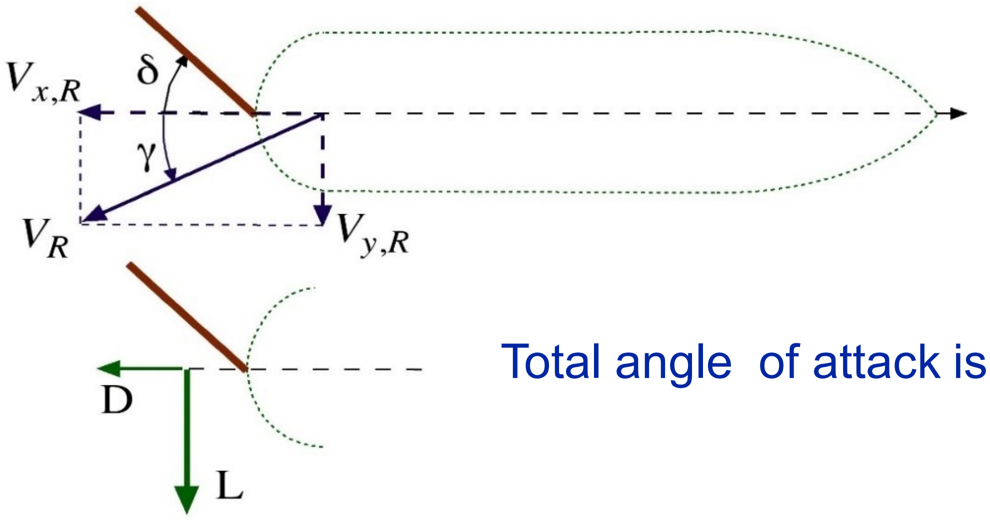
Translation or rotation	Axis	Description	Positive sense
Translation	Along x	Surge	Forwards
	Along y	Sway	To starboard
	Along z	Heave	Downwards
Rotation	About x	Roll	Starboard side down
	About y	Pitch	Bow up
	About z	Yaw	Bow to starboard

Fig. 12.1 Ship motions

Effective angle of water inflow

- To evaluate the rudder forces the flow velocoties at the rudder location have to be evaluated first
- The effect of ship motion and wave motion is to change the angle of attack of the rudder by the amount

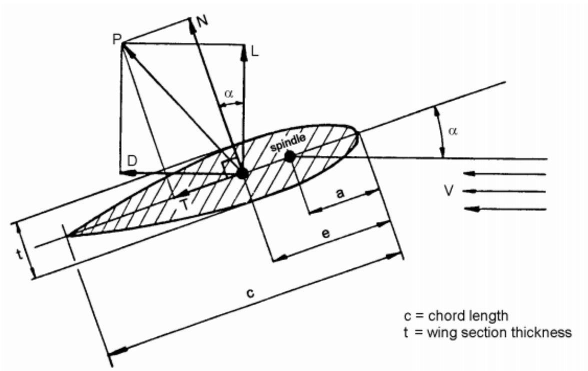
$$\gamma = \arctan\left(V_{y,R} / V_{x,R}\right)$$



Total angle of attack is $\alpha=\delta+\gamma$.

Rudder forces

- Rudder forces are evaluated according to Söding (1982) and Brix (1993) *[Ref : Matiusek Book, pages 140 & 142]*



Stagnation point

Projected rudder area

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

Frictional resistance Cd as per ITTC-57 or ITTC-78 methods for model ship correlation line

Drag Coefficient

$$C_D = 1.1\frac{C_L^2}{\pi\Lambda} + C_{D0},$$

Lift Coefficient

$$C_L = \frac{2\pi\Lambda(\Lambda+1)}{(\Lambda+2)^2}\sin(\delta+\gamma),$$

$\Lambda = b^2/A_R$ is aspect ratio and b denotes rudder length. Note that rudder area is not a wetted area. It is defined as a projected area of the side view of the rudder.

Effect of propeller action on rudder flow

- Rudder operates usually in the propeller slipstream
- As a result the forces developed by the rudder are substantially higher than the ones generated by the rudder placed outside the slipstream
- According to potential flow theory and considering the momentum conservation (ideal propulsion model), the mean axial flow velocity far downstream of the propeller is

$$V_\infty = V_A + U_{A0} = V_A\sqrt{1 + C_T},$$

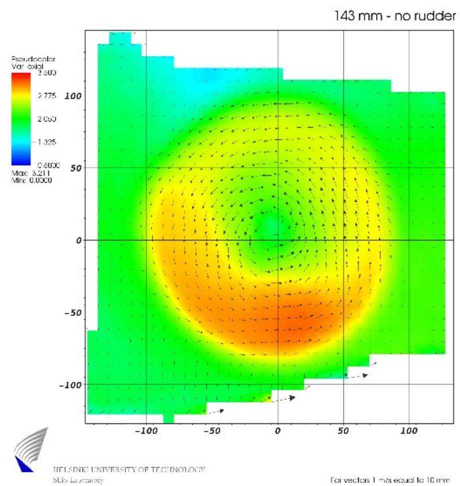
Thrust loading coefficient

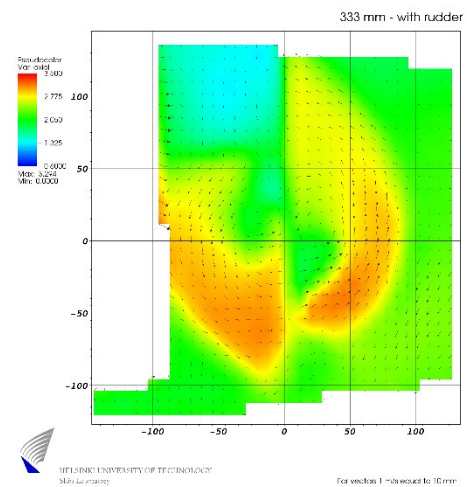
$$C_T = \frac{Thrust}{0.5\rho V_A^2 \pi D^2/4} = \frac{8}{\pi}\frac{K_T}{J^2}$$

$$r_\infty = r_0\sqrt{\frac{1}{2}\left(1 + \frac{V_A}{V_\infty}\right)},$$

Radius of slipstream behind propeller

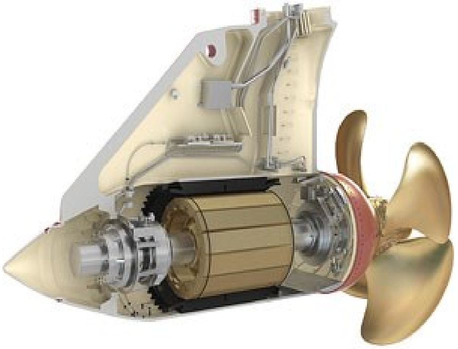
Propeller radius





Azimuth thrusters

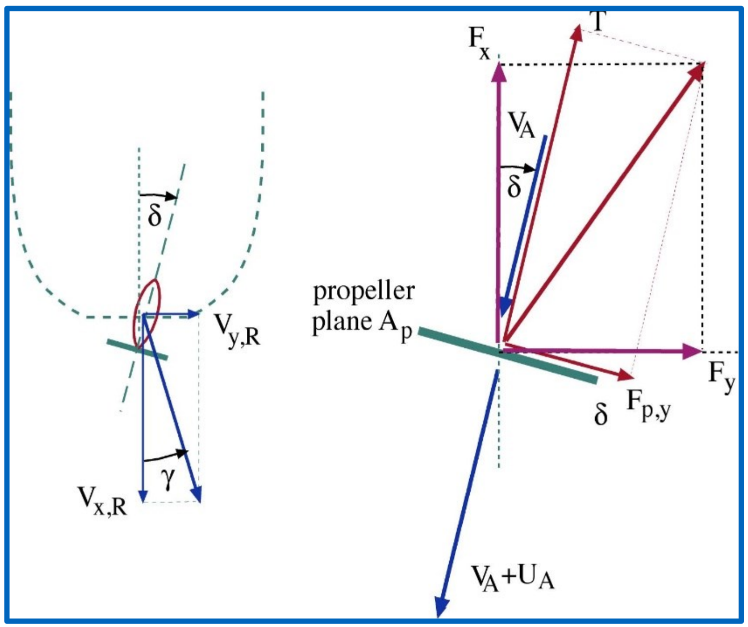
- Azimuth thruster units have become very popular in a variety of ship types within the last two decades, a.k.a. podded propellers
- Benefits
  - good maneuvering qualities
  - low vibration and noise
  - overall propulsion characteristics are good thanks to an absence of propeller shafts and supporting brackets.
- The biggest difference is that they operate frequently in oblique inflow



For the case of an azimuth thruster knowledge of the forces developed by propeller in ***oblique inflow is very important*** *in order to evaluate the ship's maneuvering. In particular stopping a vessel may be conducted quite differently and faster than in a case of traditional propulsion arrangement*

Oblique flow and in-plane force

Oblique flow on prop disk means change of forces on propeller.



Flow kinematics on propeller in oblique flow

In plane force component

Propeller disc area

$$F_{py} = \rho A_p (V_A + U_A) V_{py},$$

$$V_A = V_{x,R}\cos\delta - V_{y,R}\sin\delta$$

Propeller advance velocity

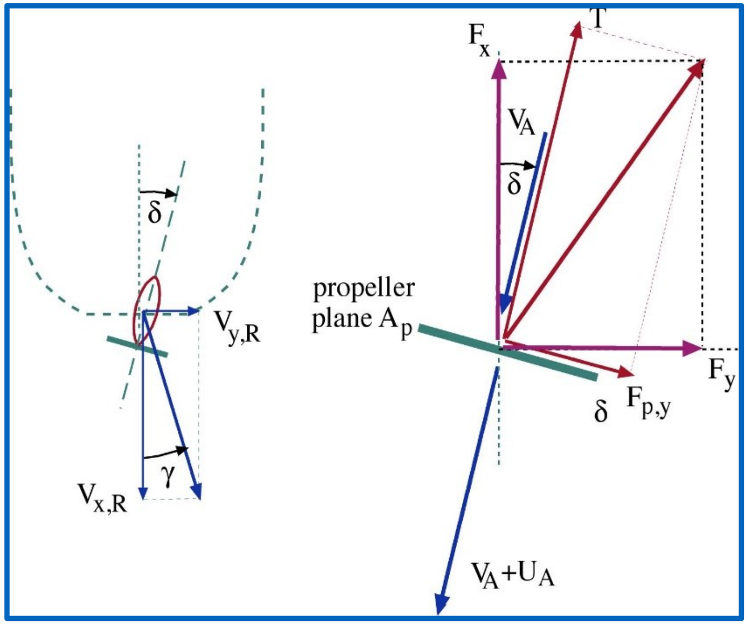
$$V_{py} = V_{x,R}\sin\delta + V_{y,R}\cos\delta$$

In plane flow velocity

$$U_A = V_A\left(-1 + \sqrt{1 + C_T}\right)/2,$$

Propeller induced velocity

Oblique flow and thrust



Flow kinematics on propeller in oblique flow

The propeller thrust is evaluated from the known thrust coefficient K_T as a function of the advance ratio $J=V_A/(nD)$ where n and D are propeller revolutions and diameter respectively.

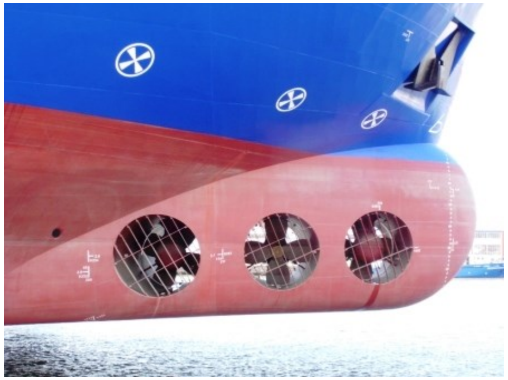
$$F_x = T\cos\delta - F_{py}\sin\delta$$
$$F_y = T\sin\delta + F_{py}\cos\delta.$$

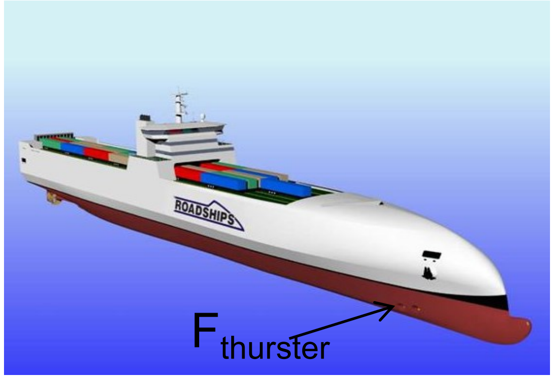
For further details you may refer to Molland & Turnock (2007) - Marine Rudders and Control Surfaces (Elsevier) - https://www.elsevier.com/books/marine-rudders-and-control-surfaces/molland/978-0-7506-6944-3

Bow thrusters

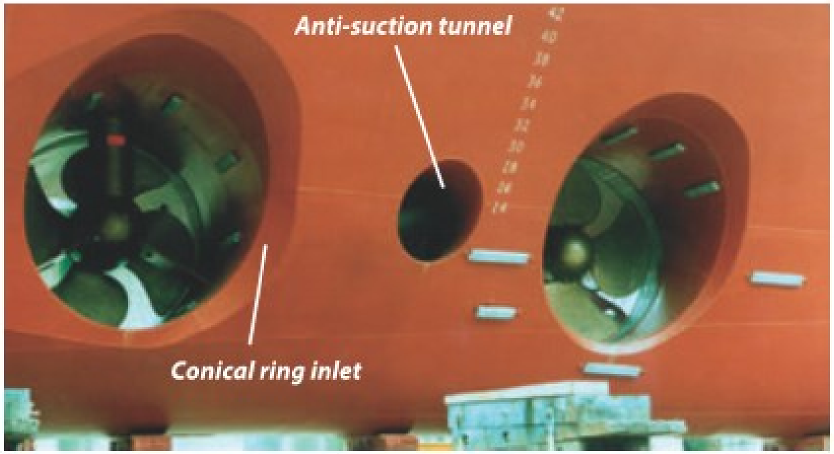
- Bow thrusters are needed in manoeuvring in harbour operations
- Thruster works well with very low speeds in surge motion
- Depending on the required manoeuvrability there might be several (1-4) thrusters in bow (and aft)

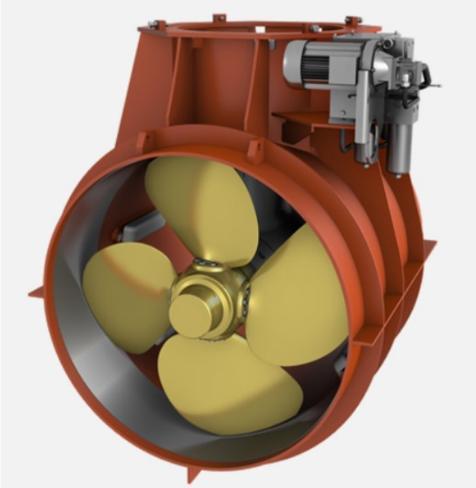
https://www.youtube.com/watch?v=PzjFEe47bzA



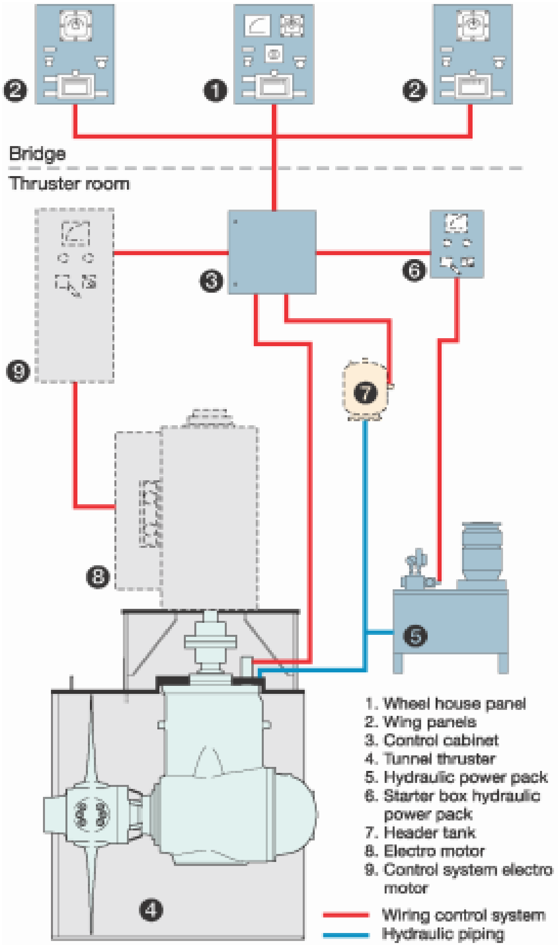


Bow thrusters





Illustrations courtesy of Wärtsilä Corporation



https://www.wartsila.com/marine/build/propulsors-and-gears/thrusters/wartsila-transverse-thrusters

Hull form dynamics

- Hull form has significant impact on ship dynamics
- Too low freeboard may cause shipping of green water
- Too low draft can cause bow or aft slamming and/or propeller emergence
- The positioning of equipment and superstructure design should take into account the heavy loading due to rough seas
- The shape of hull form should be such that impact loads are minimised

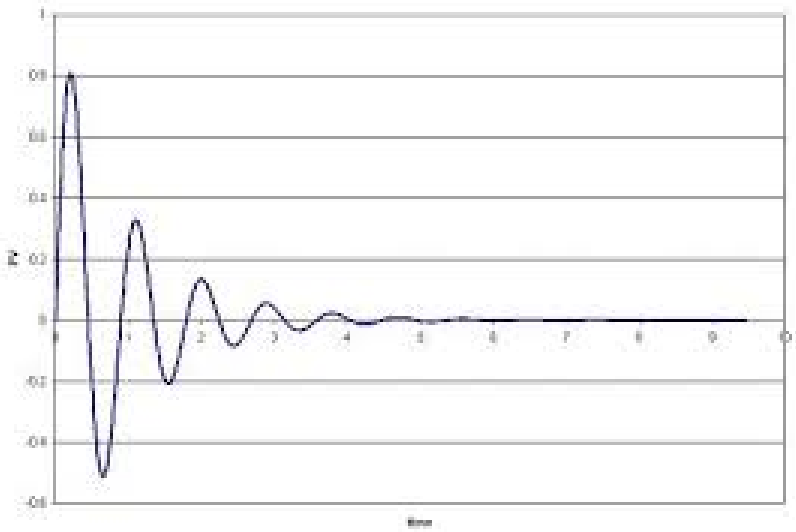
Hull form dynamics - Motion Reduction

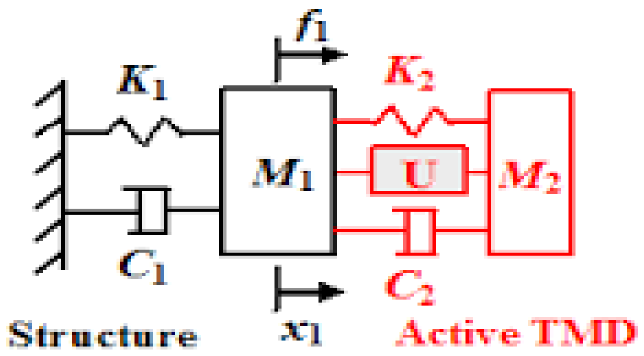
- Motion reduction is possible provided that we know the motions of the ship so that we create a mounted counter system that eliminates these movements

- Most often the motion reduction is most effectively done by dampers

- Dampers control forces and moments. However they should be design in a way that doe not lead to significant hull space augmentations/corrections

- Roll is the motion that can be most effectively reduced using small forces and moments





Hull form dynamics - Motion Reduction

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

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

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

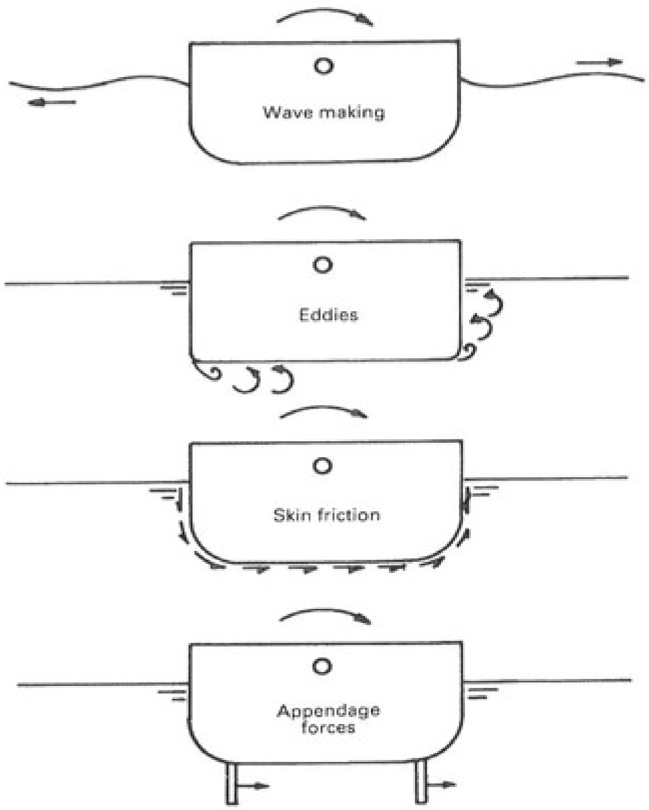


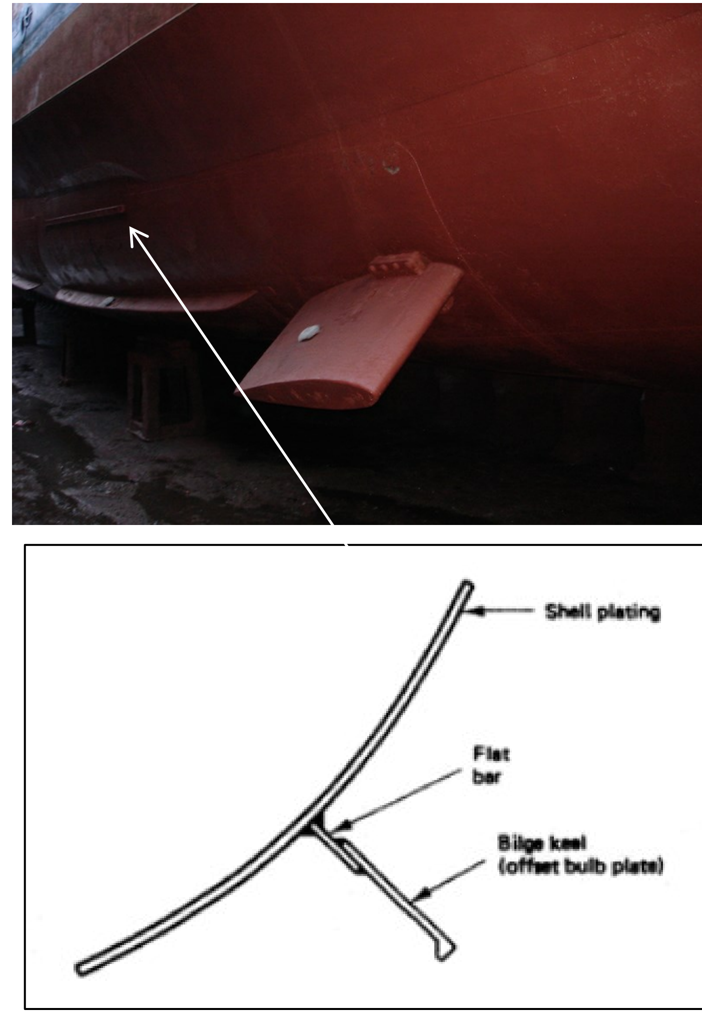
Fig. 12.1 — Sources of roll damping.

Bilge Keels

- Bilge keels are passive structures welded to the bilge region

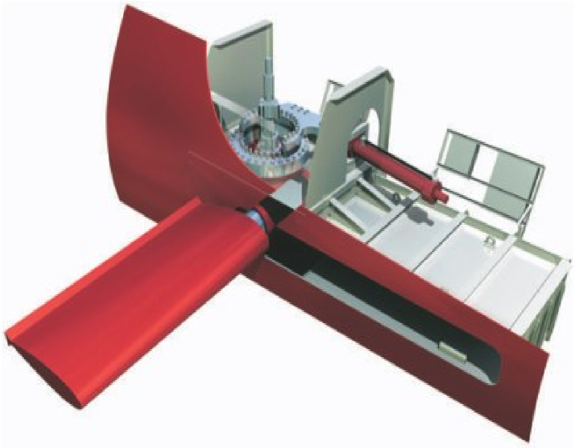
- They are considered one of the most cost effective ways to reduce roll motions because they:
  - Work well at all speeds
  - Have no moving parts
  - Require no special maintenance
  - They increase the resistance of the ship unless flow is not taken into account in the design (CFD, model tests)

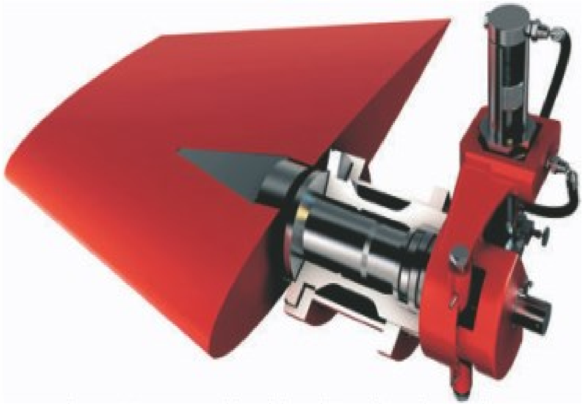
- Bilge keels work by creating drag forces which oppose the roll motions



Stabilizer fins

- Active roll stabilizer fins are typically located near the bilge and amidships
- The angle of incidence is adjusted based on ship rolling motions
- The fins create counter rolling motion to that caused by the waves
- They cannot solve problems of very rough seas and are quite expensive to install and maintain. They also require extra space
- Retractable fins are often used in commercial ships. Thhey require more hull space https://www.youtube.com/watch?v=bjn_gRuBeV4
- Their interference with bilge keels should always be checked





Passive Tanks

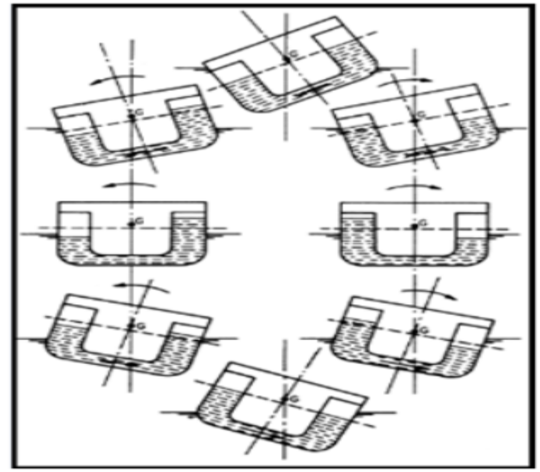
- The liquid in partially filled tanks will slosh back and forth in ship as it rolls

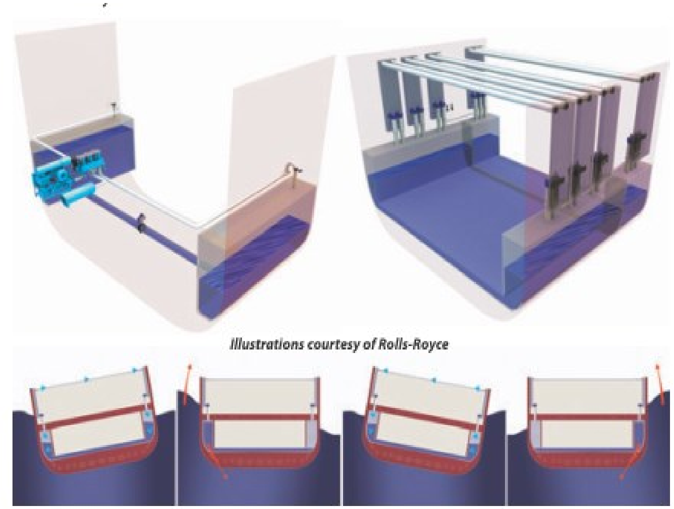
- The shifting weight will exert a roll moment that is damping the rolling motion when suitably designed

- U-tube tanks are commonly used in which the flow can be controlled with
  - Valves
  - Pumps

- This tank works typically very well in slow speeds

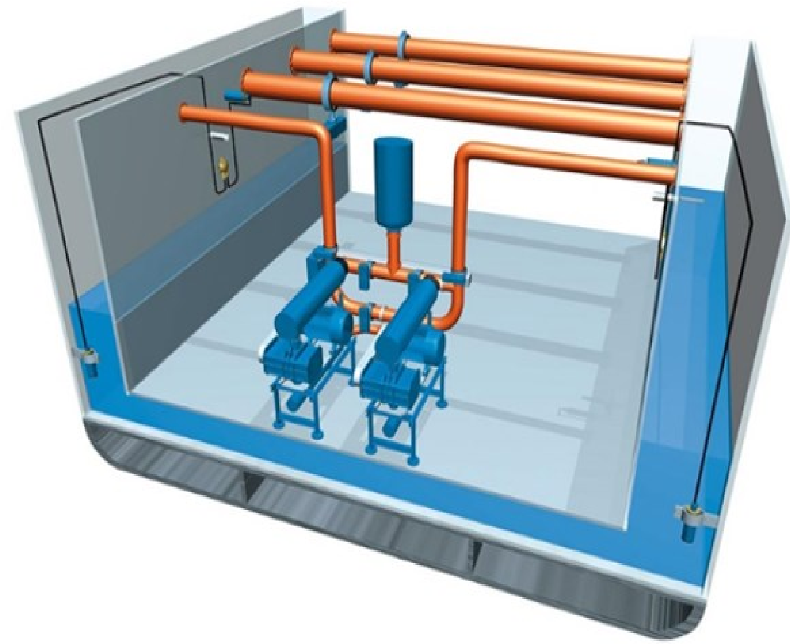
- The system has no moving parts so the maintenance costs are low. However, extra hull space is required.





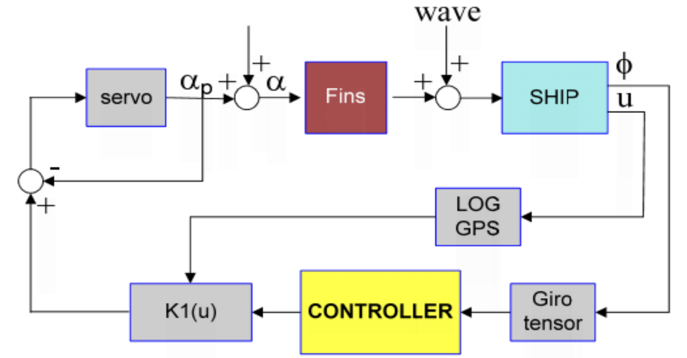
Active Tanks

- Similar to the principle of passive tank system
- The movement of water is controlled by
  - Pumps
  - Air pressure above the water surface.
- The tanks either side of the ship may be connected by a lower limb or two separate tanks can be used
- The air duct contains valves operated by a roll sensing device

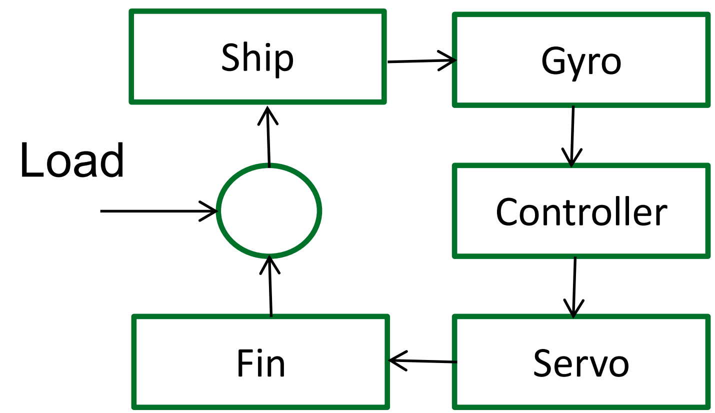


Control Systems

- Active roll stabilizer fins require a control system
- When the ship experiences external load it moves
- Gyro measures the movement
- Controller sets the stabilizing command
- Servo adjusts the fin
- Fin produces the counter force



Schema of the control system for fin stabilizers.



Control Systems

TRANSNAV
http://www.transnav.eu

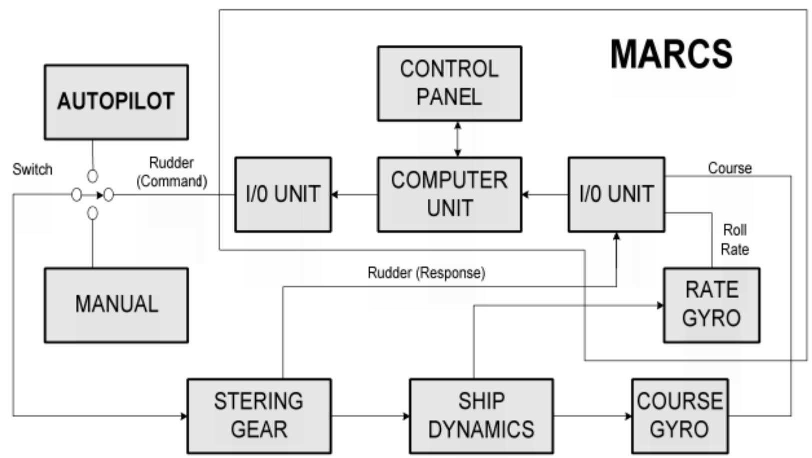
the International Journal
on Marine Navigation
and Safety of Sea Transportation

Volume 9
Number 3
September 2015

DOI: 10.12716/1001.09.03.14

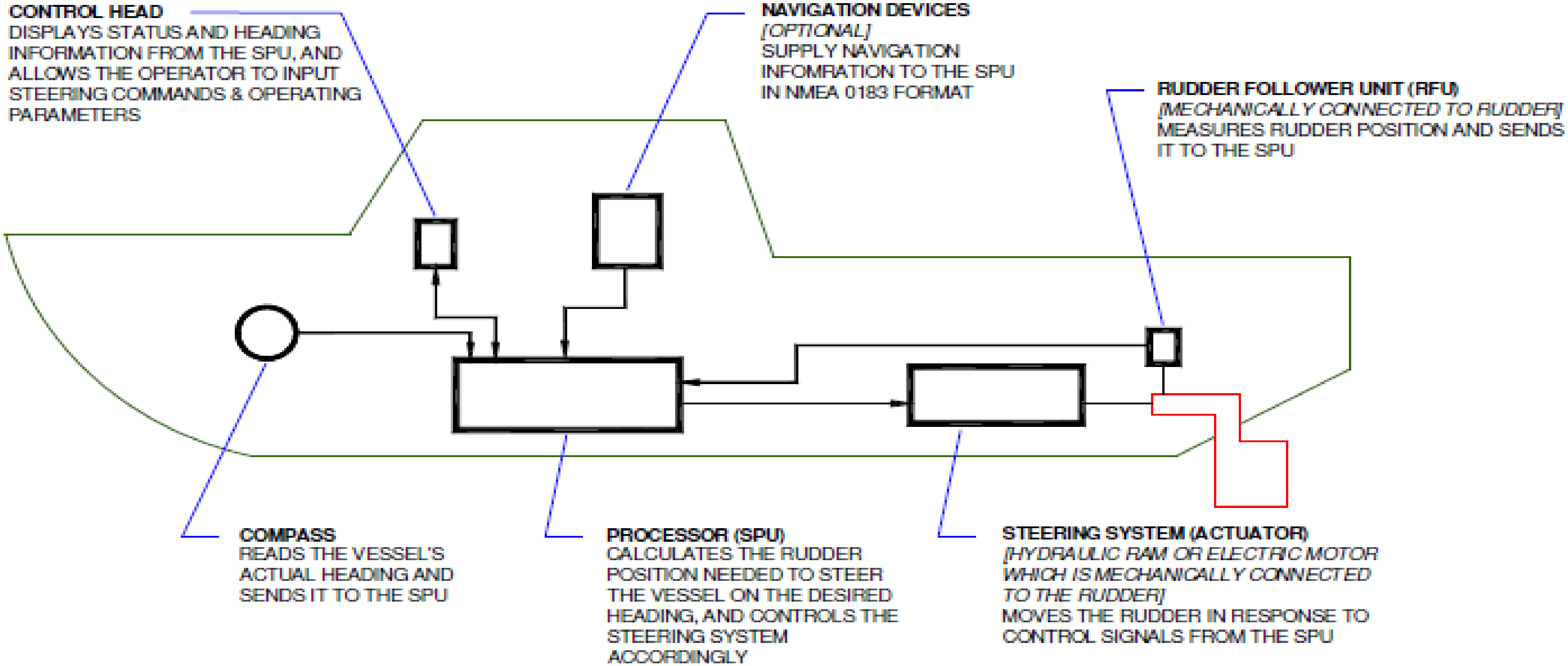
An Overview of Roll Stabilizers and Systems for Their Control

K.S. Kula
Gdynia Maritime University, Poland



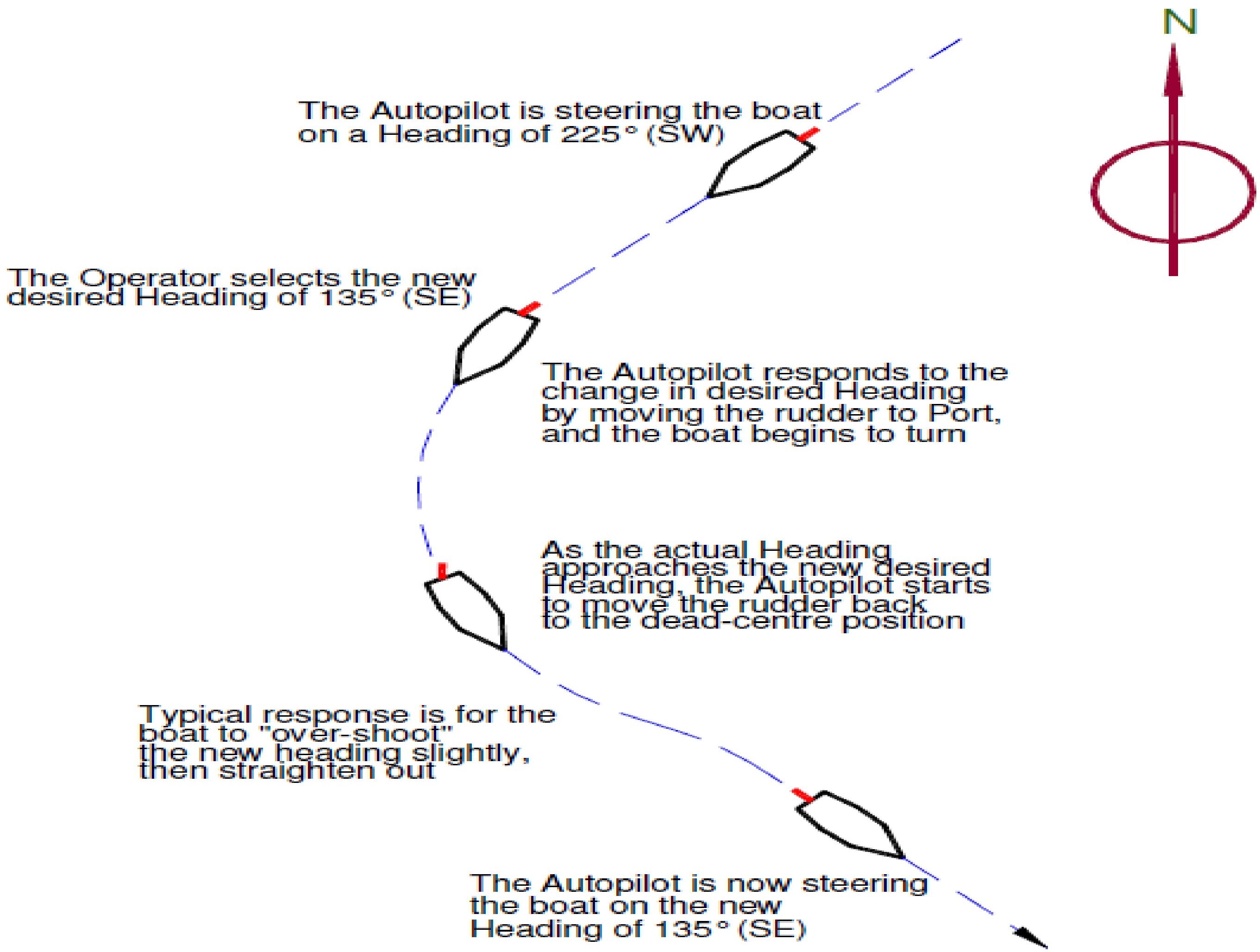
Block scheme of the rudder/roll control system.

Autopilot steering system example



[Propulsion And Manoeuvring Systems - YouTube]

Autopilot steering system example



Summary

- A ship must be able to operate according to her mission
- Forces and moments emerging from different devices (e.g. propellers, rudders, pods, thrusters) are generated and affect ship dynamics.
- The hull form and her interaction with the ship propulsion systems affects ship dynamics.
- Ship motions can be controlled by different systems that affect dynamics
  - Roll damping can be controled more easily than other motions that would require the use of heavy equipment affecting the lightship weight
  - Systems such as bilge keels, active fins, active and passive tanks may be used to control motions but each bear prons and cons depending on the type of vessel and her operating conditions.

For next time please review your knowledge on fluid mechanics and ocean waves

Thank you