Propellers and propulsion

MEC E2001 - Ship Hydrodynamics

Summary on Propeller cavitation

- List and describe types of cavitation
- How do you take into account the cavitation in the design of the propeller?
- How does the cavitation affect the performance of the propeller?
- What are the secondary effects of the cavitation?
- How can you evaluate the cavitation?

Content of the course

- Resistance
- Propulsion
    - Introduction, Momentum theory on propeller action
    - Screw propeller
    - Propeller-hull interaction
    - Early design of a propeller
    - Propeller – main engine interaction
    - Stopping, accelerating and backing properties
    - Propeller cavitation
    - Special types of propulsors ← All propulsors that are not open marine screw propellers
    - Afterbody form of a ship

Special types of propulsors

Additional reading

- Matusiak J (2010) *Laivan propulsio*. M-176. Chapter 9
- Matusiak J (2008) Short introduction to Ship Resistance and Propulsion. Section 3.11

Outline: Special types of propulsors

All propulsors that are not open marine screw propellers

- Supercavitating propellers
- Ducted propellers / Propeller in a nozzle ← Most common special propulsor
- Rotatable thrusters
- Steering thrusters
- Contra rotating propellers
- Hybrid propulsion
- Grim's vane wheel
- Water jet propulsion

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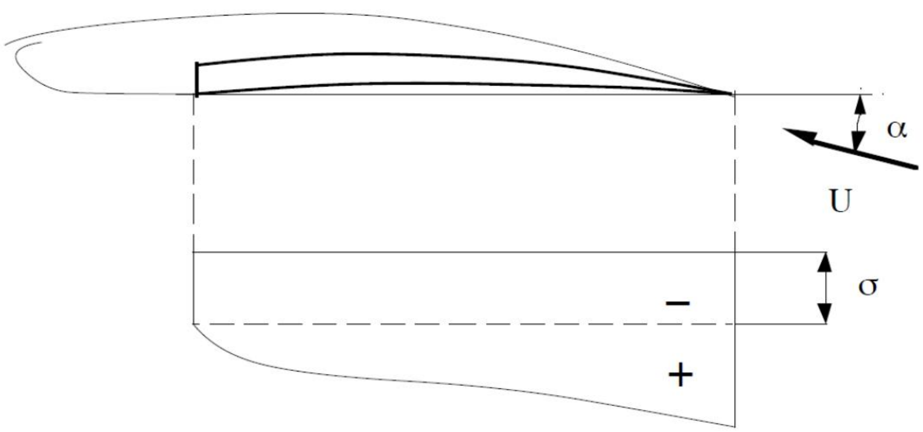
Super cavitating propellers

Cavitation covers entire suction side of a blade.

- Length of sheet cavitation is kept larger than the hydrofoil length.
- It's volume changes are kept moderate.
- Lift is generated as a difference of pressure side pressure and the vapour pressure

How to stimulate cavitation?

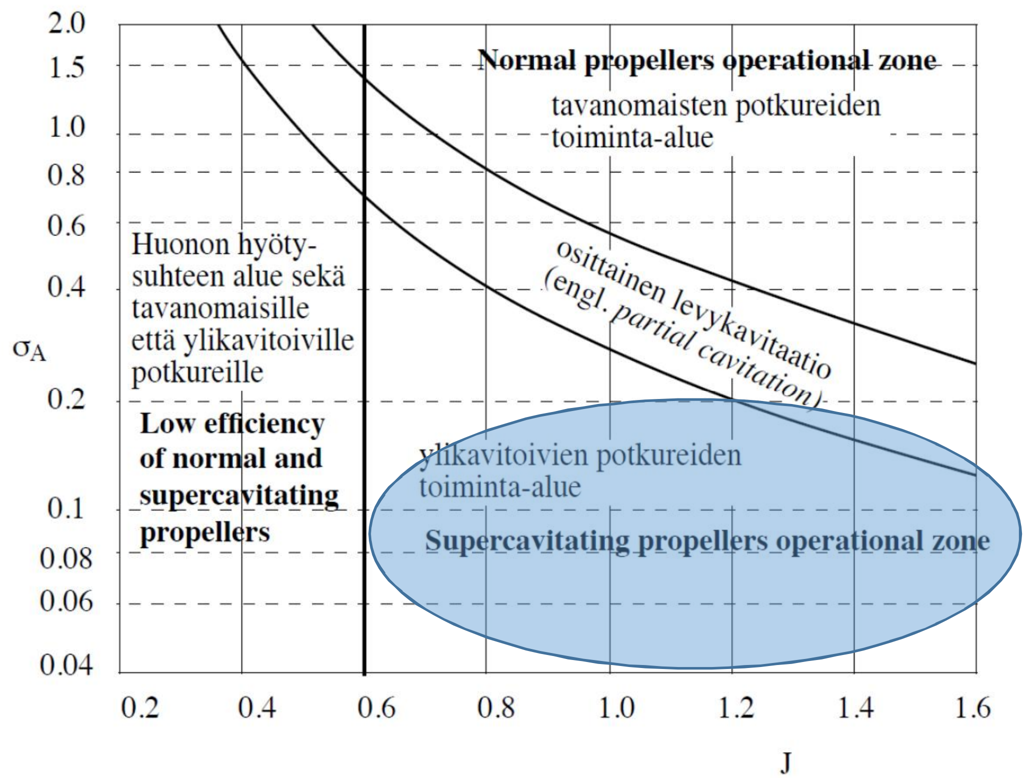
- Propeller diameter: relatively small
- Pitch: low
- Revolutions: high
- Shape of hydrofoil: wedge



Super cavitating propellers

On the operation of supercavitating propellers

- Efficiency is relatively low
  - If possible a normal propeller is preferred
- Operates properly for a design condition
- Running astern: poor quality
- Generates high frequency noise



Super cavitating propellers

Surface piercing propellers

- Low immersion and high load may yield propeller ventillation
  - Normal propeller: this results in thrust breakdown and high revolutions.
  - Wedge-shaped hydrofoil with a sharp leading edge: not so bad thrust ($K_T/J^2 \leq 0.5$)
- Advantage
  - Absence of resistance of shaft and brackets
- Disadvantage:
  - Poor efficiency for off-design operation
  - Unsteady thrust and torque

J = 0.75

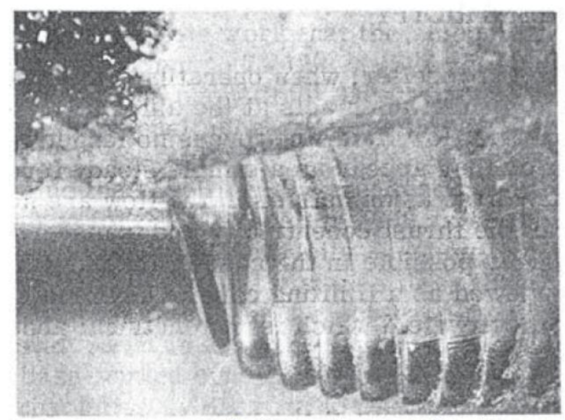


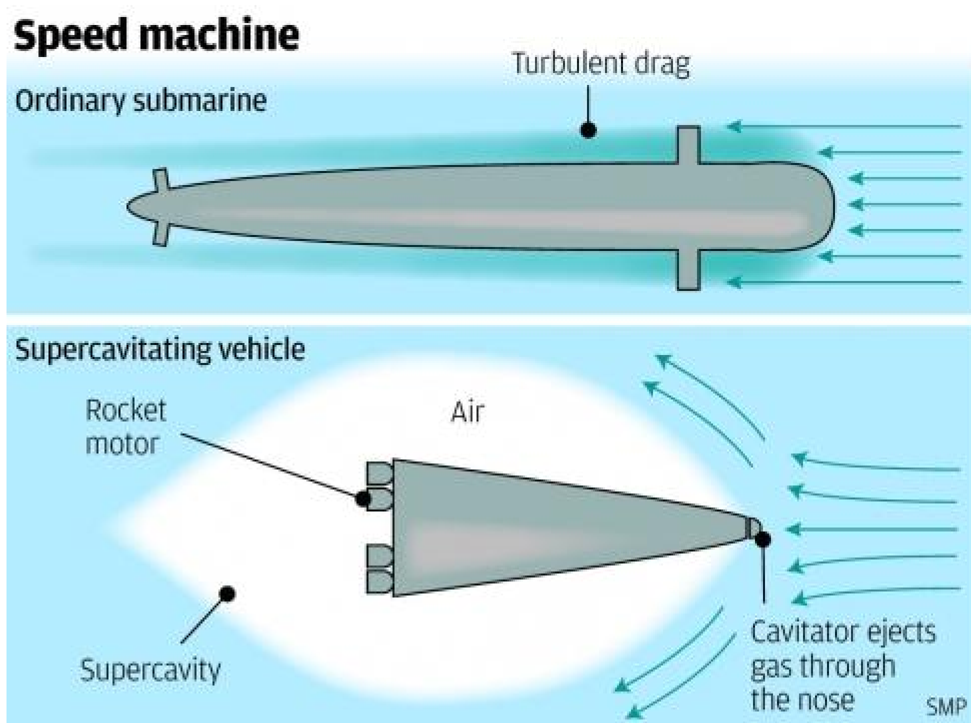
Figure 10.8 Photograph of propeller partially submerged.

Super cavitating propellers

Further curiosity on supercavitation?

- Google e.g. *Shkval torpedo*
- This figure: scmp.com
- The gas works to stimulate

and control cavitation



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Ducted propeller / Propeller in nozzle

Consist of

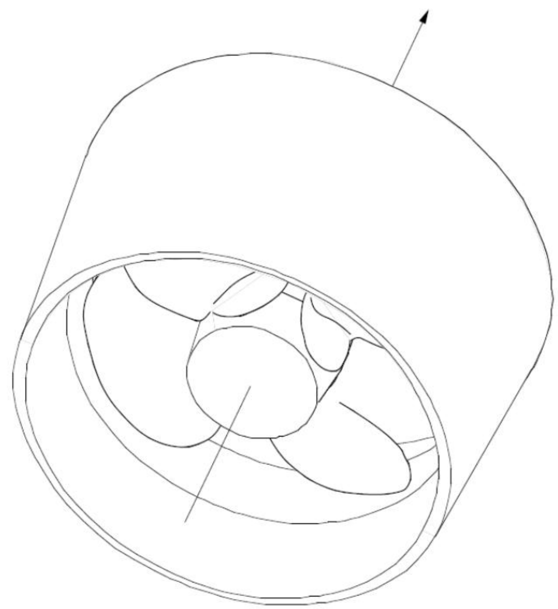
- FPP or CPP
- Axially symmetric nozzle around the propeller

Function of the nozzle

- Changes the inflow to propeller
- Generates thrust

Options

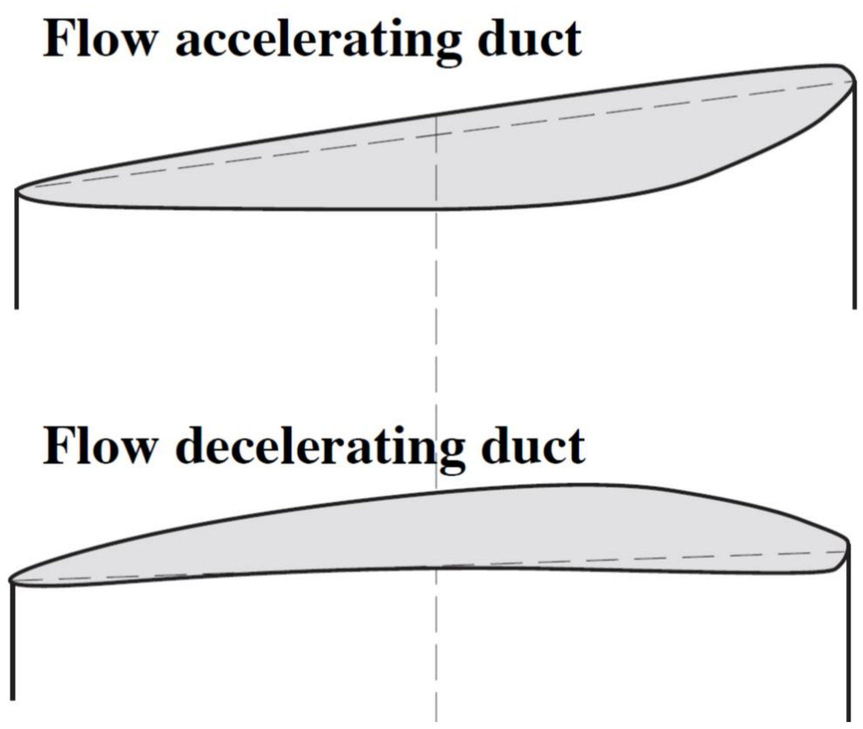
- Flow accelerating duct
- Flow decelelerating ducts



Ducted propeller / Propeller in nozzle

Flow accelerating duct

- When *good bollard pull qualities* are important
- Low advance number *J*: thrust and efficiency increase
- At high *J*: Total thrust of the propeller decreases



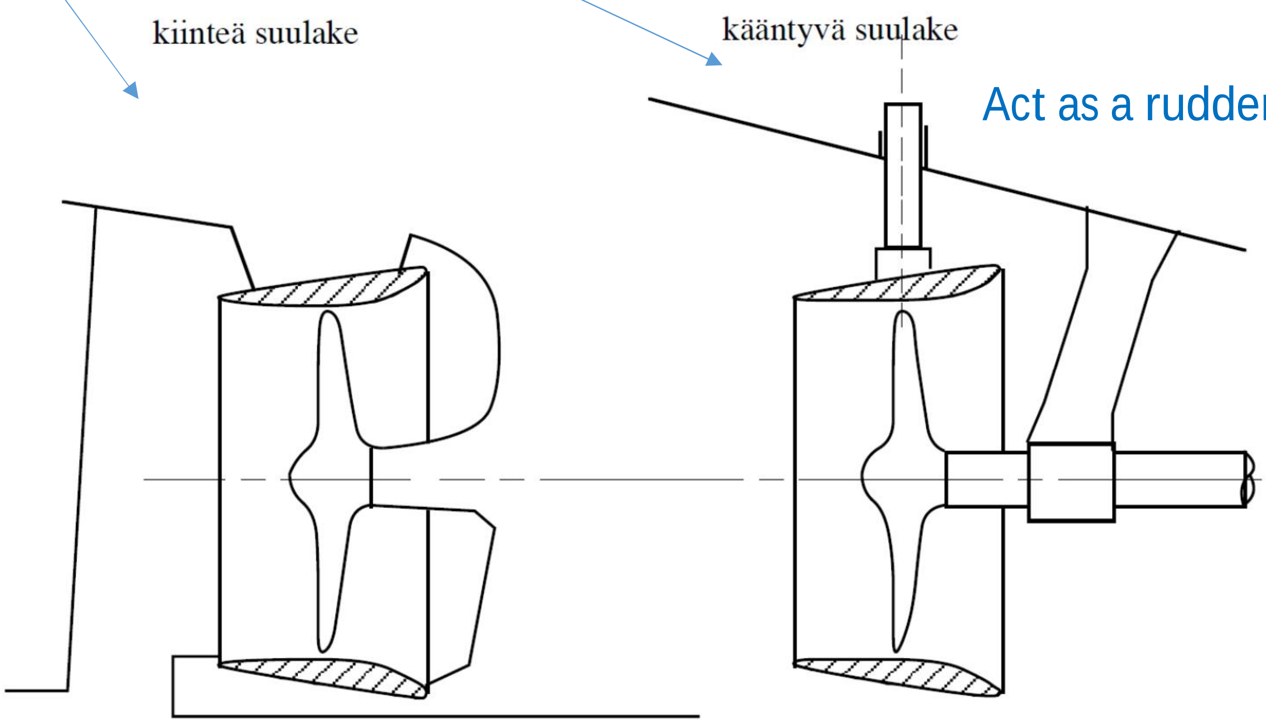
Flow decelelerating ducts

- *Fast* naval vessels
- Improve cavitation qualities
- Decrease efficiency

In the following slides, we will refer only to Flow accelerating ducts

Ducted propeller / Propeller in nozzle

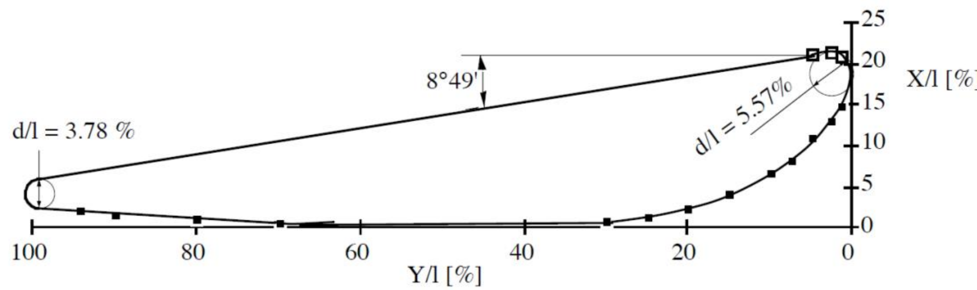
Fixed and steerable ducts



Act as a rudder

Ducted propeller / Propeller in nozzle

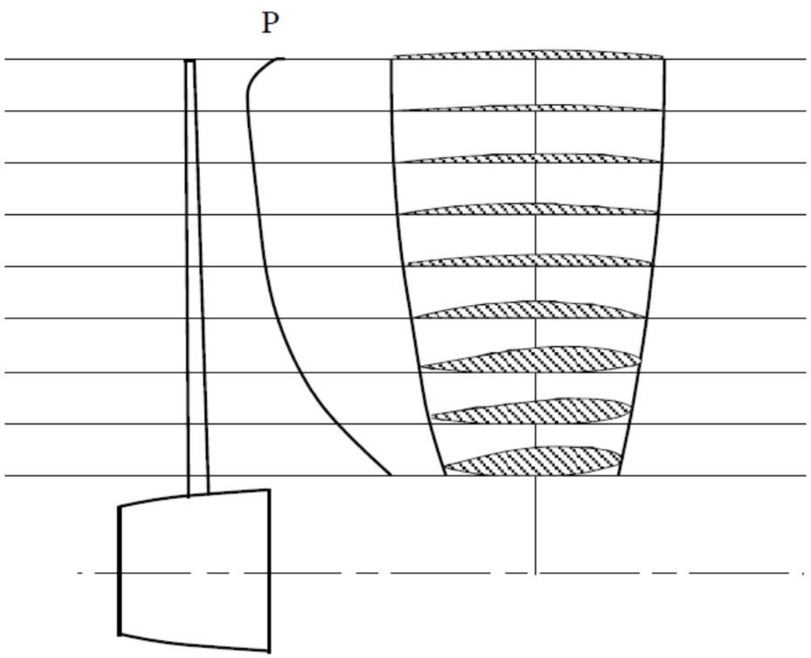
On the geometry of the duct



- Length
  - (0.5... 0.7)•D.
  - The more loaded the propeller is, the longer the nozzle need to be.
- Diameter: ~1.2 times the propeller diameter D
- Tip clearance (distance form propeller tip to nozzle surface)
  - As small as possible
  - Typical value is 0.005•D.
- Wageningen 19A nozzle type is used frequently

Ducted propeller / Propeller in nozzle

Propeller in a nozzle



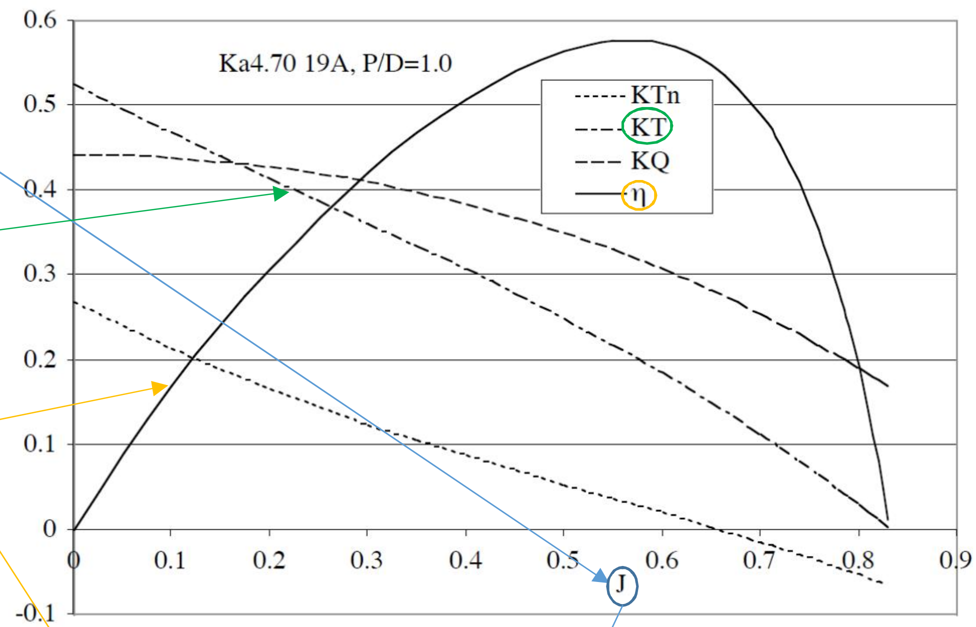
- Diameter of propeller in a nozzle is approx. 90% of a normal propeller diameter
- Nozzle accelerated flow makes it possible to increase a load at blade tips
- This can be done by broadening the blades at tip or increasing pitch

Ducted propeller / Propeller in nozzle

Effect of the nozzle on the performance of the propeller

Nozzle accelerates the flow and generate thrust itself, KTn

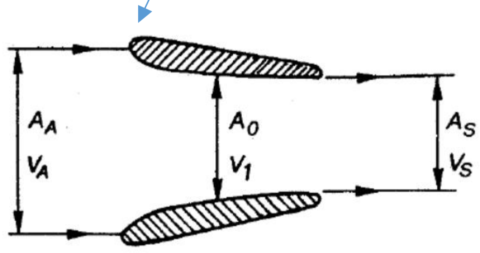
- The advance number *J* of the propeller grows at the propeller disk
- Total thrust *T* (sum of the propeller thrust and nozzle thrust) decreases for high advance number.
- Efficiency *η* increases as the loading of the propeller decreases.



Nozzle decreases flow losses at blade tip

- Thrust and torque increase in comparison to open propeller.

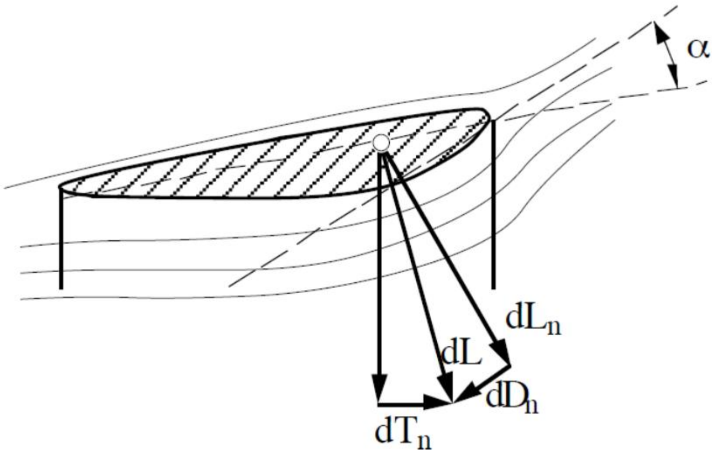
$$C_T = \frac{T}{\frac{1}{2}\rho A_0 V_A^2}$$



Ducted propeller / Propeller in nozzle

On the action of the nozzle

- Ahead of propeller plane, there is a region of low pressure.
    - As a result the nozzle produces lift and drag (dL_n &dD_n).
- The x-directional component dT_n of the resultant force dL is a thrust element produced by a nozzle
- Nozzle thrust Tn is a sum of these



Ducted propeller / Propeller in nozzle

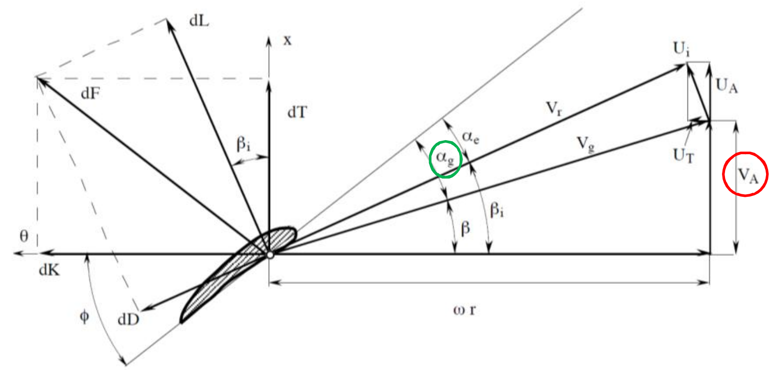
On the action of the nozzle

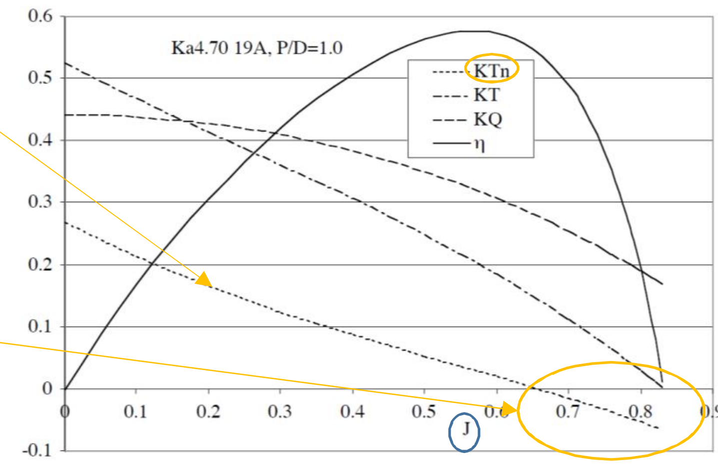
When the advance velocity V_A increases

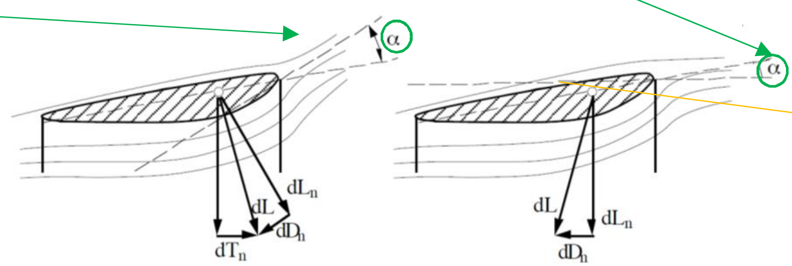
- Advance number J increases
- Angle of attack α decreases
    - This reduces nozzle thrust T_n.

For large J

- α gets negative
- Thrust T_n becomes negative as well





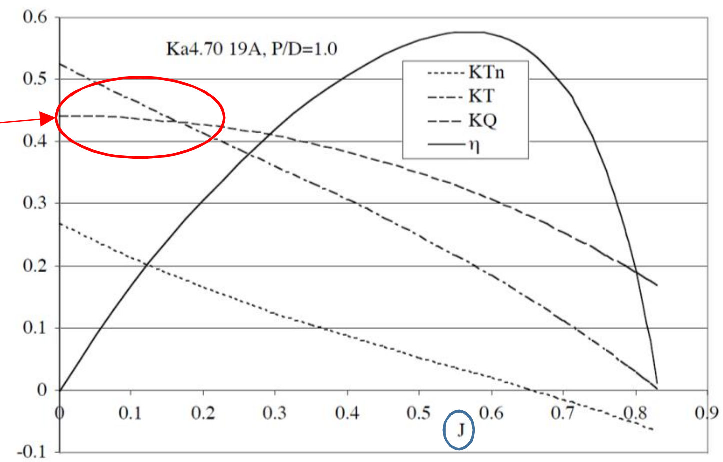


Ducted propeller / Propeller in nozzle

Open water characteristics of ducted propellers

Low advance velocity V_A and low J

- Torque curve is quite flat.
- This means that ducted propeller is capable to absorb efficiently engine power at low speeds.



Bollard pull condition

- Ducted propeler may deliver 60% more thrust than the conventional propeller.
- Nozzle smoothens the flow and protects propeller.

Ducted propeller / Propeller in nozzle

Disadvantage

- Cavitation at tip may be stronger than in the open propeller.
- Running astern may be difficult.
    - Steerable nozzle and rounding the trailing edge improves the situation
- Exchanging a propeller may be difficult
- More expensive

Design

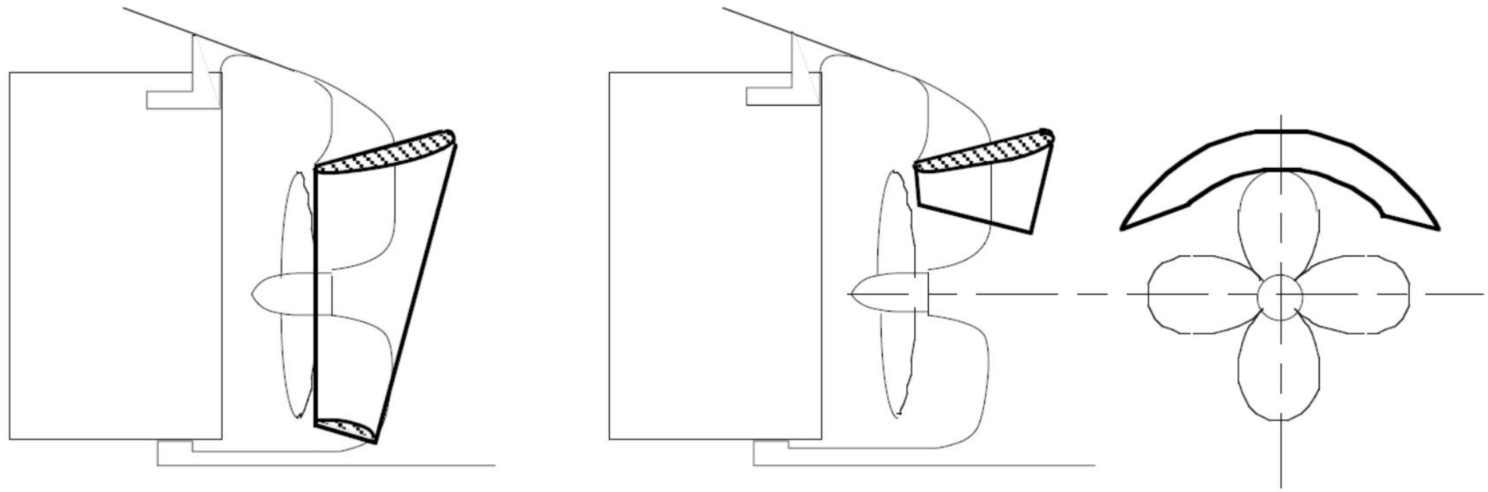
- Preliminary design utilizes systematic model test series

Ducted propeller / Propeller in nozzle

Ducts and semi-tunnels

Improving the quality of the “bad” wake

- In particular, full hull forms with serious flow separation above and in front of the propeller.
- Partial nozzle (segment) or tunnel directs and accelerates the flow.



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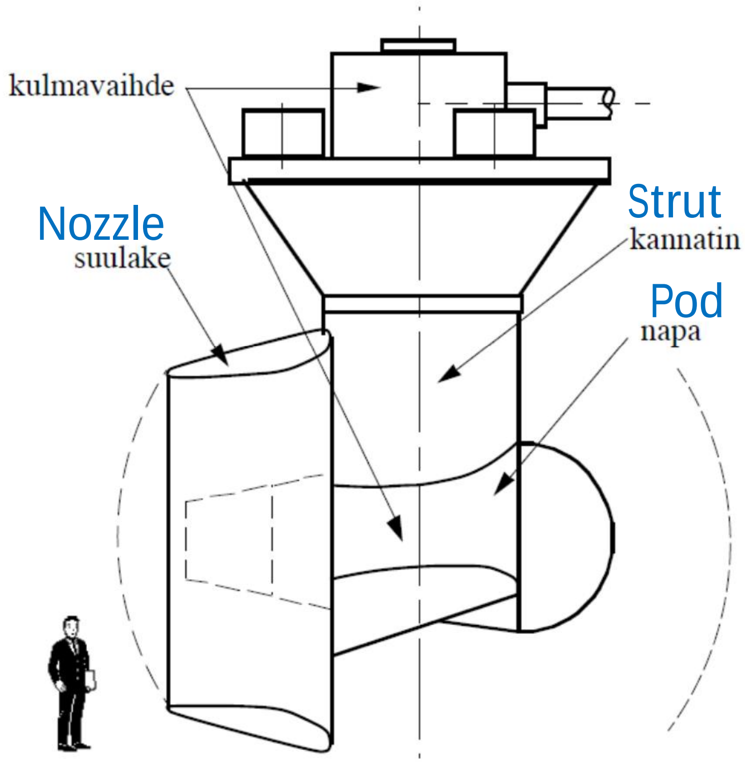
Rotatable thrusters

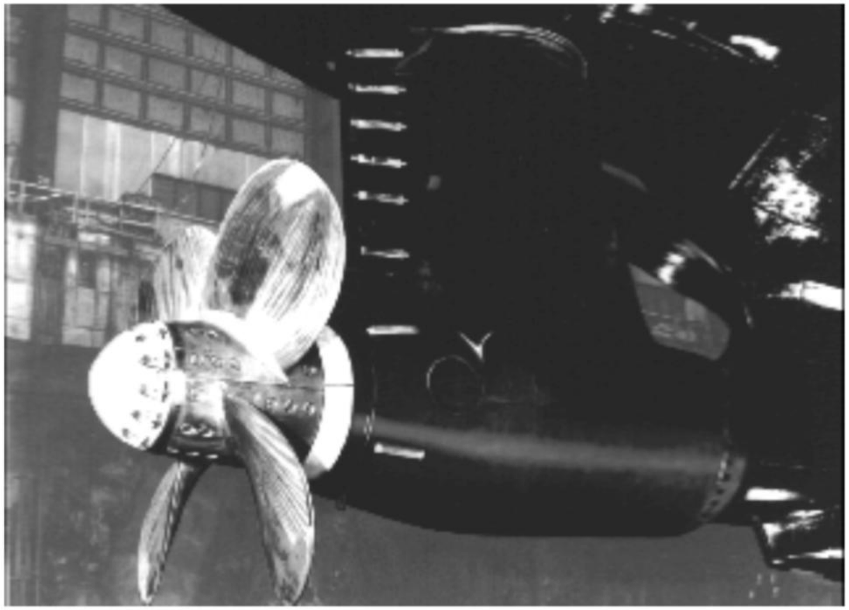
Turnable propulsors (z-drives, pods)



- Rotatable thruster or z-drive propulsion comprise propeller (open or ducted), pod , strut and possibly a fin
- They can be mechanically driven (Rolls Royce- former Aquamaster Ltd or Steerprop of Rauma) or having a direct electric motor drive in a pod (ABB's Azipod-propulsion).
- Device turns 360^0 and can be used in different type of vessels

Rotatable thrusters

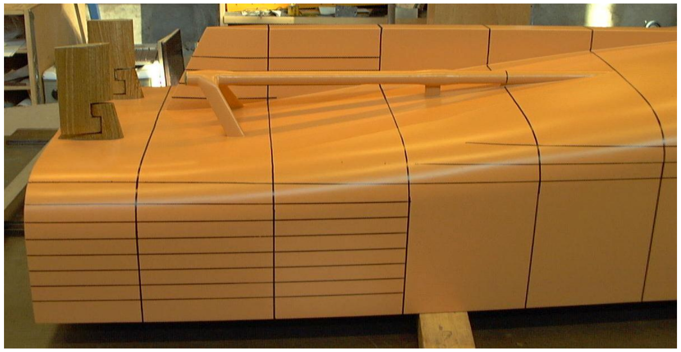
Azipod installed at Uikku



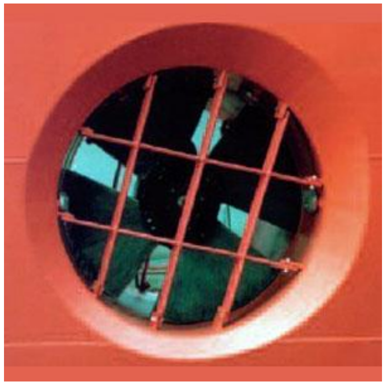
Freedom-class ship

Rotatable thrusters

On the power demand: less appendages



- No need for the propeller shaft, rudder, supporting structures.
  - These have a significant contribution to the resistance
  - Typical multi-screw vessel: The resistance of appendages is 5-15% of total resistance.

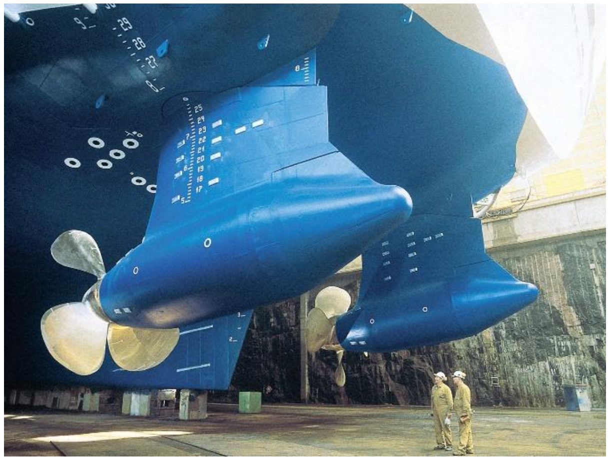


- No need for transversal tunnel thrusters at stern if rotatable thrusters are used.
  - Operating at low speeds requires often transverse thrusters
  - Thruster tunnels involve extra resistance

Rotatable thrusters

On the power demand: inflow to propeller

- Rotatable thruster can be tilted to meet the oncoming inflow at an optimal angle
  - The propeller plane is normally oriented to the oncoming flow.
  - This results in a better propulsive efficiency.
  - Cavitation characteristics improve.



The above-mentioned benefits on the power demand apply for multi-screw vessels.

Rotatable thrusters

Vibration and noise

Twin-screw vessel

- Shaft and its supports are the main reason for the propeller-induced vibration and noise
- Non-homogeneous wake which results in cavitation

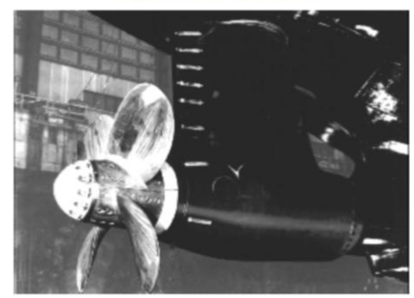
Azipod installed at Uikku

Pulling pod

- Flow is decelerated only due to the hull
- This is quite small usually and does not cause problems on cavitation and vibration.

Pushing pod

- Works in worse inflow
- may cause some problems

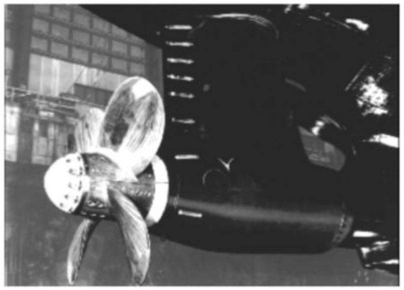


Rotatable thrusters

Which is better: pulling or pushing version?

- Well designed pulling unit is better than a pushing version
  - The difference is more pronounced with speed

Azipod installed at Uikku



- Pushing version may be better for a not so well streamlined shape of a pod
  - Propeller accelerates the flow and prevents separation
  - Beneficial to have a pushing for a blunt form pod

Rotatable thrusters

On the manoeuvring

- Manoeuvring and control of ship equipped with rotatable thrusters is much better than that of a conventional one
- There may be problems with directional stability if ship is not equipped with a skeg at stern

Rotatable thrusters

Design of the hull form when using rotatable thrusters

- No need for long shaft lines, no rudder

- Take into account the volume of the pod
  - Much larger than that of a traditional propulsion system
  - Locates within a short longitudinal distance
  - Generates an own wave system

Rotatable thrusters

Interaction of the wave systems of the pod and of the hull affects the propulsive efficiency

Positive effect

- The pod-induced waves smoothens the wave troughs of the waves generated by the hull and makes the stern wave higher.

Negative effect

- Steeper wave troughs, stern wave rise to transom and breaks.
- Consequences: larger resistance, additional loading of the propellers and decreased efficiency
- Solutions:
  - More streamlined pod (larger length / breadth ratio)
  - The volume of the pod can be compensated by decreasing the volume of the hull at the location of the pod. (E.g. so-called "half-tunnel stern" whose location shape and volume depend on the ship speed, depth of the propulsor device, loading of the propulsor)

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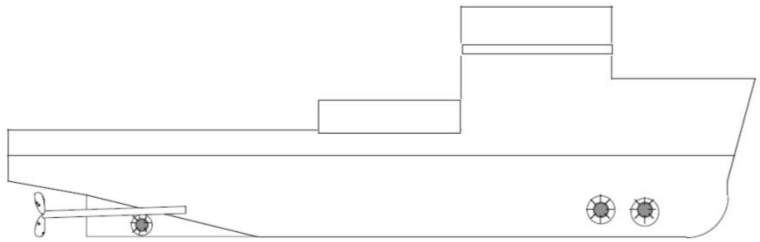
Steering thrusters

Improve manoeuvring qualities of ship at low speeds

- At bow
- Sometimes also art stern

Propeller operates

- in cylindrical tunnels located transversally to ship centre plane
- as an axial pump



Steering thrusters

Thrust

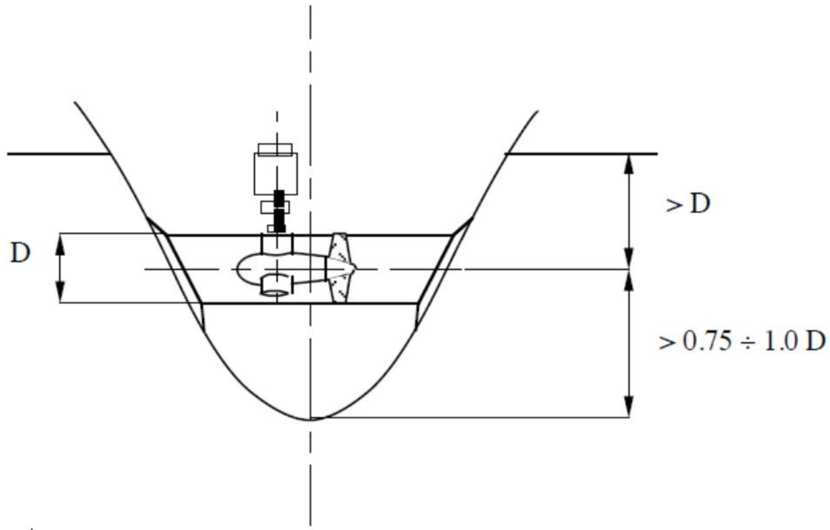
Components

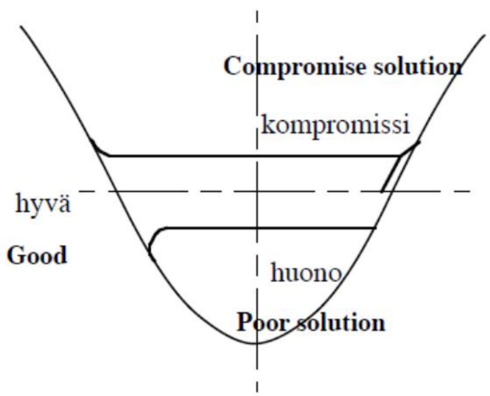
1. Thrust of the propeller
2. Side force created by hull-thruster interaction
   - result of flow acceleration at hull in the vicinity of tunnel
   - 35% ... 40% of total thrusting force
   - Decreases with ship's speed

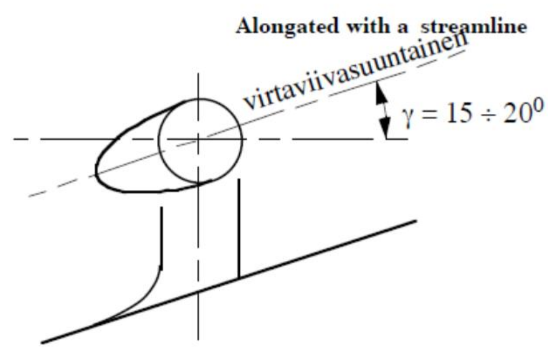
Estimation $T = k\,(P_D\,D)^{2/3},\ [\mathrm{kN}]$

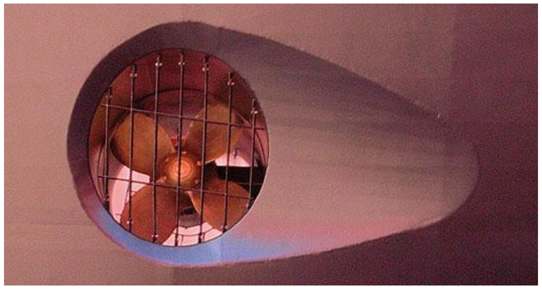
- FPP: $k \approx 1.08$ and CPP: $k \approx 0.97$
- P_D in kW and propeller diameter D in metres.

Steering thrusters



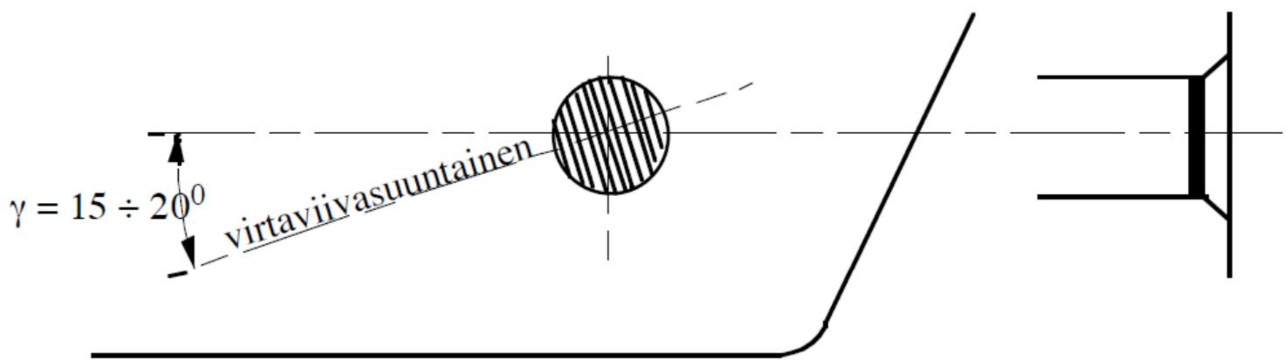






Steering thrusters

Protecting screen



- In order to protect steerable propeller from ice pieced and other solid objects (debris) a screen is used as shown above
- This decreases the thrust by 5 ÷ 10%.
- If screen is manufactured using pipes or tusses, these should be oriented normally ot the streamlines.

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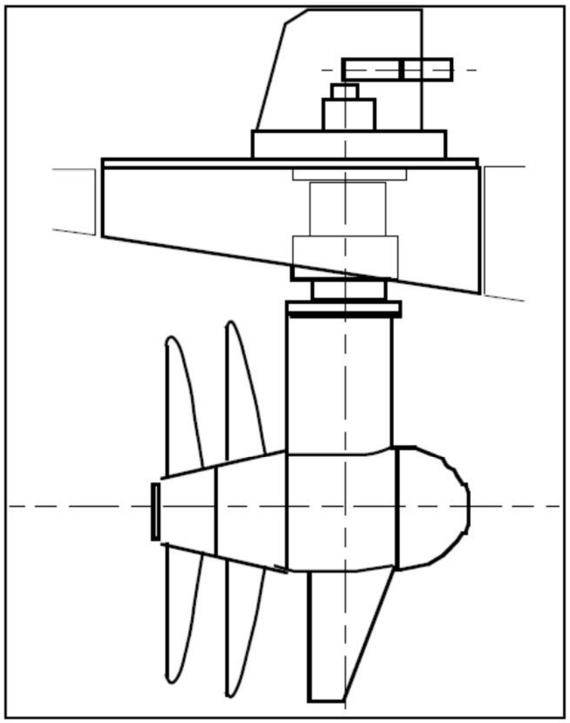
Contra rotating propellers

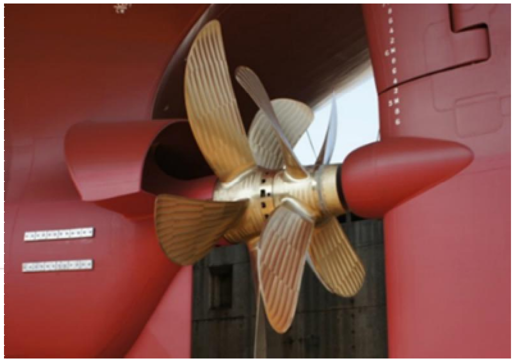
CRP



- *Contra rotating propellers - CRP* or tandem-propellers are used when a single propeller arrangement would result into too highloading
- For a single shaft vessel hull efficiency η_H is higher than in the multi-shaft arrangements
- If diameter of single screw arrangement is too small, high loading results in serious cavitation problems
- This can be prevented by locating two propellers on the same shaft

- If propelers rotate in the same direction and with same speed, we cal tham tandem propellers
- If they rotate in the opposite directions, they are calledcontra rotating propellers

Contra rotating propellers



Efficiency of CRP

- Efficiency of CRP is higher than that of tandem propellers
  - This is mainly due to induced tangential velocity U_T which increases angles of attack α_i of the rear propeller.
  - As the rear propeller induces also a tangential velocity of a different orientation (signum), this produces less rotational flow losses than a single or tandem propellers
- In order to work efficiently in a slipstream of the front propeller the diameter of the rear propeller is smaller
- On the other hand, pitch of the rear propeller is higher because it works in the axially accelerated flow of the forward propeller.
- Although, CRP's have much good features, they are not very popular
  - Their problems are mechanical if normal shaft arrangement is used. In case of rotatable mechanical thruster having short shaft, CRP concept can be utilized efficiently and without much problems
  - CRP's are used in torpedo's.
  - Apart higher efficiency they have smaller wake

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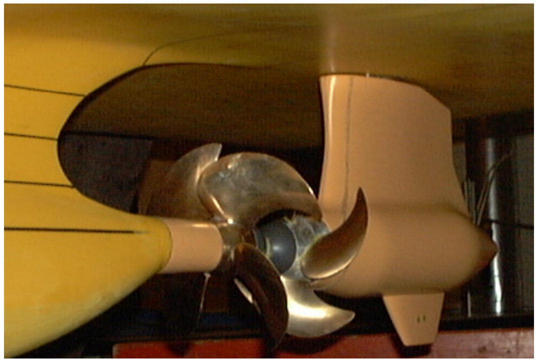
Hybrid propulsion

- CRP concept



Hybrid propulsion

- Utilises at least two different propulsion concepts
  - For instance, single water-jet and screw propellers

- An interesting concept: a normal propeller arrangement combined with a pod propulsor
  - Pod compensates for a rudder
  - The good features of pod-propulsion and that of CRP are combined
  - Good propulsion features
  - Good maneuvering qualities

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Grim’s vane wheel

Combination of

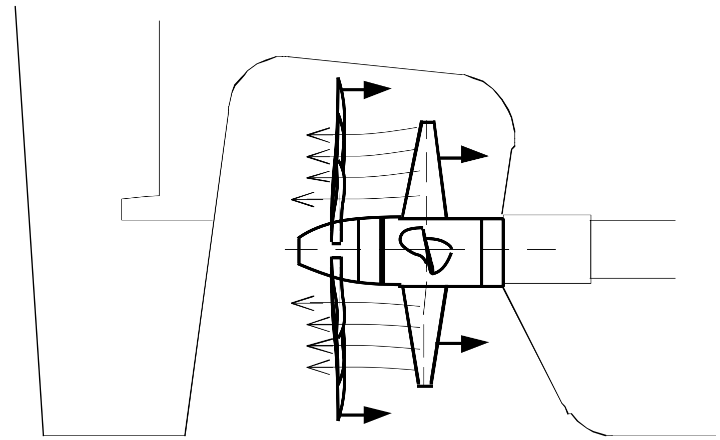
- normal screw propeller and
- turbine located aft of it

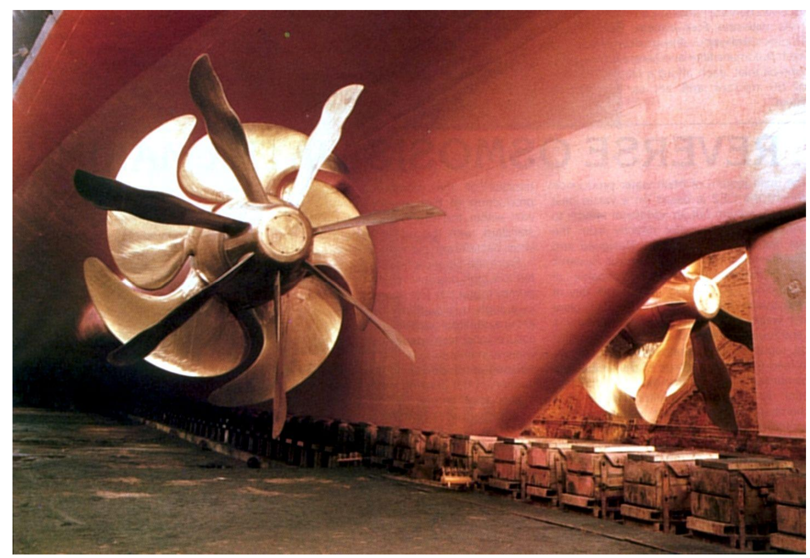
Turbine

- Diameter approx. 20% higher than that of the propeller.
- Several blades (7 to 9)
- Middle part of each blade works as a turbine
- Tip generates a positive thrust similarly as propeller.

Efficiency gain is 5%...15%

- Rotational speed of a turbine: 50%...65% lower than that of the propeller.





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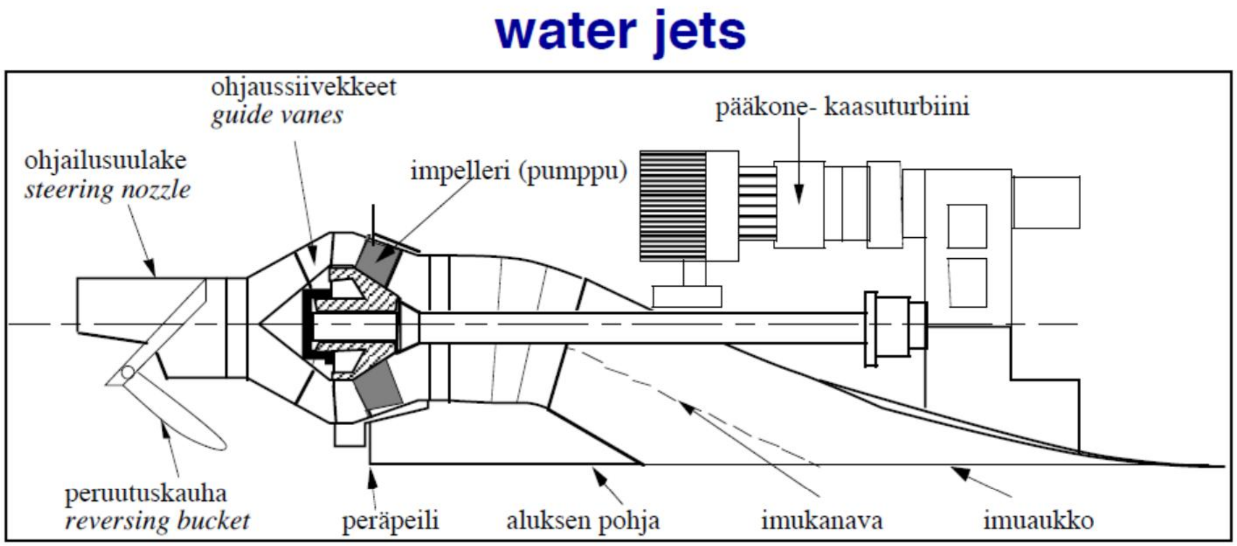
Water jet propulsion

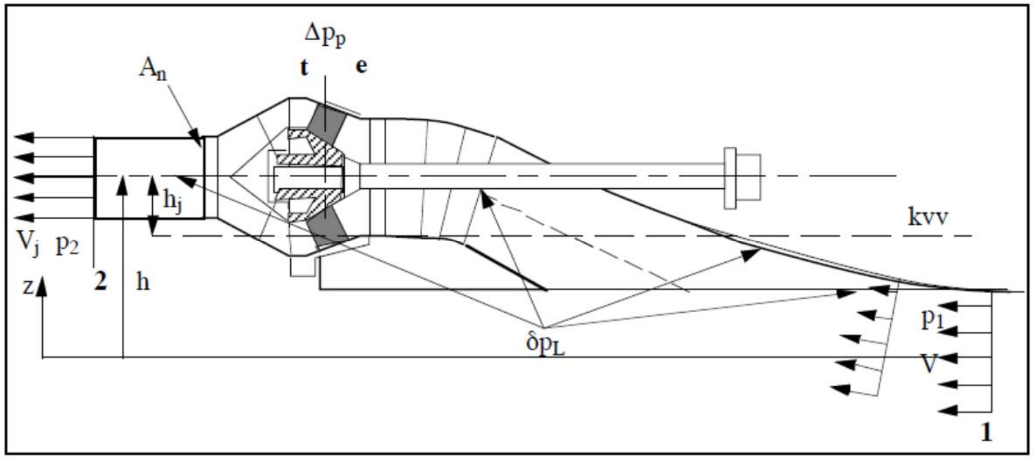
Water jet propulsion



- Impeller located inside the water jet, accelerates water and discharges it through the nozzle
- Water enters the pump thru opening in ship bottom located close to symmetry plane, transfers thru a duct to impeller
- Nozzle is made turnable to steer the vessel
- Reversing bucket makes it possible to orientate the thrust in the reversing direction.
- Gas turbine is often used to propel the pump

Water jet propulsion

Efficiency of waterjets/1



- Similar derivation as for ideal propulsor
- Momentum and Bernoulli eqs. are used
- Thrust is obtained from the moentum change applied to sections **1** and**2**

$$T = \dot{m}\left(V_j - V\right),$$

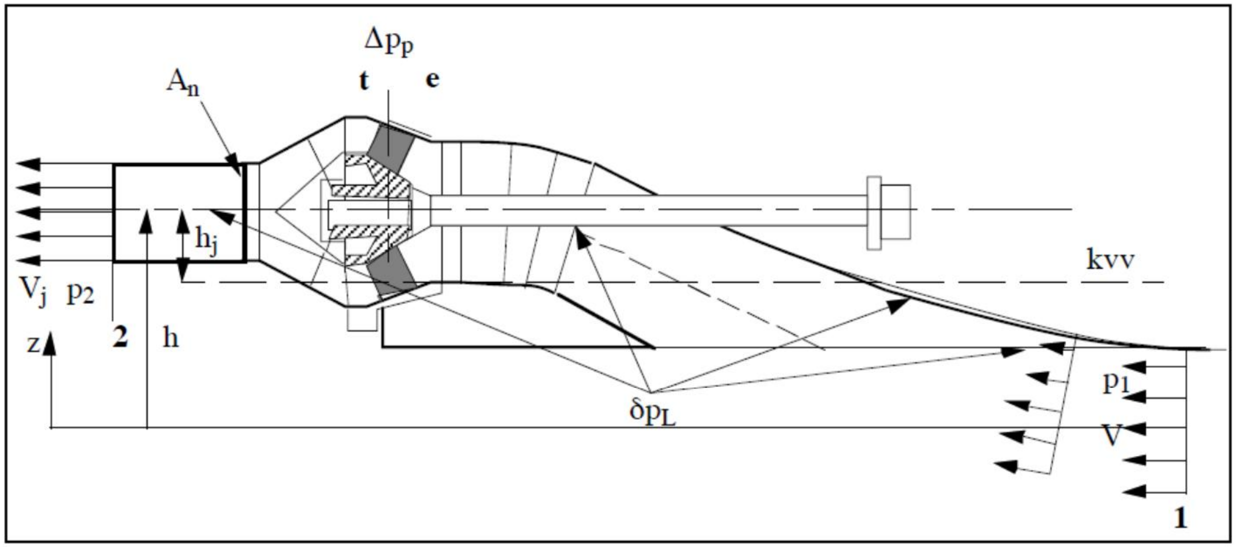
$$\dot{m} = \rho\, V_j\, A_n$$

- We consider a change of pressure and flow velocity in succesive sections: **1, e, t** and **2**).
- We assume that flow velocity suffciently far ahead off bottom opening **1**, is same as the ship's sped V and is homogeneous.
- Moereover, pressure p_1 is

$$p_1 = p_a + \rho\, g\, (h - h_j)$$

Water jet propulsion

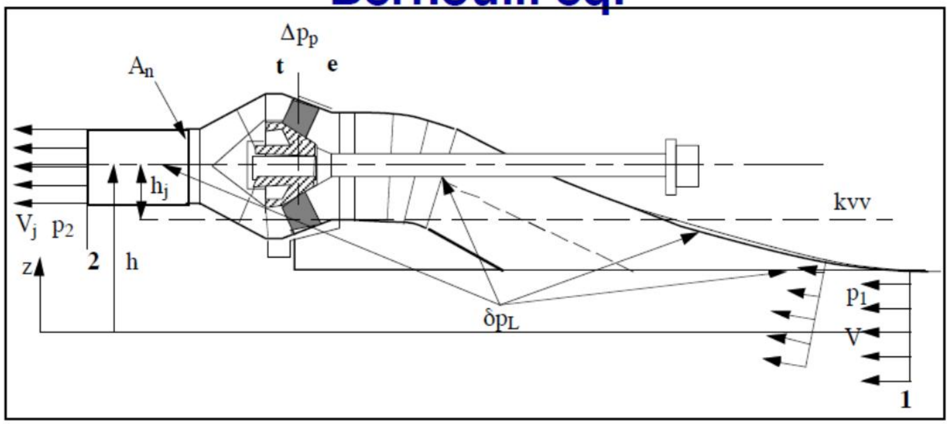
at the impeller



- Flow velocity at the impeller plane is V_P.
- Flow velocities at section e and t are same (continuity of flow)
- Behind impeller (section t) pressure is $p_t = p_e + \Delta p_P$
- Water jet discharges with velocity V_j at the nozzle (section 2) where pressure equals atmospheric that is $p_2 = p_a$.

Water jet propulsion

Bernoulli eq.



- Bernoulli eq. Is applied to sections: 1 and e and to 2 and t resulting in

$$p_a + \frac{1}{2}\rho V^2 + \rho g \left(h - h_j\right) = p_e + \frac{1}{2}\rho V_P^2 + \rho g h + \delta p_L$$

$$p_a + \frac{1}{2}\rho V_j^2 + \rho g h = p_e + \Delta p_P + \frac{1}{2}\rho V_P^2 + \rho g h .$$

- Pressure losses, mainly due to viscous effects with k being a non-dimensional coefficient.

$$\delta p_L = \frac{1}{2}\rho k V^2$$

$$\Delta p_p = \frac{1}{2}\rho \left(V_j^2 - V^2\right) + \rho g h_j + \frac{1}{2}\rho k V^2$$

- Energy flux delivered to water bt´y the pump, ie delivered power

$$P_p = V_j A_n \Delta p_p = V_j A_n \left[\frac{1}{2}\rho\left(V_j^2 - V^2\right) + \rho g h_j + \frac{1}{2}\rho k V^2\right]$$

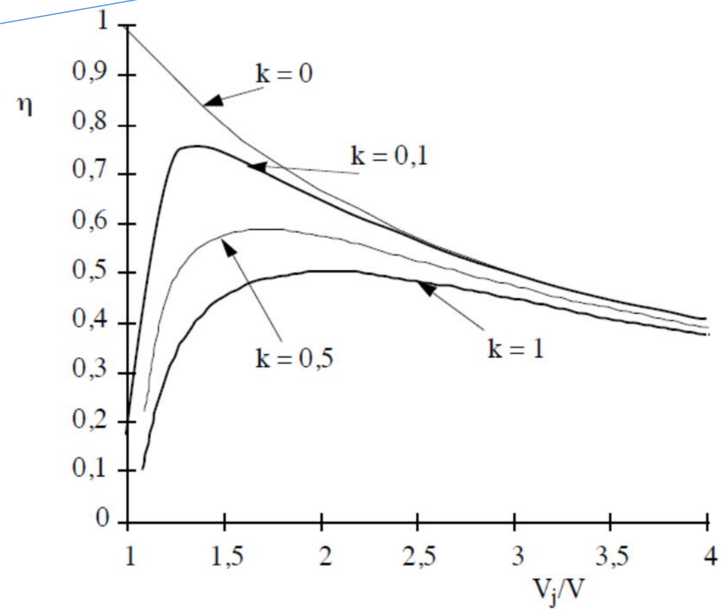
Water jet propulsion

efficiency

- Efficiency is a power ratio

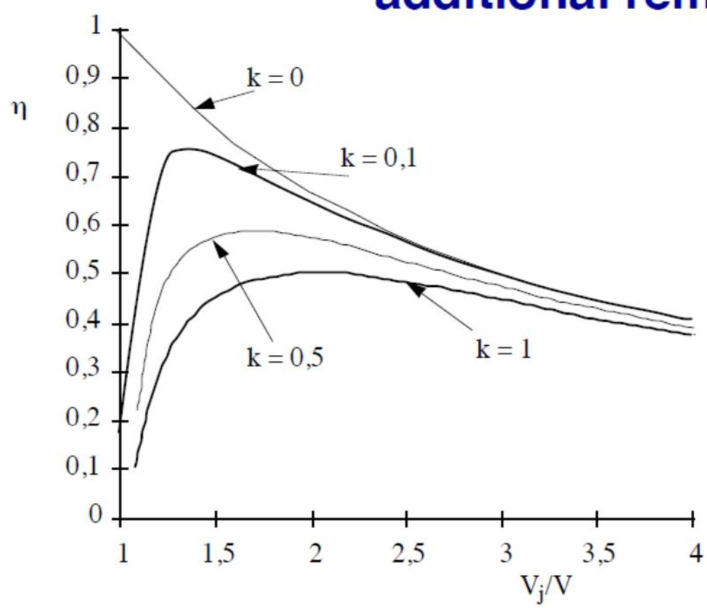
$$\eta = \frac{TV}{P_p} = \frac{\rho V_j A_n \left(V_j - V\right) V}{\rho V_j A_n \left[\frac{1}{2}\left(V_j^2 - V^2\right) + g h_j + \frac{1}{2} k V^2\right]} = \frac{2\left(V_j - V\right) V}{V_j^2 - V^2 + 2 g h_j + k V^2}.$$

- If for a sake of simplicity $h_j=0$ is assumed, the efficiency can be expresed using flow velocity ratio
- Efficiency is at maximum (100%) for the idel situatuion where velocity ratio equals 1. (i.e. k=0)
- However, thrust is zero than



Water jet propulsion

additional remarks on the efficiency



- For small velocities
- Viscous losses play much role for low velocity ratio
- For high jet velocities they are not so important
- In order to vave high efficiency and good thrust, the nozzle area should be sufficiently high

- Bottom opening and duct should provide the pump with a high velocity homogenous inflow
- If pump accelerates the flow from rest and coefficient k ≥ 1 than the efficiency is 50% at most
- Non-homogeneous inflow to pump results in cavitation problems

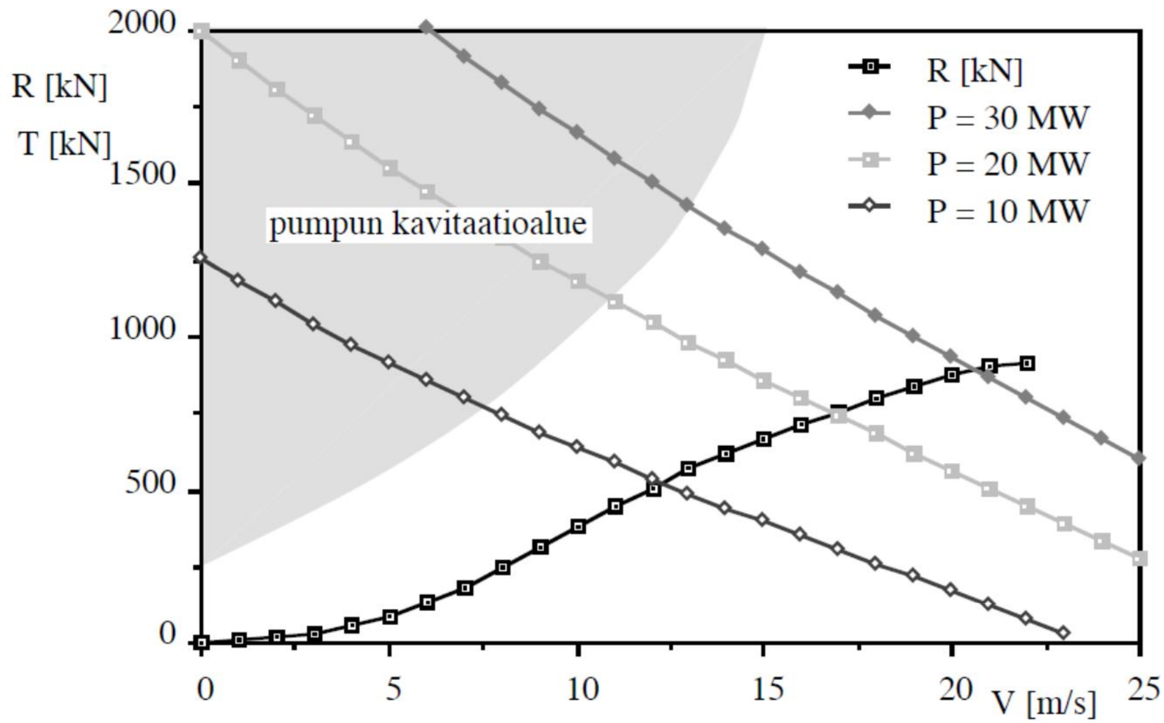
Water jet propulsion

Propulsion coefficients w & t

- Efficiency of pump is usually high (close to 100%)
- We assumed hull efficiency to be 100% as well
  - However, the flow at ship bottom is decelerated due to boundary layer and accelerated by the action of pump
- Thrust deduction (t) and wake (w) should be taken into account when extrapolating model test results to ship scale

Water jet propulsion

Example



- Nozzle area A_n = 5 m^2 and pressure loss coef. k = 0.3.

$$P_p = V_j A_n \Delta p_p = V_j A_n \left[\frac{1}{2}\rho\left(V_j^2 - V^2\right) + \rho g h_j + \frac{1}{2}\rho k V^2\right]$$

P_p → constant

$V_j A_n \Delta p_p$ → $V_j = \text{function}(V)$ → $T = \dot{m}\left(V_j - V\right) = \rho V_j A_n \left(V_j - V\right)$

Water jet propulsion

Summary on water-jets

- Water-jet is not suitable for slow ships. At low speeds the nozzle area has to be large to compensate for the axial losse and have efficiency similar to screw propeller.
- Good features of water-jets
  - Good manoevering
  - No need for apandages
  - Good for shallow water operation
  - Low noise level
- Bad features
  - Good for fast vessels
  - Requires much space
  - Expensive

Content of the course

- Resistance
- Propulsion
  - Introduction, Momentum theory on propeller action
  - Screw propeller
  - Propeller-hull interaction
  - Early design of a propeller
  - Propeller – main engine interaction
  - Stopping, accelerating and backing properties
  - Propeller cavitation
  - Special types of propulsors
  - Afterbody form of a ship

Special types of propulsors

Additional reading

- Matusiak J (2010) *Laivan propulsio*. M-176. Chapter 10
- Matusiak J (2008) Short introduction to Ship Resistance and Propulsion. Something in Section 2.6

Afterbody form of a ship

- Single screw ships
- Twin screw ships
- Supports of propeller shaft

Afterbody form of a ship

- Single screw ships
- Twin screw ships
- Supports of propeller shaft

Afterbody form of a ship

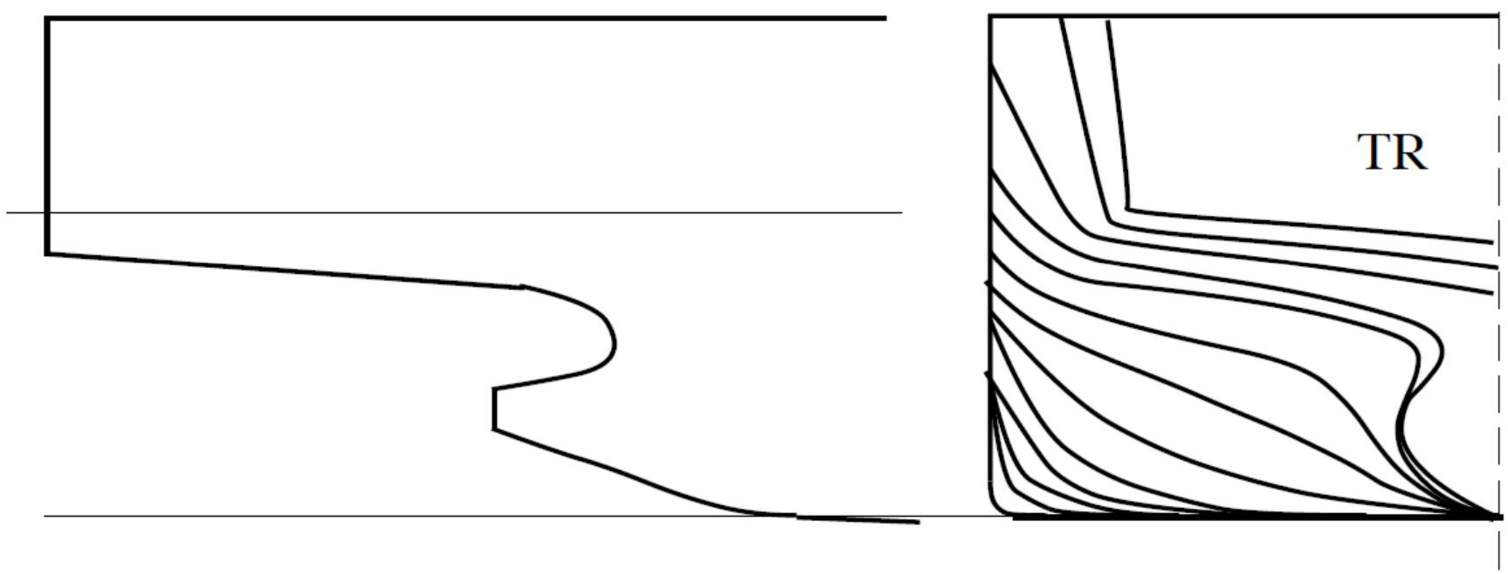
Single screw ship

- From the point of propulsive efficiency it is important that propeller accelerates the flow slowed down by a hull
  - That is why single screw arrangement with propeller located in wake is more efficient than the multi-screw arrangement
  - Propeller should have a diameter close to optimum and it should not cavitate much
  - For slow and full-form ship U-shaped stern is recommended.
  - With an increase of ship's speed and revs this form changes to V-shape

Afterbody form of a ship

Pram type stern with bulb shape support for propeller

- Good propulsion characteristics and even wake
- Accommodates large propeller
- Slamming type wave impact loads

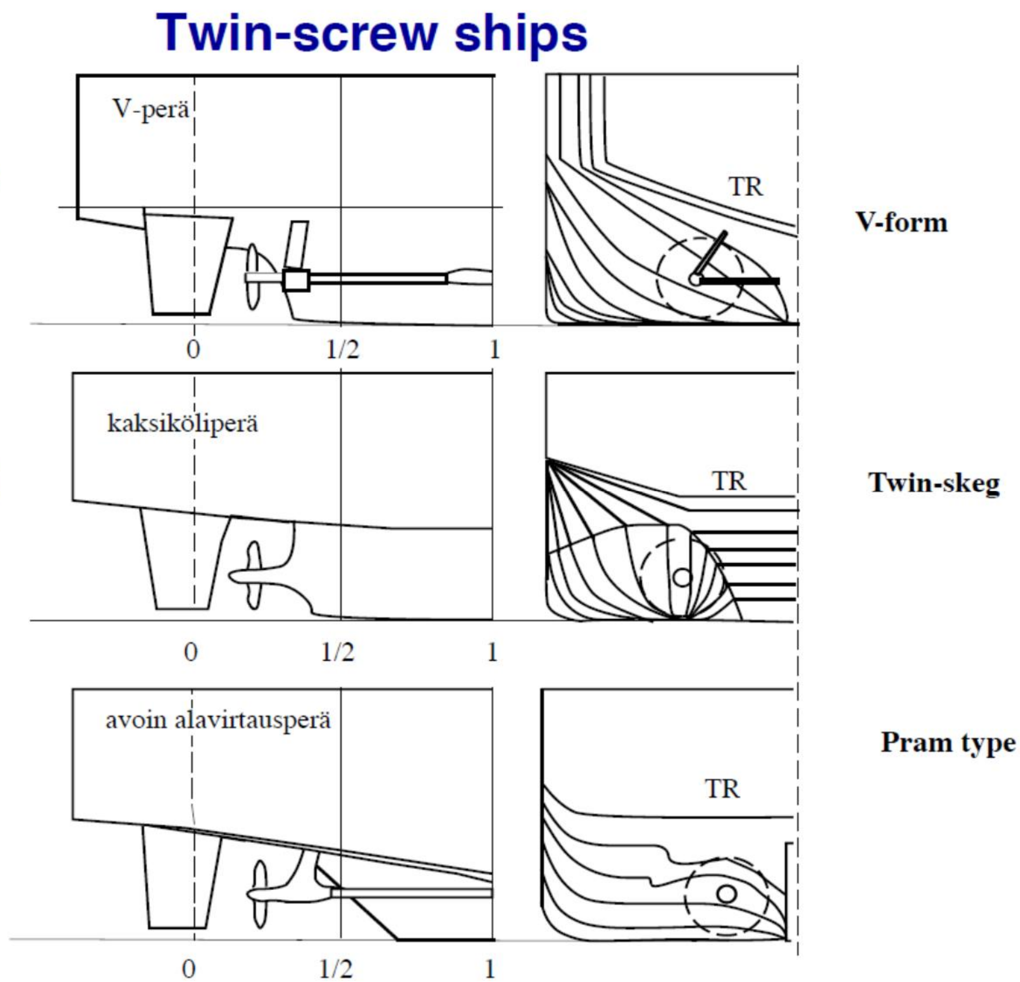


Afterbody form of a ship

- Single screw ships
- Twin screw ships
- Supports of propeller shaft

Afterbody form of a ship

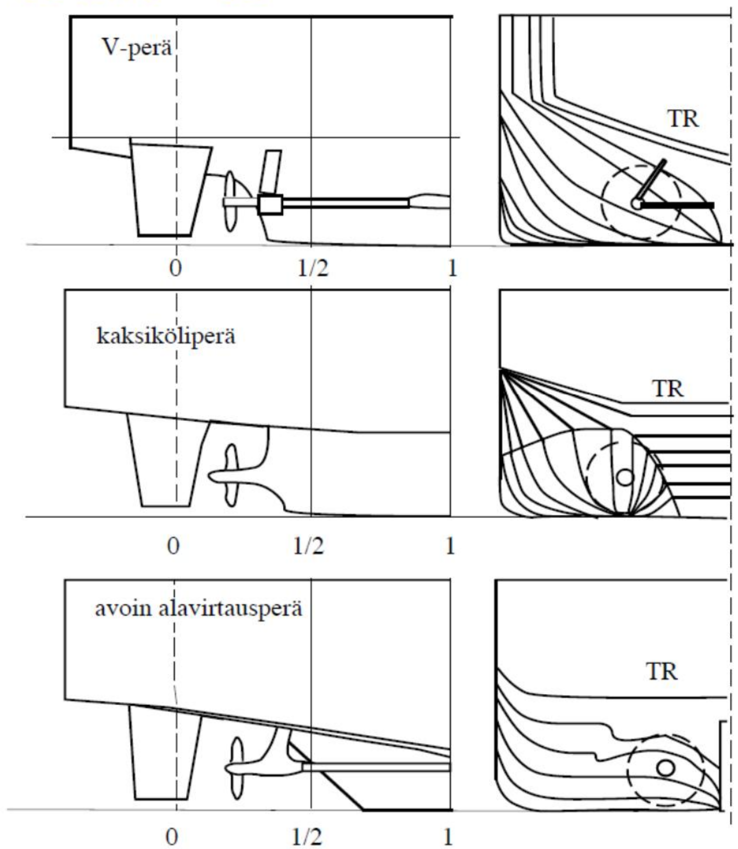
- If there is no possibility to have a single screw arrangement because of large breadth/draft ratio, twin screw solution should be used
- This can be divided into 3 types



Afterbody form of a ship

Features: +'es and –'es

- V-form good for open ocean operation requiring good seakeeping performance
- Large breadth at stern (Ro-Ro vessels) precludes V-form use
- Twin-skeg can be uses instead.
  - This requires careful design securing no separation condition.
- Pram-type stern secures good quality flow for high breadth and fullness stern forms



Afterbody form of a ship

Pram type stern

- Pram type stern can be categorized as follows:
  - Open stern with propellers supported by struts or with the podded propellers
  - Skeg-type stern (both for single and twin-screw arrangement),
  - Bulb-type support for a single screw
    - » *Twin-skeg is usually better form the propulsive efficiency than the open stern arrangement*
      - However, the resistance of twin-screw is higher
      - It is quite easy to have a half tunnel implemented in pram type stern
        - This allows a larger propeller

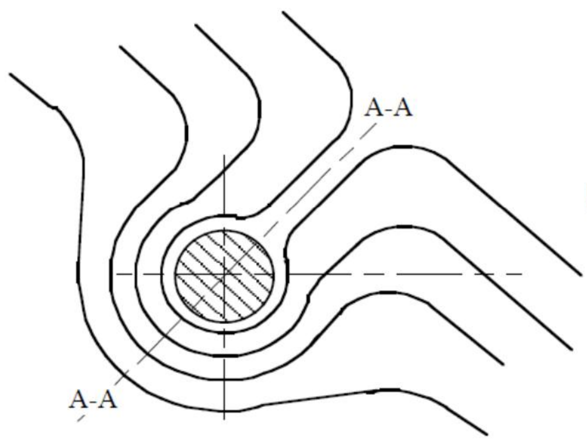
Afterbody form of a ship

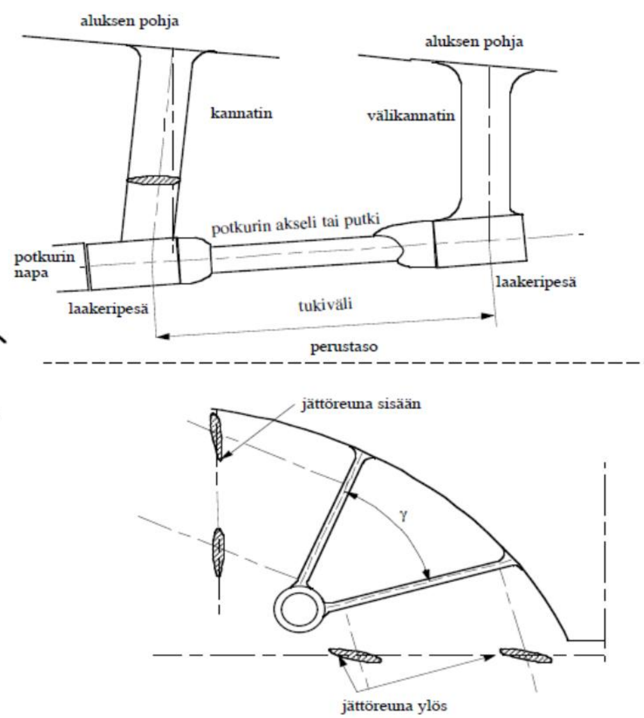
- Single screw ships
- Twin screw ships
- Supports of propeller shaft

Afterbody form of a ship

How to support propeller shaft?

- The support to the fixed (no-turnable) propellers is provided either by bossings or by struts

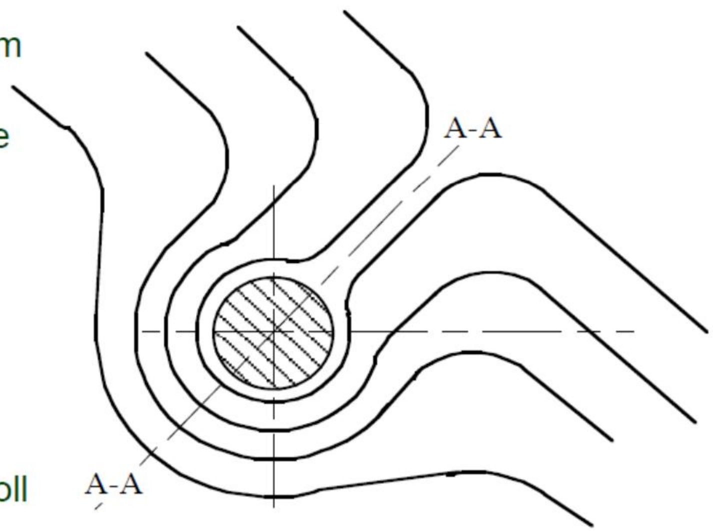




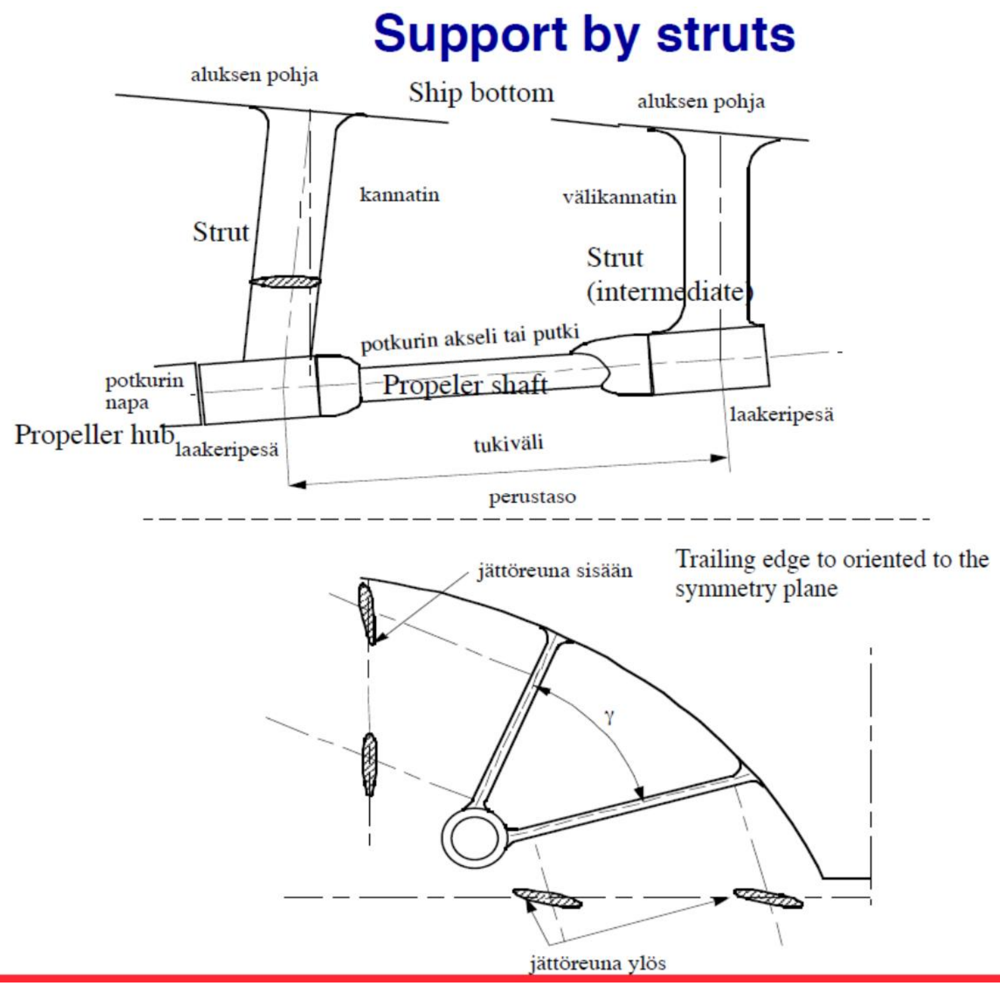
Afterbody form of a ship

Bossing

- Hull plating encompasses propeller shaft up to the last bearing forming a bossing.
- Symmetric form of it's profile is normally the best from the resistance point of view.
- The symmetry plane A-A should be oriented as close as normal to hull surface as possible
- It is possible to locate bossing in the longitudinal direction so that a proper pre-rotation of flow into propeller is obtained
- Non-symmetric bossing forms yield an increse of resistance not compensated by the benefits in propulsion gains
- Bossings improve directional stability and increase roll damping



Afterbody form of a ship



Afterbody form of a ship

Support by struts

- Propeller shaft leaves hull and aft-most bearing is supported by a strut.
- For long shafts intermediate struts are used as well
- Shaft can be protected by a pipe
- Strut support involves lower resistance provided that strts orientation in respect to flow at stern is correct
- This is checked by so-called flow visualization tests or sophisticated CFD-computations
- It is possible to have a hybrid support comprised of bossing and strut
- The free span of shaft should be checked by conducting vibration analysis
- Struts should be kept as short as possible and their angular in respect to hull plating orientation close to 90^0
- In order to avoid vibration the angle between the struts should be different from the the angle made up by propeller blades by at least 10^0.

Summary

- List and describe relevant characteristics of different propulsors. E.g.
  - Ducted propellers
  - Rotatable thrusters
  - Steering thrusters
  - Water jet propulsion

- What do you need to consider when designing the ship stern?

References

- Matusiak J (2010) *Laivan kulkuvastus*. M-289. Available in Noppa
- Matusiak J (2013) Slides Propulsion ENG 4 and 5. Available in Noppa

Pictures

- Kerwin and Hadler (2010) Propulsion. The Principles of Naval Architecture Series. Available in Knovel.
- scmp.com
- http://www.boatdesign.net