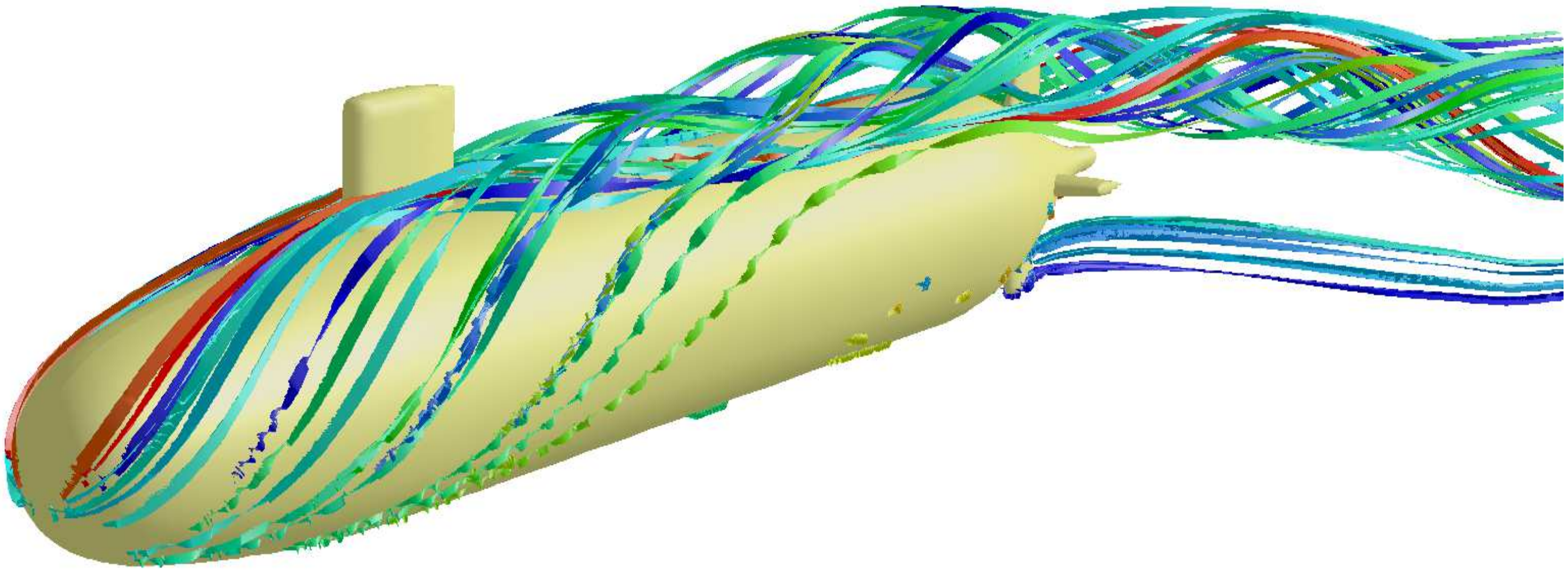


VOLKER BERTRAM

# Submarine Hull Design

# Navigator

Hull Design Aspects

**Overview of problems and approaches**

General guidelines for submarine hull design

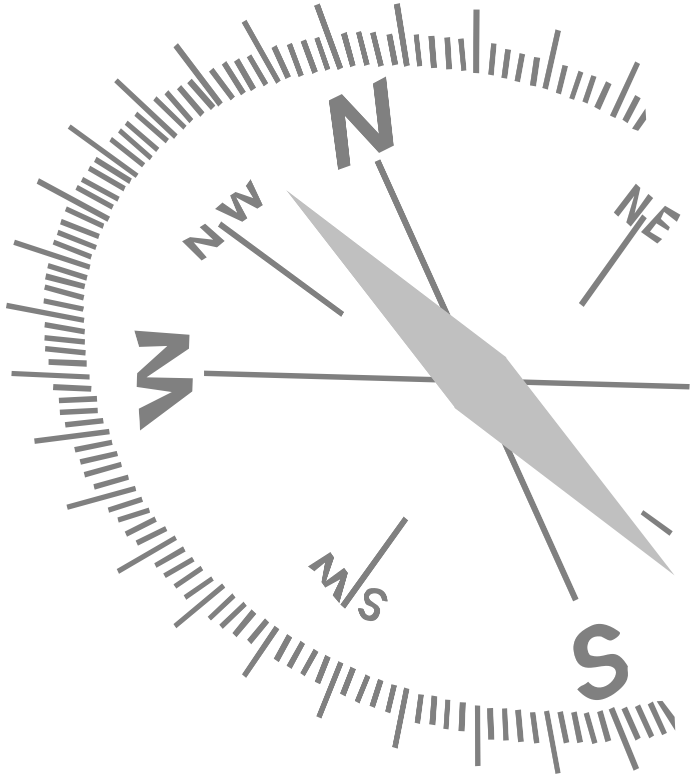
Quiz

Hydrodynamic Assessment

Hull-Appendages Interference

Analysis Methods for Snorkels

Quiz



# Recommended reading

Monograph on Submarine Design and Engineering

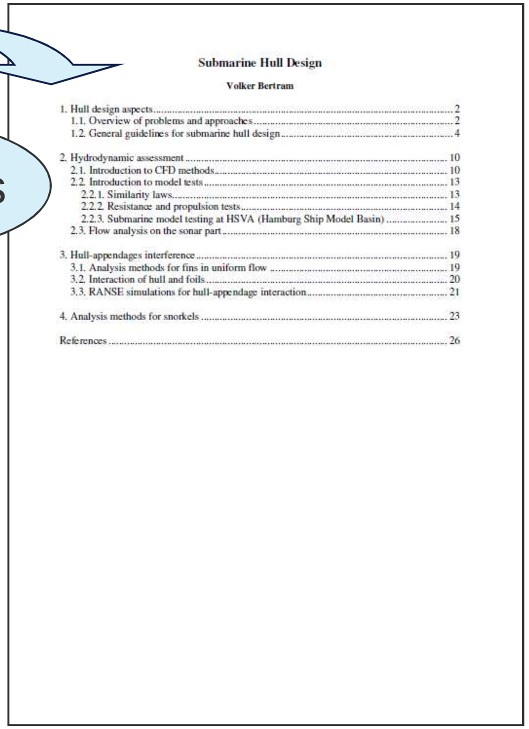
Image of INS Sindhukirti and general arrangement of INS Arihant (courtesy: www.militaryimages.net and www.indiandefence.com)

Editors: S. K. Bhattacharyya, R. Sharma, V. Anantha Subramanian and P. Krishnankutty

Department of Ocean Engineering, Indian Institute of Technology
Madras, Chennai (TN) – 600 036, India
January 2012.

Sponsored by Naval Research Board, DRDO, India.

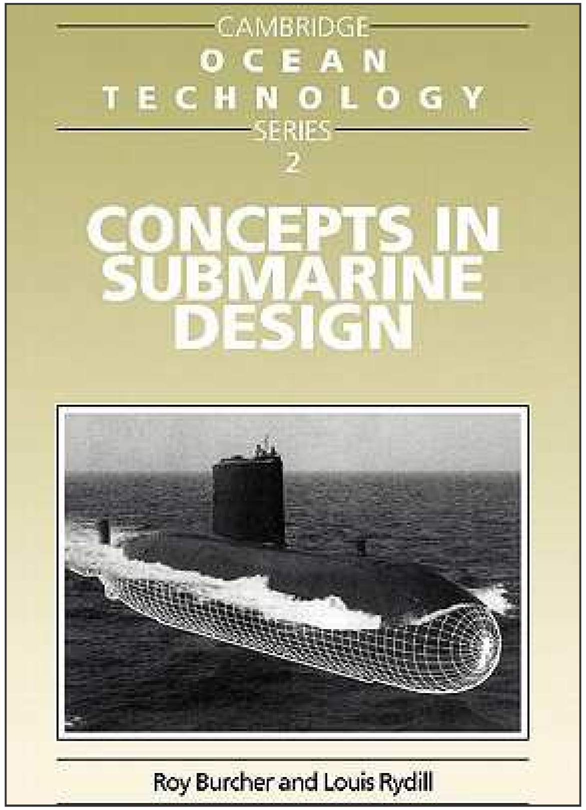
27 pages



Submarine Hull Design

Volker Bertram

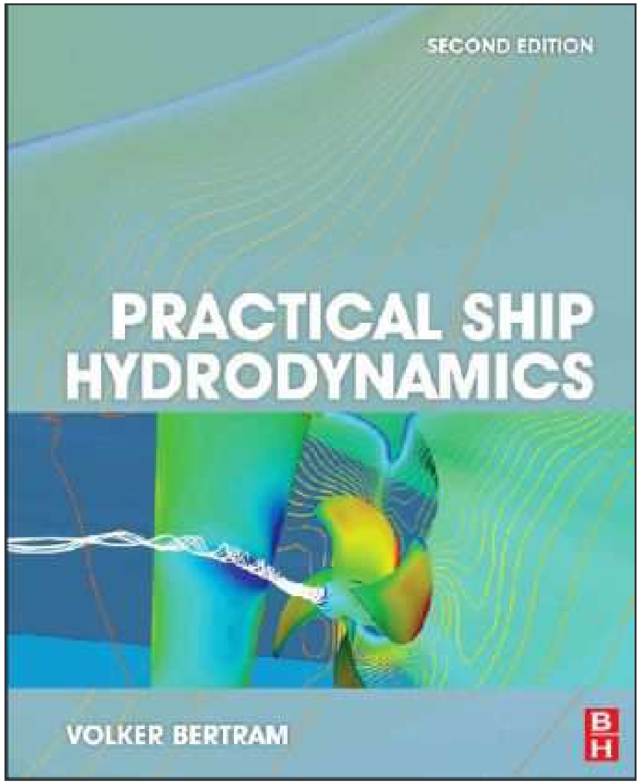
# Recommended reading



# Focus on resistance & propulsion

Main areas of ship hydrodynamics

- resistance & propulsion
- propellers
- manoeuvring
- seakeeping



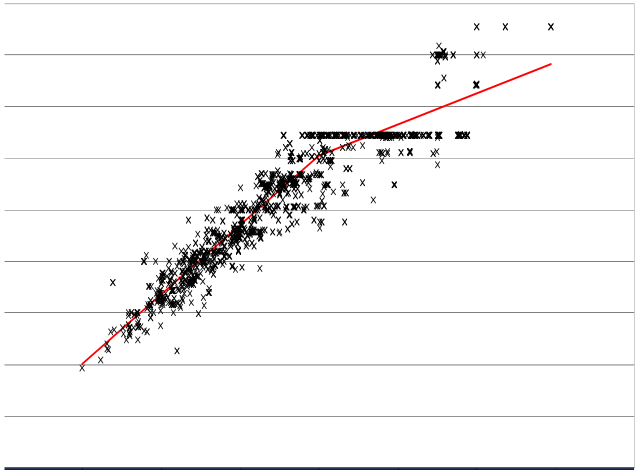
# Basic approaches

| | |
|---|---|
| • empirical / statistical approaches | ☺ fast & simple |
| | ☹ limited applicability |
| • experimental approaches | ☺ much experience |
| | ☹ scaling errors |
| • numerical approaches | ☺ accurate and detailed |
| | ☹ requires special resources |

## Empirical approach

- ☺ Simple (pocket calculator, excel)
- ☺ Fast
- ☺ Cheap



Great, like free lunch

# Empirical approach - Serious drawbacks

- ☹ Cannot reflect details
- ☹ Based on statistical evaluation of yesterday's designs

Do not expect much from a free lunch

## Empirical approach - Serious drawbacks

- ☹ No standard series for submarines

- ☺ Extensive experiments with axisymmetric bodies

  David Taylor Model Basin:

  Gertler (1950)

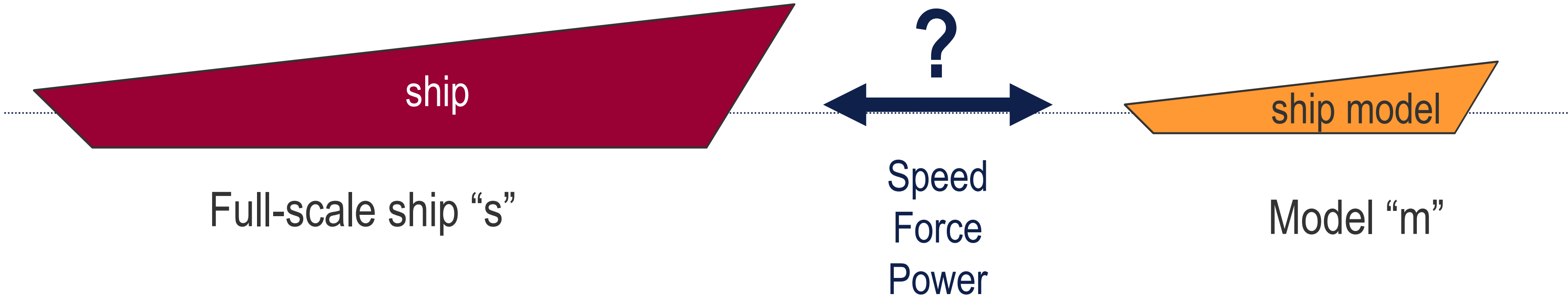
  Landweber & Gertler (1950)

# Experimental approach

Basic idea:

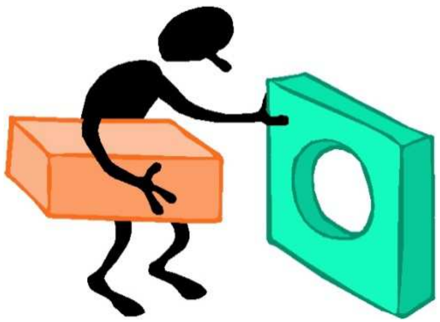
- perform test on scaled down model
- extract information
- scale (transform) to full-scale ship

Main uncertainty: model-to-ship correlation

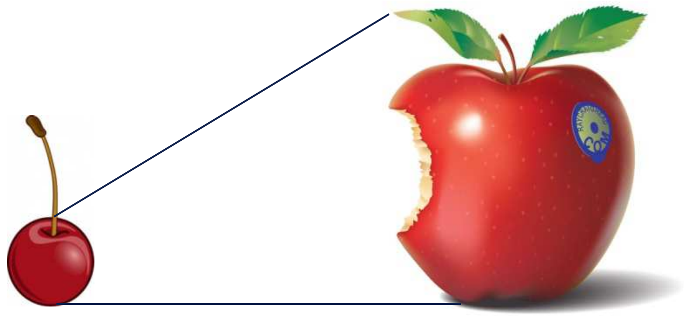


## Experimental approach

- ☹ Procedure differ between model basins
  → incompatible data bases



- ☹ Different physics (”scaling errors”)



# Experimental approach

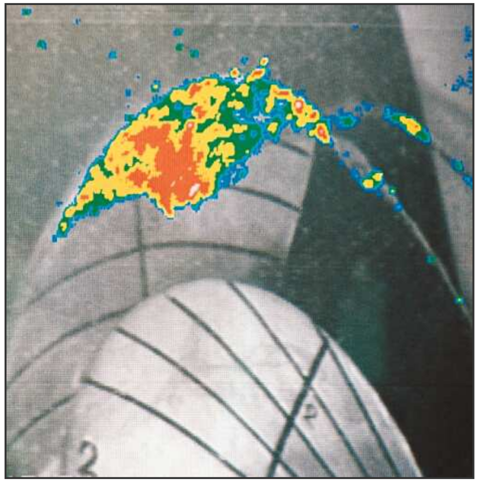
☺ > 100 years experience

- resistance test (resistance, nominal wake)
- propulsion test (thrust, torque)
- open-water test (propeller design support)

☺ progress in detailed measurements

→ Laser Doppler Velocimetry (LDV)

→ Particle Image Velocimetry (PIV)



Source: HSVA

# Experimental approach

- ☺ General confidence in model test
- ☺ Scaling procedures well accepted

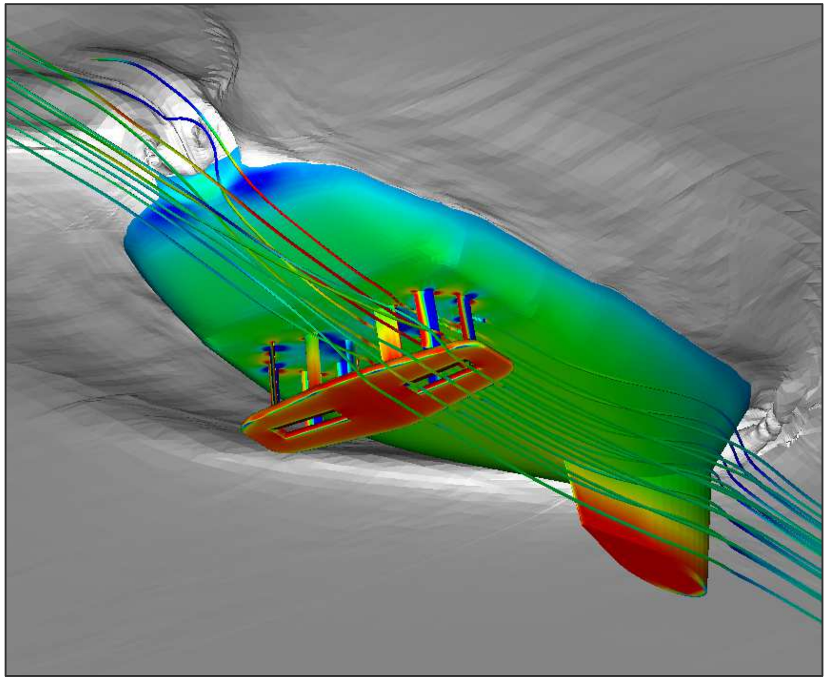

**No full-scale data for submarines**

## Numerical approaches

CFD = Computational Fluid Dynamics

Solves flow equations
using numerical techniques

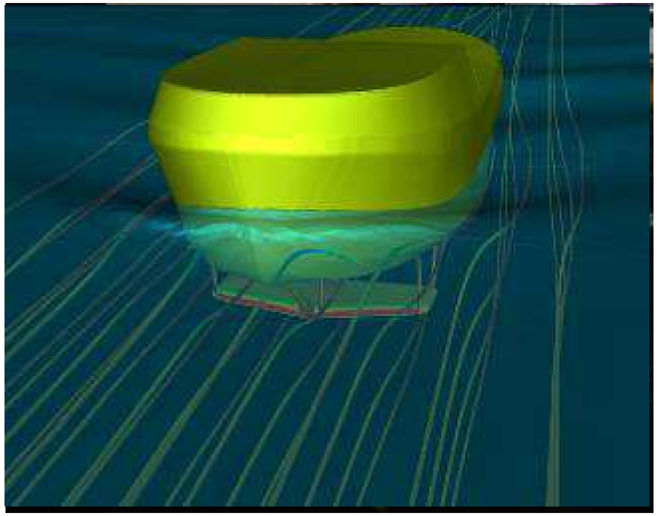
“Numerical towing tank”



Source: Voith

## CFD used increasingly for manoeuvring

- Force coefficient approach; coefficients determined in CFD
- Fast (real-time) simulation with given coefficients

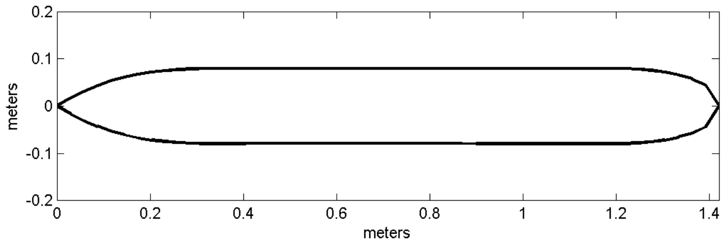


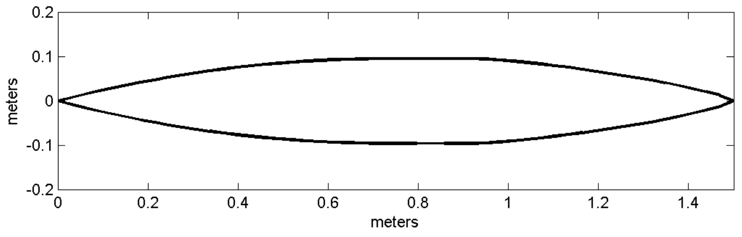
Hydrodynamic Coefficients

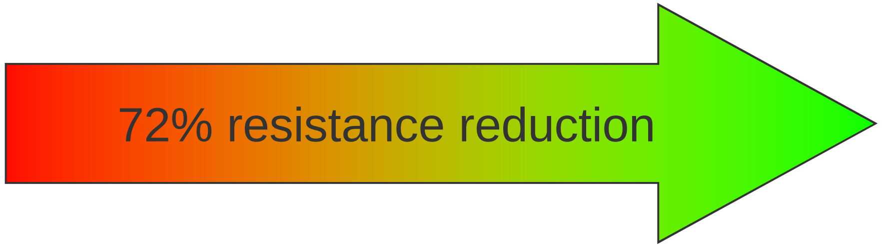
Source: Voith

# CFD allows formal optimization

- Parametric design
- Design evaluation by CFD
- Formal optimization



# Navigator

➡ Hull Design Aspects

Overview of problems and approaches

**General guidelines for submarine hull design**

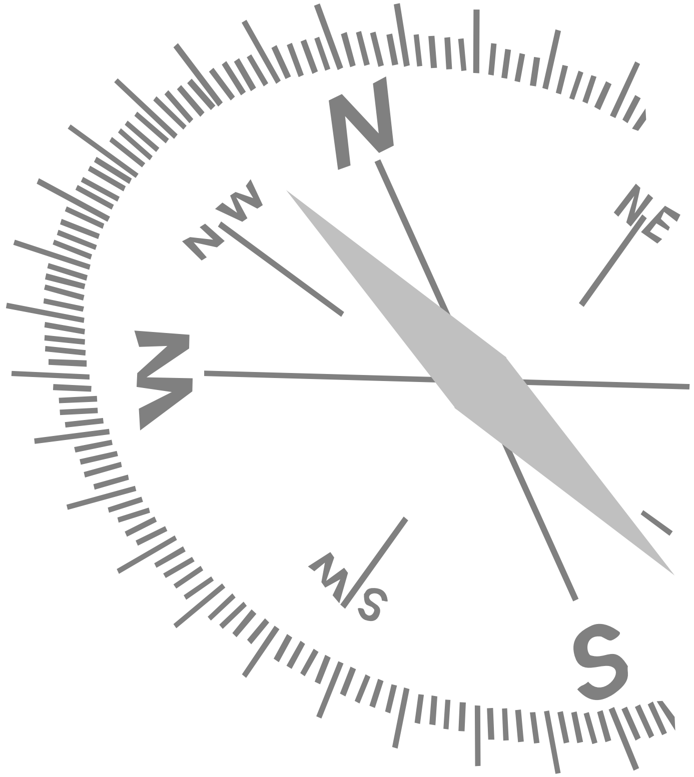
Quiz

Hydrodynamic Assessment

Hull-Appendages Interference

Analysis Methods for Snorkels

Quiz



# Design target: Hydrodynamic efficiency

Important design target in all designs:

- Minimize required power for given speed (weight, endurance)
- Maximize speed for given power

Two fundamental aspects:

- Resistance
- Propulsive efficiency

These interact !

## Consider mission profile

Design starts with **operational conditions** and **constraints**:

- predominantly submerged operation (stealth)
- low speed in surfaced condition


Conclusion:

- Virtually zero wave resistance
- Wave making only important for signature in snorkeling condition

## Resistance usually decomposed

Resistance cannot be measured at full-scale ship

Knowledge about ship resistance comes from model tests

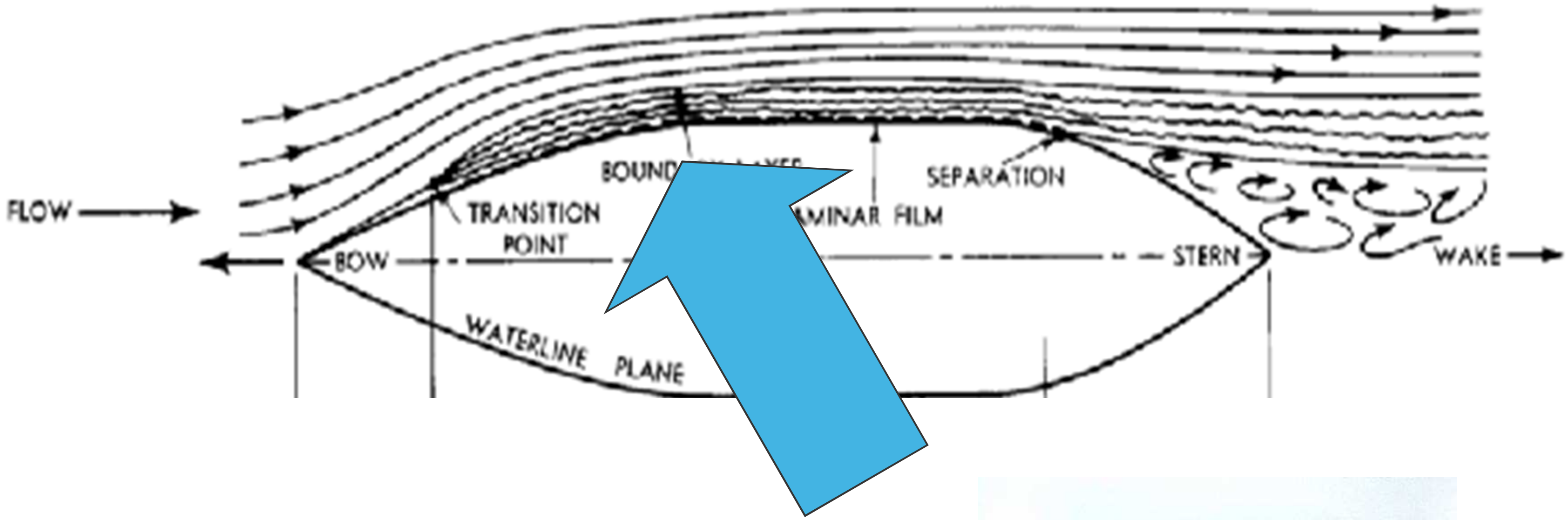
Decomposition somewhat artificial:

- resistance components interact
- most components cannot be measured individually

Main components (for bare hull): friction
form
~~wave~~

We want to reduce power required, not resistance!

# Friction resistance




60-70%

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# Friction resistance

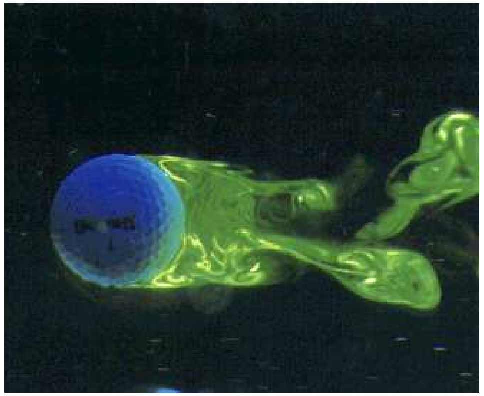
- Large shear stresses in boundary layer due to high velocity gradient
- Friction resistance = Sum of shear stresses over wetted surface
- Boundary layer in aftbody of submarine ≈ 0.5 m

Friction resistance depends on

- **wetted surface (given by CAD)**
- **speed**
- **surface roughness**

## Sphere as best solution?

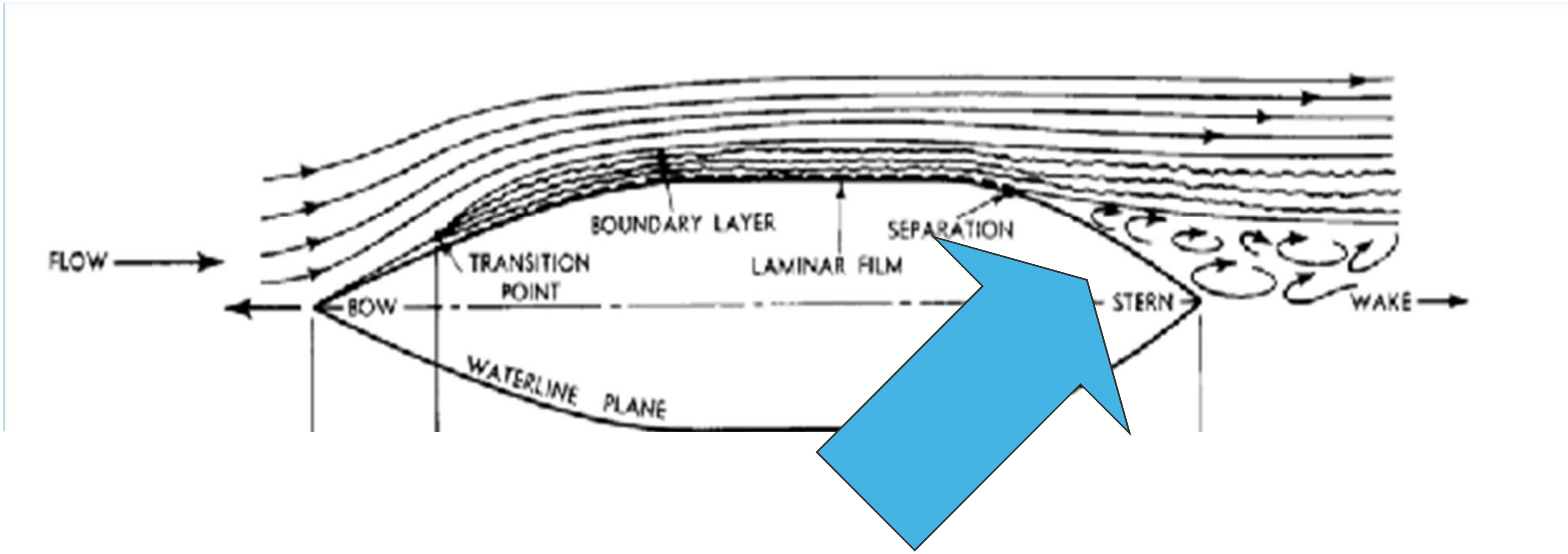
- least surface for given volume
- L/D = 1



But:

- Form resistance
- Propulsive efficiency
- (other design aspects: strength, producibility, manoeuvrability, ...)

# Form resistance (Viscous pressure resistance)




Form induces local flow changes which increase resistance

DNV·GL

## Form resistance

- local velocity sometimes higher/lower than ship speed

➡ average of resulting shear stresses higher

- energy losses in boundary layer, vortices, flow separation

  **avoid flow changes and hindrances**

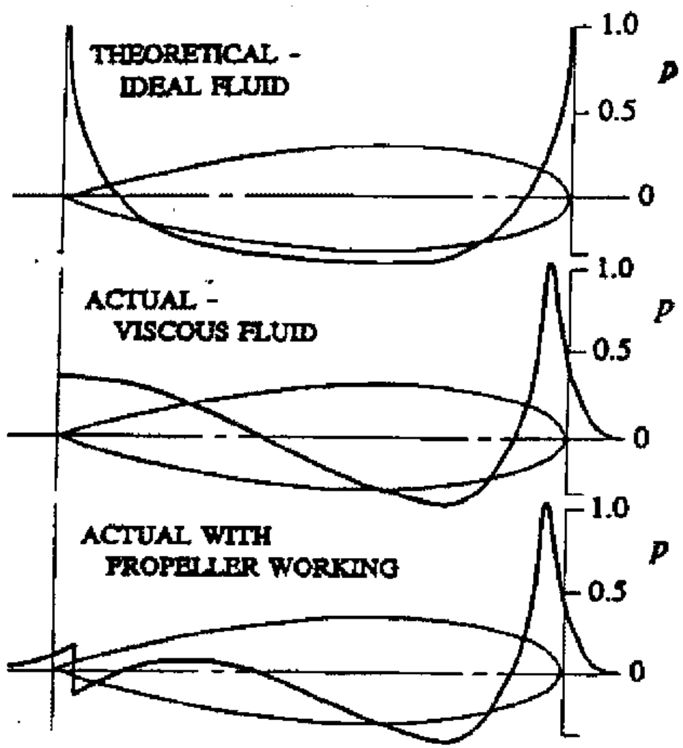
  **the ideal is a needle...**

- full hull shapes have higher form resistance than slender shapes

## Opposing requirements...

- Optimum for sum of both components exists
  - very shallow
  - shifts when propulsion is considered

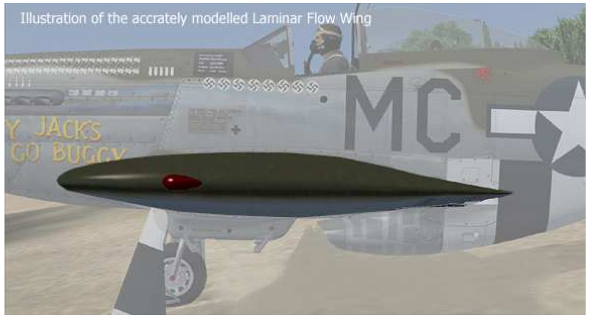





DNV·GL

## Laminar Flow Designs

- buzzword since the 1970s
- inspired by laminar flow aero-foil designs
- theoretically drag reduction up to 65% (on small hulls) based on model tests
- thought to revolutionize submarine designs




Then "pop", there goes the dream:

- real water has inherent turbulence level and numerous impurities
- laminar flow in sea water virtually impossible

Influence of some general hull parameters

key work at **David Taylor Model Basin**

GERTLER, M. (1950), *Resistance experiments on a systematic series of streamlined bodies of revolution - for application to the design of high-speed submarines*, DTMB Report C-297, Bethesda

LANDWEBER, L.; GERTLER, M. (1950), *Mathematical formulation of bodies of revolution*, DTMB Report 719, Bethesda

# Systematic series

- systematic tests with streamlined bodies
- 6th polynomial envelope (no parallel midbody)
- axisymmetric bodies

Parameters varied:

- Fineness ratio $L/D$
- Prismatic coefficient $C_P = \nabla/(\pi \cdot 0.25 \cdot D^2 \cdot L)$
- Nose radius (nondim.) $r_0 = R_0 \cdot L/D^2$
- Tail radius (nondim.) $r_1 = R_1 \cdot L/D^2$
- Distance of max. cross section from nose: $m = x/L$

## Fineness ratio

- key parameter for resistance (influences wetted surface for given volume)
- $L/D \approx 7$ optimum (considering also control surfaces)

Real submarines: $L/D > 9$

- due to practical requirements (space, producibility)
- penalty for “sub-optimum” shape is small
- $L/D = 7$ may be good for underwater robots

## Prismatic coefficient

- key parameter for resistance
- $C_P \approx 0.61$ optimum
- no significant change if considering also control surfaces

Caution: local shape (slope of body lines) influences form drag

This is not captured by simple variations as in Gertler (1950)

Near surface (snorkeling) condition:

- optimum unchanged for $F_n < 0.23$
- beyond that significant increase (but usually never operated in practice)

## Nose Radius

- different $r_0$ [0...1] investigated, but mostly $r_0 = 0.5$
- real submarines:

| | | | |
|---|---|---|---|
| German submarines: | typically | $r_0 \approx 2.5$ |
| based on L w/o parallel midbody | | $r_0 < 1.0$ |
| US nuclear submarines: | typically | $r_0 \approx 1.5$ |

- resistance minimum at $r_0 = 0.5$ (Gertler)

Results little more than indication due to much higher nose radius in practice

## Tail Radius

- different $r_1$ [0...0.2] investigated, but mostly $r_1 = 0.1$
- drag differences in this range: ±1%

Not really relevant, because propeller changes all...

## Position of maximum cross section

- resistance minimum at $x/L \approx 0.37 \cdot L$ (for $L/D = 7$, $C_P = 0.65$, $r_0 = 0.5$, $r_1 = 0.1$)
- strong increase of drag as *x/L* moves forward
- moderate increase as *x/L* moves aft

No statement on effect of parallel midbody

# Some background 3/4

## Forebody

- slender forebody good for resistance and low noise
- no consensus on forebody shape

Constraints on forebody design for submarines in practice:

- arrangement of torpedo tubes
- arrangement of sonar equipment

CFD used for local shape design

### Aftbody

- must consider propulsion (propeller changes flow completely)
- cone angles > 20° (in propelled condition)
- thicker aftbody good for weight distribution and space requirements

CFD used for detailed assessment

# Aspects of noise and sonar reflection

## No conflict with low resistance

- Low noise — streamlined shape has low resistance & low noise
- Low sonar reflection — still no clear statements on this issue

  only some guidelines can be given:

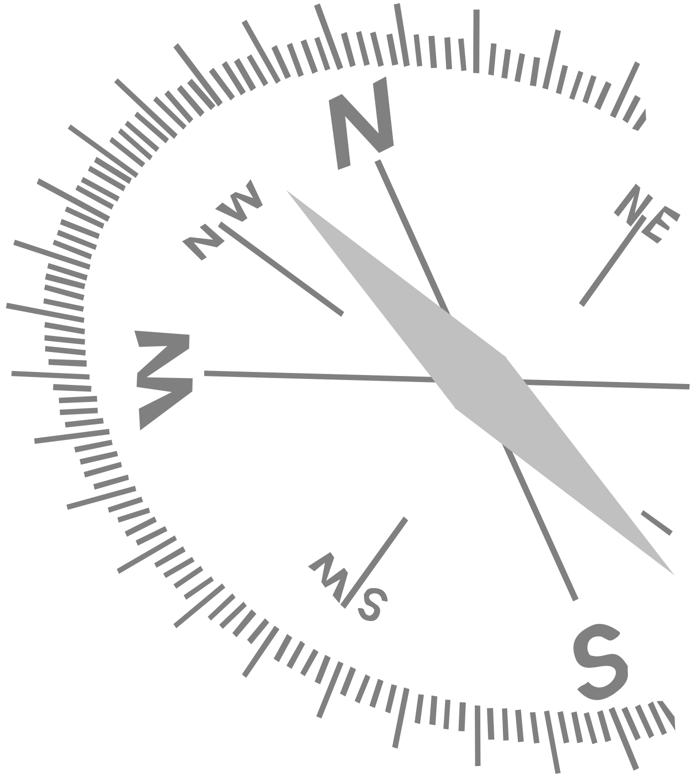
  - avoid concave surfaces

    (hull – sail connection critical in this respect)

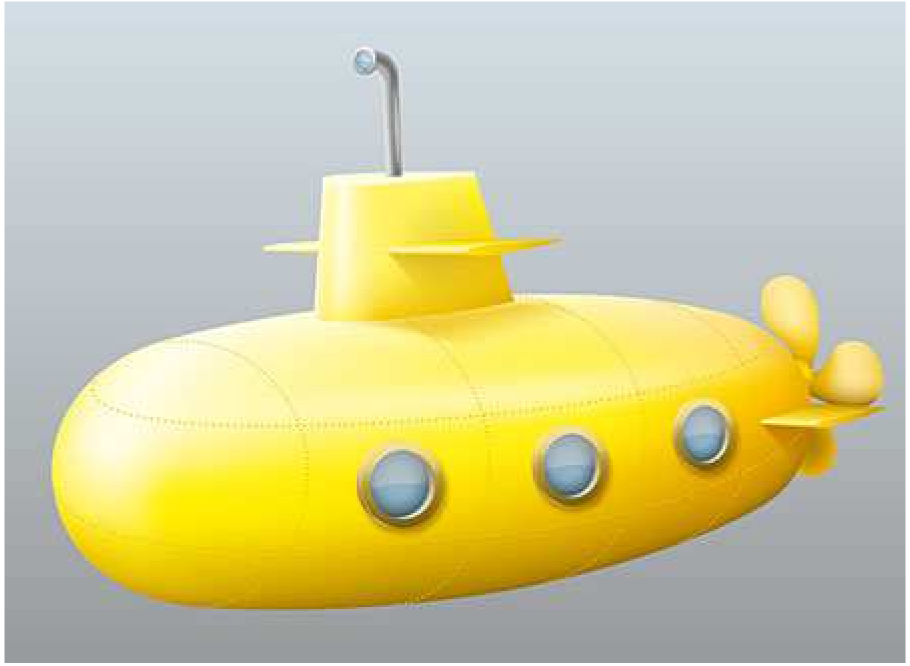
  - sonar target strength increases with size
  - length more critical than diameter (target strength ~$L^2$ and ~D)

# Navigator

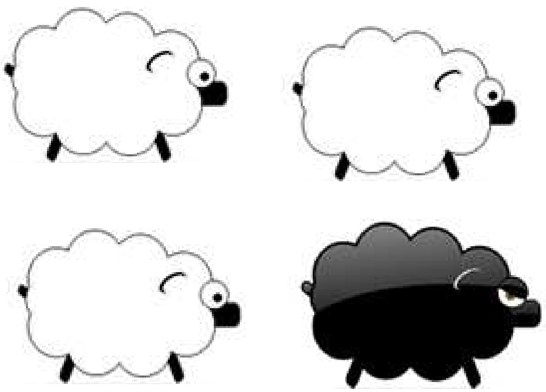
- Hull Design Aspects
- ➡ **Quiz**
- Hydrodynamic Assessment
- Hull-Appendages Interference
- Analysis Methods for Snorkels
- Quiz



# Quiz: Do you know your design of submarines ?

## What is <u>not</u> used in (submarine) design?



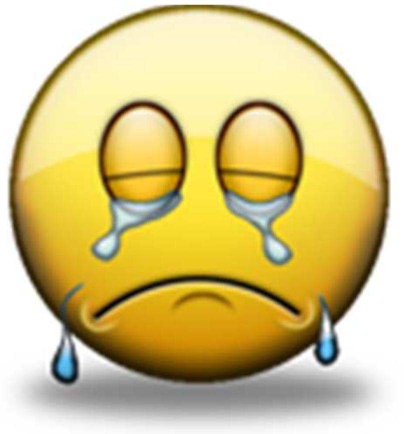
a. Broad-scale trial & error with prototypes
b. Empirical / statistical approaches
c. Model testing
d. Numerical simulation

## Which design approach is simple, fast and cheap?

a. Broad-scale trial & error with prototypes
b. Empirical / statistical approach
c. Model testing
d. Numerical simulations

## What is a typical drawback of empirical approaches?



a. cannot reflect details
b. high cost
c. scaling errors
d. time consuming to apply

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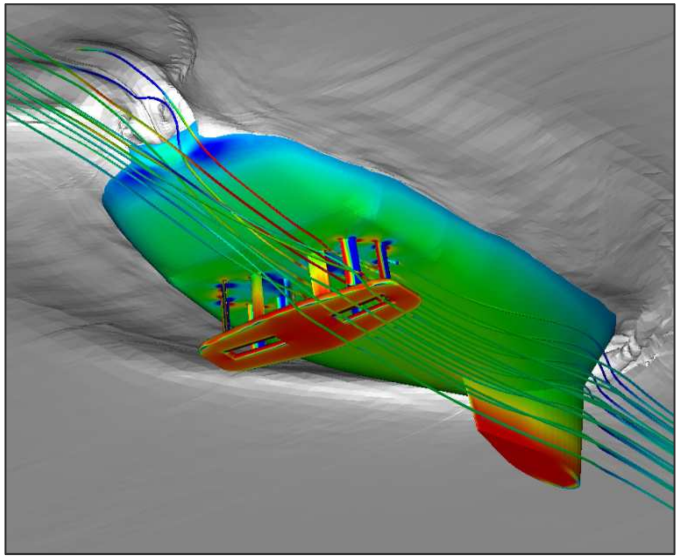
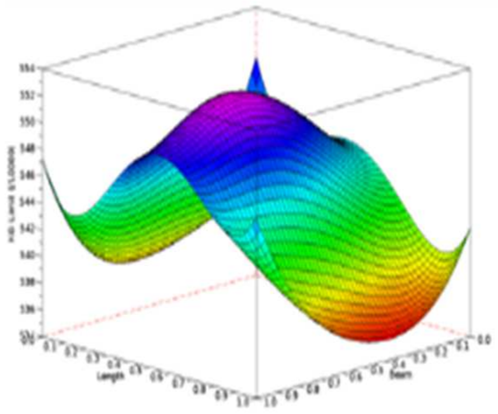
# CFD is popularly referred to as...



a. Design of Experiments
b. Rapid Prototyping
c. Numerical Towing Tank
d. Virtual Reality

# Which methods allows formal optimisation?



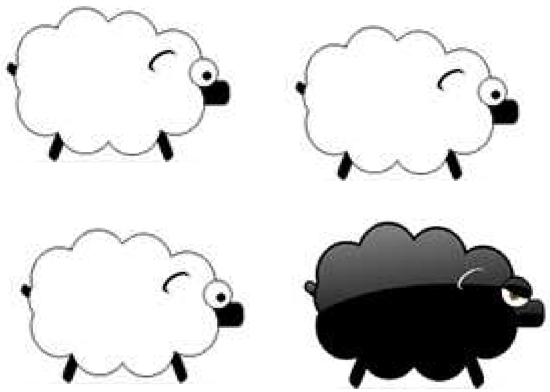
a. CFD (numerical simulation)
b. Experience-based design
c. Full-scale prototyping
d. Model testing

# To minimize required power you should...

a. decrease resistance & increase propulsive efficiency
b. decrease resistance & propulsive efficiency
c. increase resistance & propulsive efficiency
d. increase resistance & decrease propulsive efficiency

# Which resistance component can be neglected...

... for submarines?



a. appendage resistance
b. form resistance
c. friction resistance
d. wave resistance

## Friction resistance accounts for X% of hull resistance...

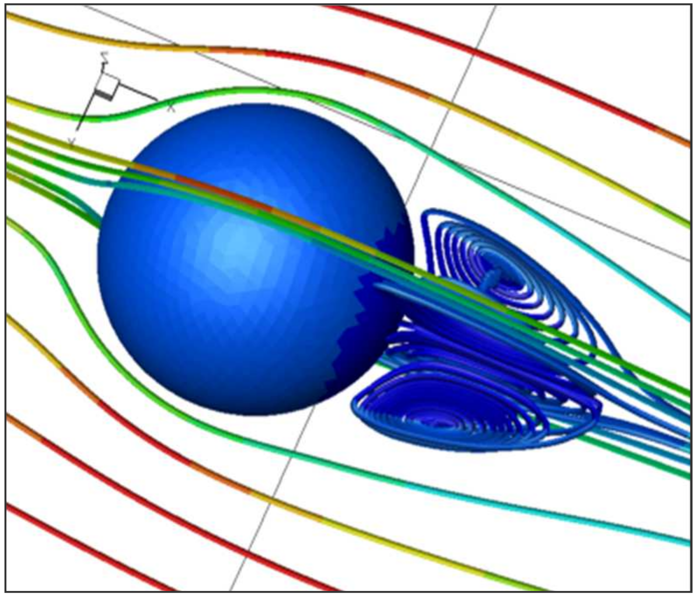
... for submarines?

a. X = 5 – 10%
b. X = 20 – 30%
c. X = 40 – 50%
d. X = 60 – 70%

# Boundary layer thickness in aftbody of submarine ≈

a. 5 mm
b. 5 cm
c. 50 cm
d. 5 m

## Sphere is best solution only in terms of…

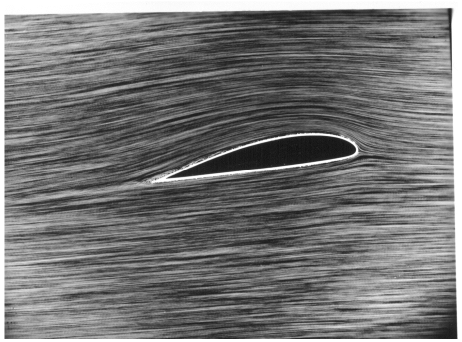


a. Form resistance
b. Friction resistance
c. Producibility
d. Propulsive efficiency

## Ideal shape for form resistance is like a …


a. needle
b. lentil (parabola)
c. teardrop shape
d. sphere

## Laminar flow designs for submarines...



a. were investigated by Landweber & Gertler
b. did not work in real ocean environment
c. reduced resistance by up to 85%
d. worked better than for aero-foils



DNV·GL

# Landweber & Gertler performed systematic tests ...

on bodies of revolution at...

Landweber Gertler

a. David Taylor Model Basin
b. DLR (Göttingen)
c. Hamburg Ship Model Basin
d. NURC (NATO Underwater Research Center)

## Landweber & Gertler's family of streamlined bodies...

... had as envelope:

a. Non-uniform rational B-spline (NURBS)
b. parabola (aft) & straight line & ellipse (nose)
c. parabola (nose) & straight line & ellipse (aft)
d. higher-order polynomial

modern AUV

AUV = autonomous underwater vehicle

## Landweber & Gertler's recommended for L/D...

... of underwater bodies of revolution:


a. 3
b. 5
c. 7
d. 9

# Forebody of real submarine less slender…

than recommended by Landweber & Gertler because:

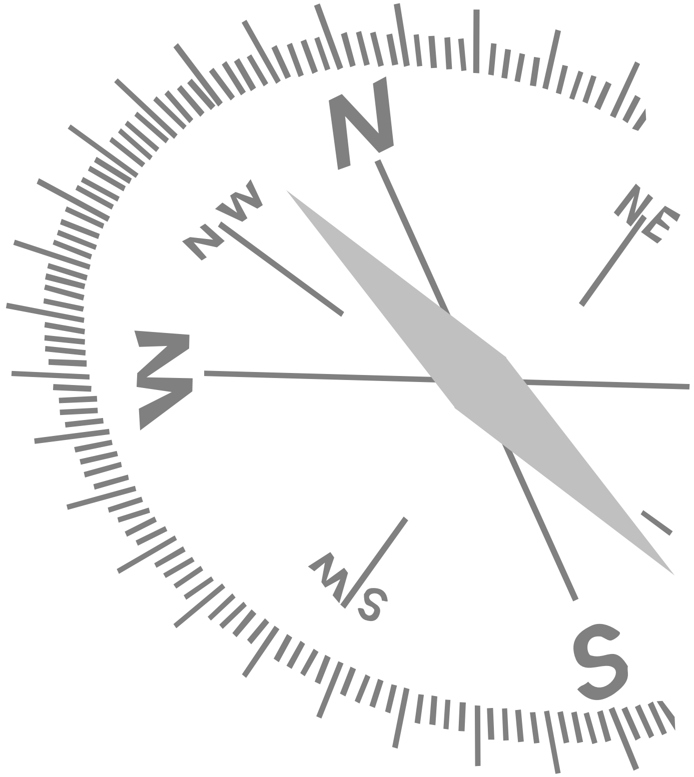

a. CFD showed fuller shapes better at full scale
b. fuller forebody reduces flow noise locally
c. fuller shape OK in propelled condition
d. internal space requirements leave no other choice

## Aftbody of real submarine less slender…

than recommended by Landweber & Gertler because:


a. CFD showed fuller shapes better at full scale
b. fuller aftbody reduces flow noise locally
c. fuller shape OK in <u>propelled</u> condition
d. internal space requirements leave no other choice

# Navigator



Hull Design Aspects

Quiz

Hydrodynamic Assessment

- **CFD Methods**
- Model tests
- Flow analysis on the sonar part

Hull-Appendages Interference

Analysis Methods for Snorkels

Quiz

## What is CFD ?

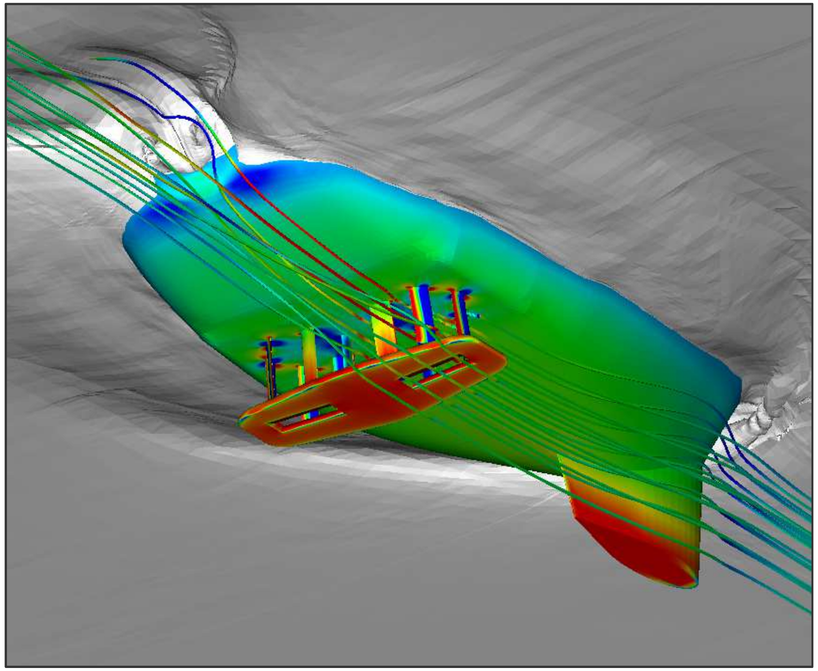
CFD = Computational Fluid Dynamics

Solves flow equations

- Navier-Stokes
- RANSE,
- Euler
- Laplace (“Poti”)

using numerical techniques

- FEM, FVM, FDM, BEM, ...



# Potential flow codes

## Potential flow codes

- neglect viscosity
- elements only on surface
- fast and cheap (optimization)
- limited accuracy

## RANSE

- expensive
- better model (breaking waves, flow separation)

## Wave resistance codes

**Can do:**

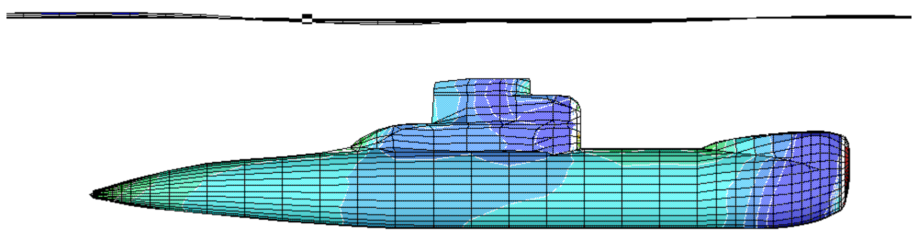
Wave formation (and wetted surface)
Dynamic trim and sinkage (squat)
(slender) lifting surfaces


**Cannot do:**

Viscosity
Breaking waves
Propulsion & Appendages

# Panel codes – fast enough for design

- Surface mesh only
- typically 2000 - 20000 panels
- mesh generation 5-50 s
- CPU times 1-5 min

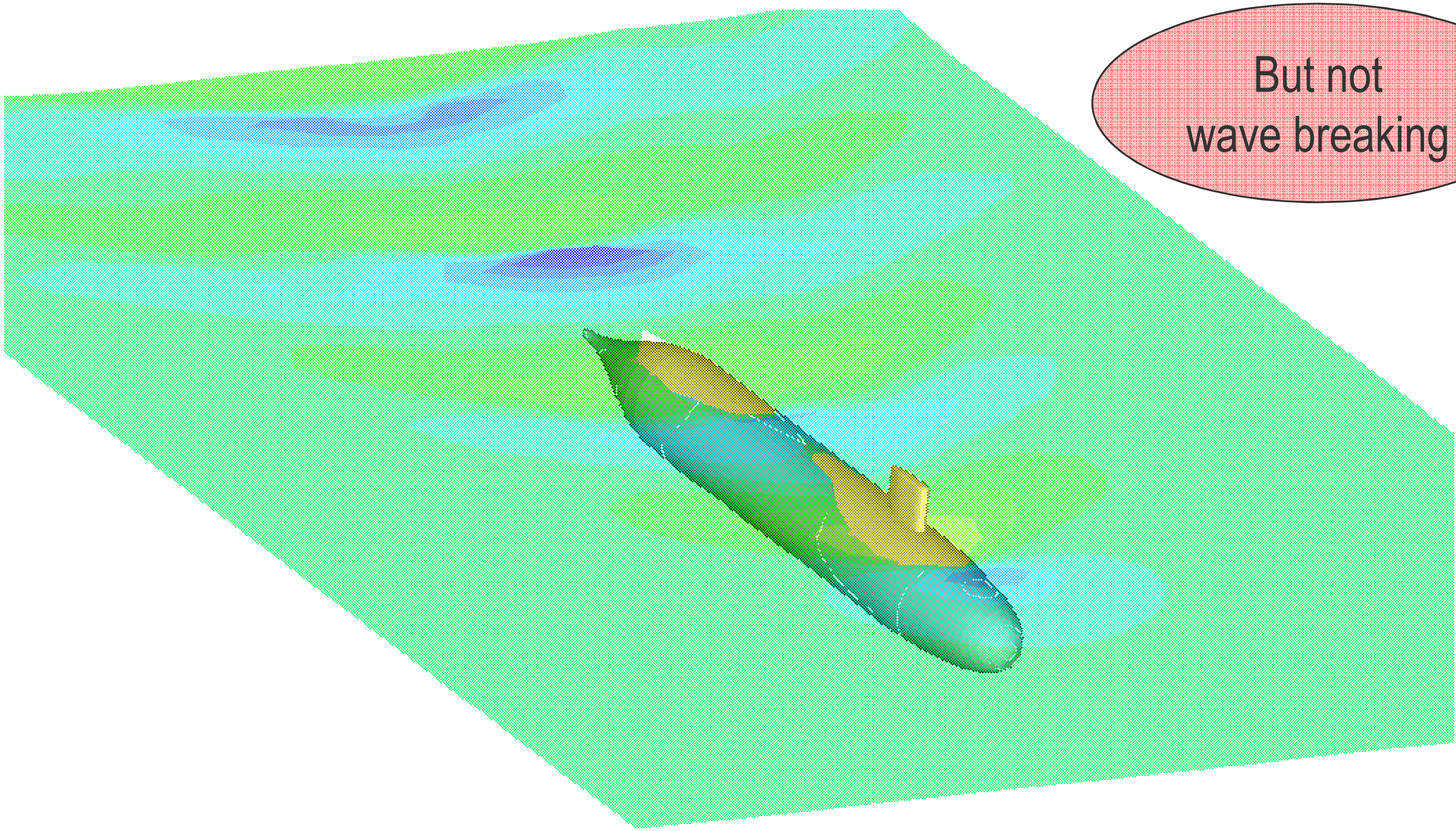


## Main application:

- analyses in snorkeling condition
- also seakeeping & propeller flows

25 years
of experience

# Moderate nonlinearities handled



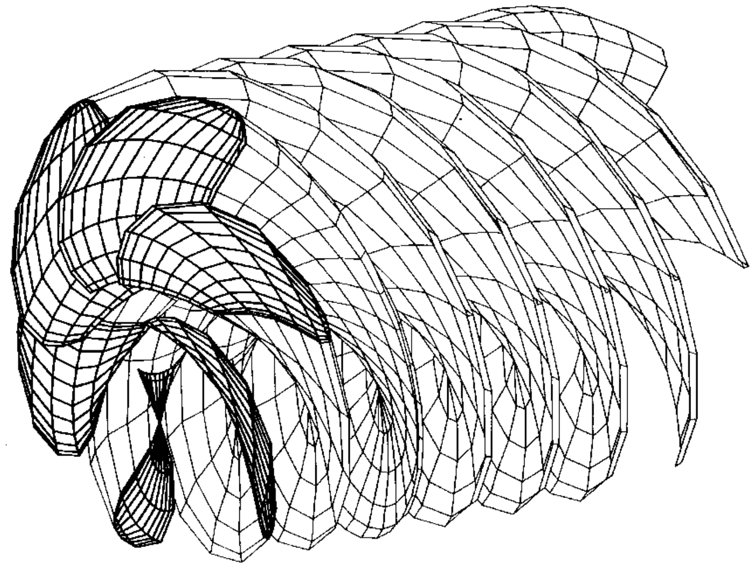
But not wave breaking

Source: HSVA

### Lifting-surface method

Particularly: Vortex-Lattice Method (VLM)

Propeller blade reduced to grid
of horseshoe vortices



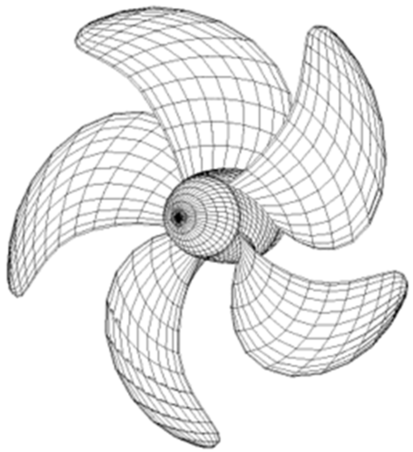
☺ blade modeled 3-d
☺ good convergence with grid refinement
☺ handles 'arbitrary' cases (CRP, unsteady inflow, nozzle-propellers,…)

☹ pressure distribution must be corrected at propeller hub
☹ tip vortex not captured

CRP = contra-rotating propeller

## Propeller "poti" methods 2/2



Panel method

Lift and thickness modeled
Propeller boss modeled

☺ no simplifications besides potential flow assumption
☺ finite velocities in hub region

☹ increased CPU time
☹ tip vortex still not captured

# Potential flow codes

## Potential flow codes

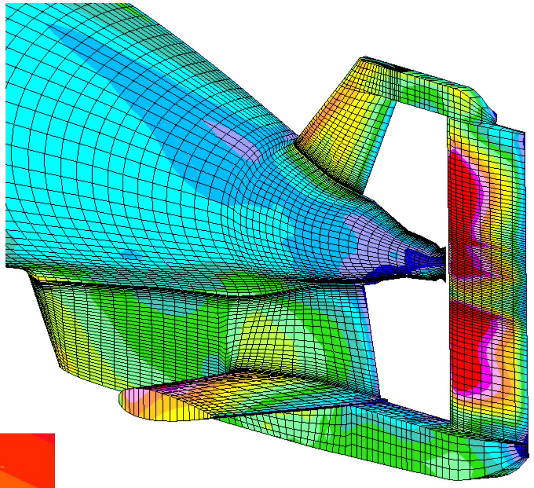
- neglect viscosity
- elements only on surface
- fast and cheap (optimization)
- limited accuracy

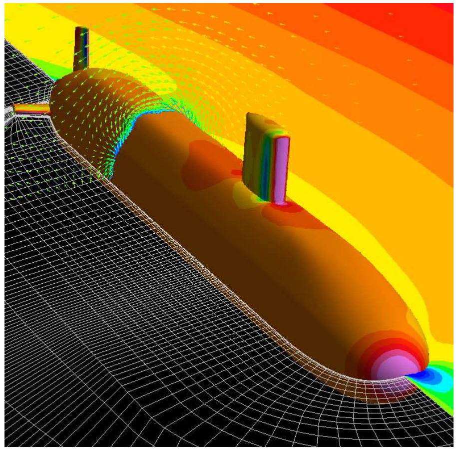
## RANSE

- expensive
- better model (breaking waves, flow separation)

# RANSE - Better model, more effort

- Volume grid
- 0.5 - 5 million cells
- mesh generation: 0.5 - 5 days
- CPU times: 1-5 days (on PC cluster)





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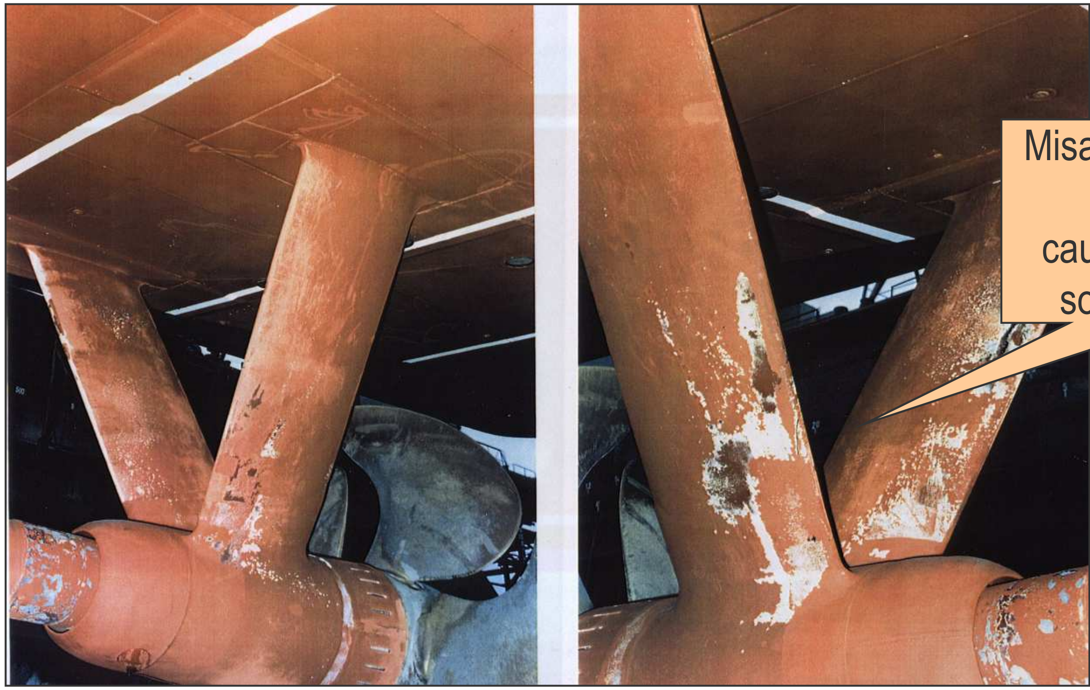
# Typical application: Appendages

## RANSE captures viscosity, dominating flows at appendages

- Example: Alignment of appendages

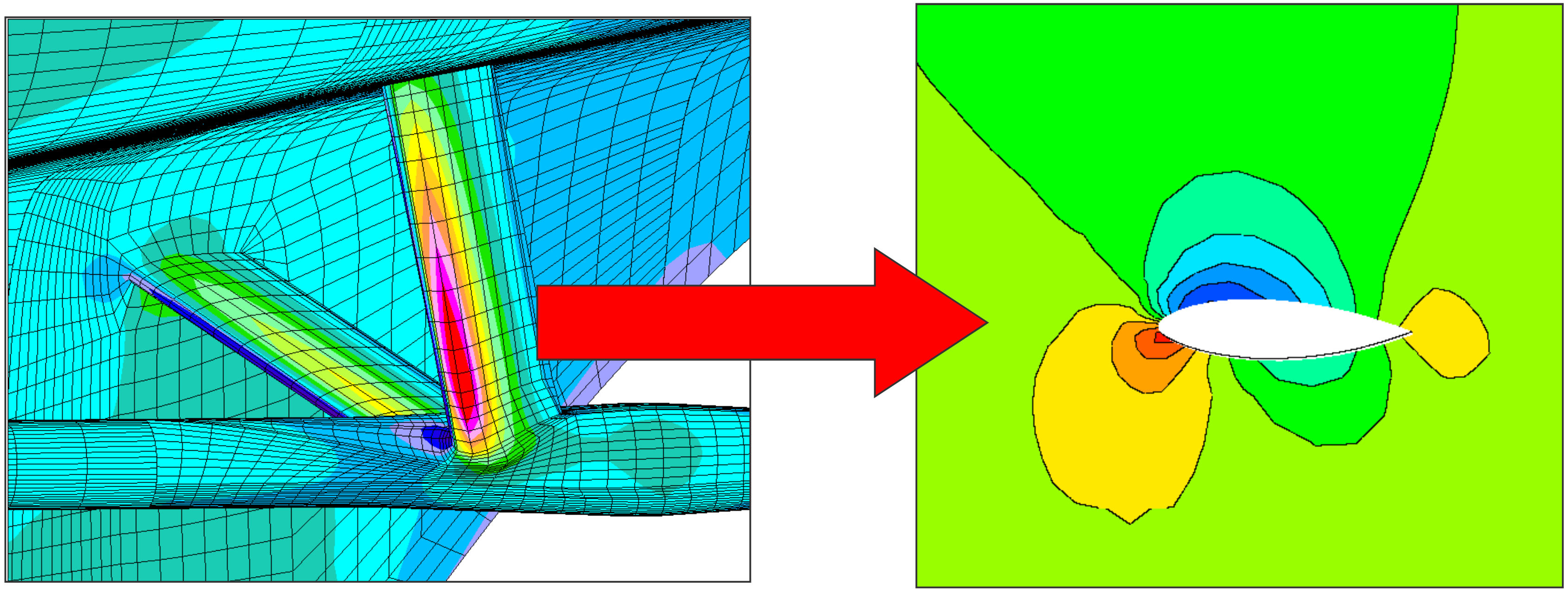


Misalignment increases resistance, causes vibrations and sometimes erosion

Soure: HSVA

## Typical application: Appendages

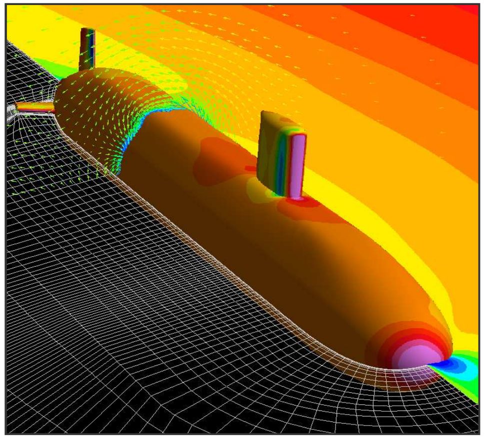
CFD analyses reveals misalignment



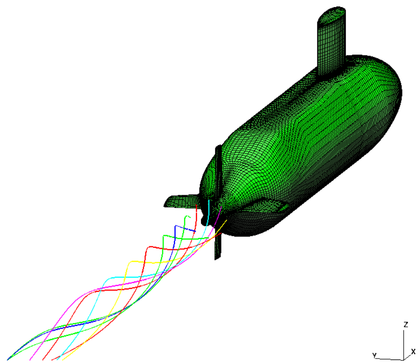
Soure: HSVA

# Submarines are prime candidates for CFD

- Not easy to observe in model test
- Viscosity dominates
- Budget and time “no problem”

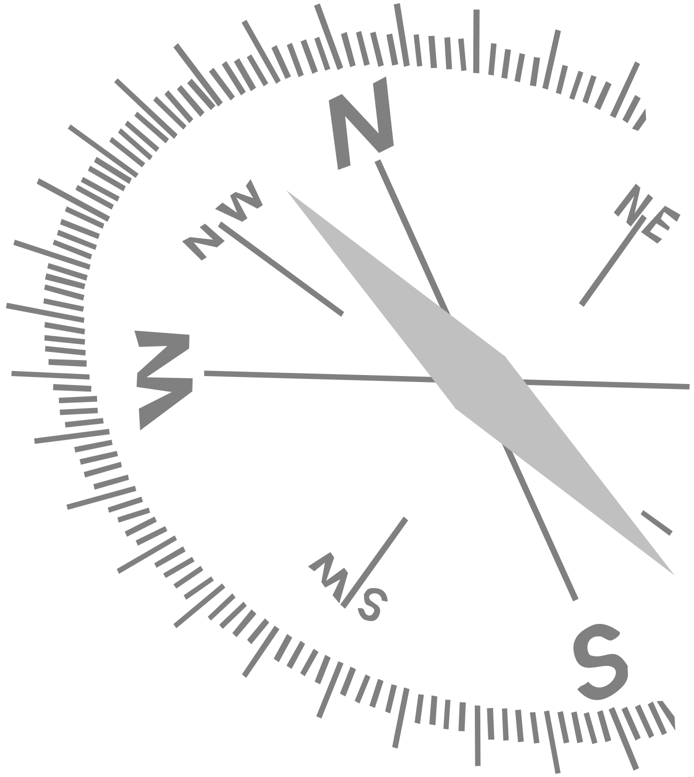


CFD applied to <u>some</u> problems



Source: HSVA

# Navigator



Hull Design Aspects

Quiz

Hydrodynamic Assessment

- CFD Methods
- **Model tests**
- Flow analysis on the sonar part

Hull-Appendages Interference

Analysis Methods for Snorkels

Quiz

# Initially it did not work...

Historic model tests (1761)



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## Wave forces follow Froude

Froude number $F_n = V / \sqrt{g \cdot L}$

Important parameter for waves,

where only gravity and inertia matter

E.g. ship wave pattern:

- geometrically similar for Froude similarity
- associated wave resistance coefficient same in model and full scale

 

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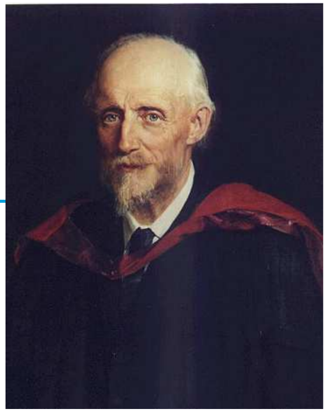
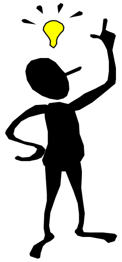
## Viscous forces follow Reynolds



$$R_n = \frac{V \cdot L}{\nu}$$

Reynolds number

Same Reynolds number in model and full scale
ensures dynamic similarity
if only inertial and friction forces present



Reality more complicated:

- laminar – turbulent transition
- surface roughness
- flow separation



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# Model test basin

Recirculation tunnel (propeller testing)

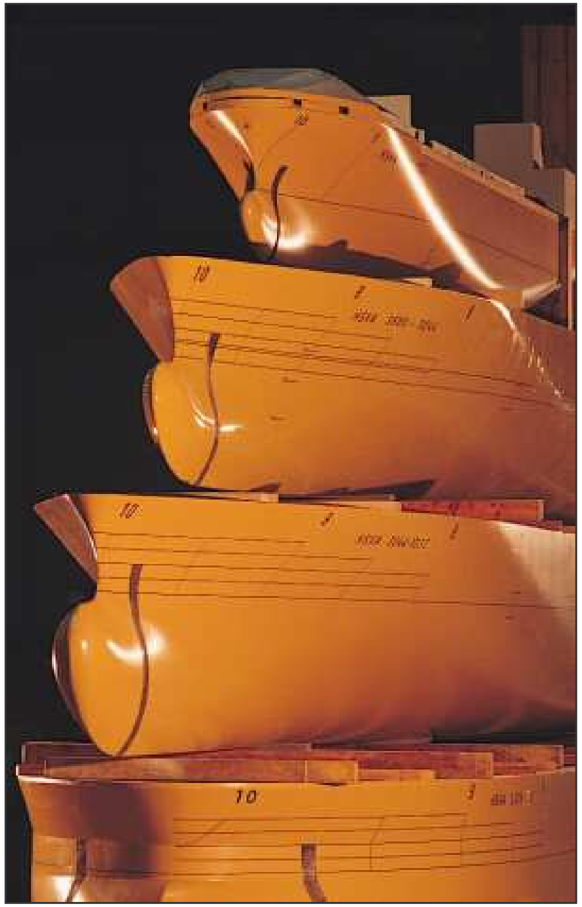

Model basin

Model storage

Model manufacturing

Source: HSVA

# Scaled-down models



- as large as possible …

... but small enough

- to avoid strength problems
  - internal strength
  - loads on test carriage
- for max. test carriage speed
- to avoid problems with restricted water

4 m < L < 10 m

~ 1000 kg

Source: HSVA

# Model tests not 100% similar

Froude number <u>and</u> Reynolds number

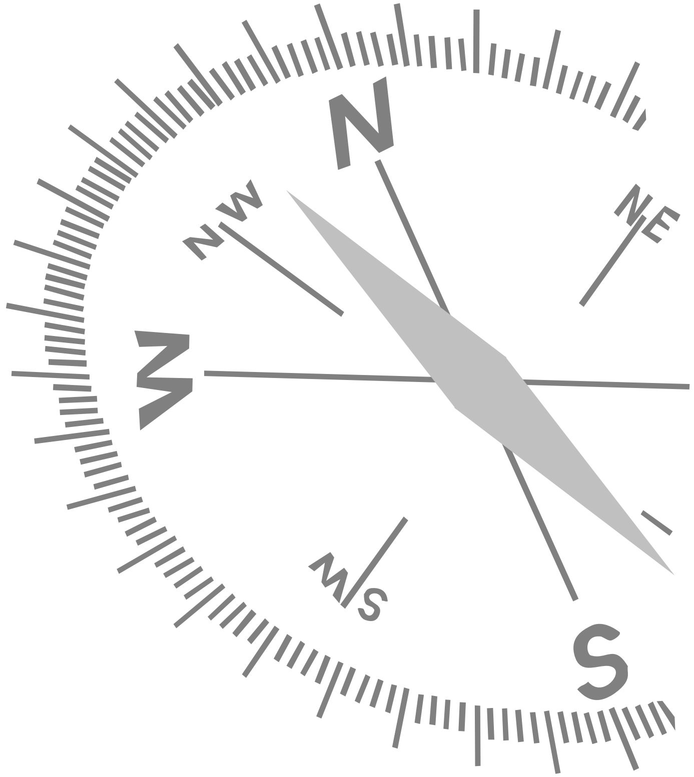
cannot be kept at model scale!

Model tests “wrong” for appendages

(which are driven by viscous forces)

# Navigator

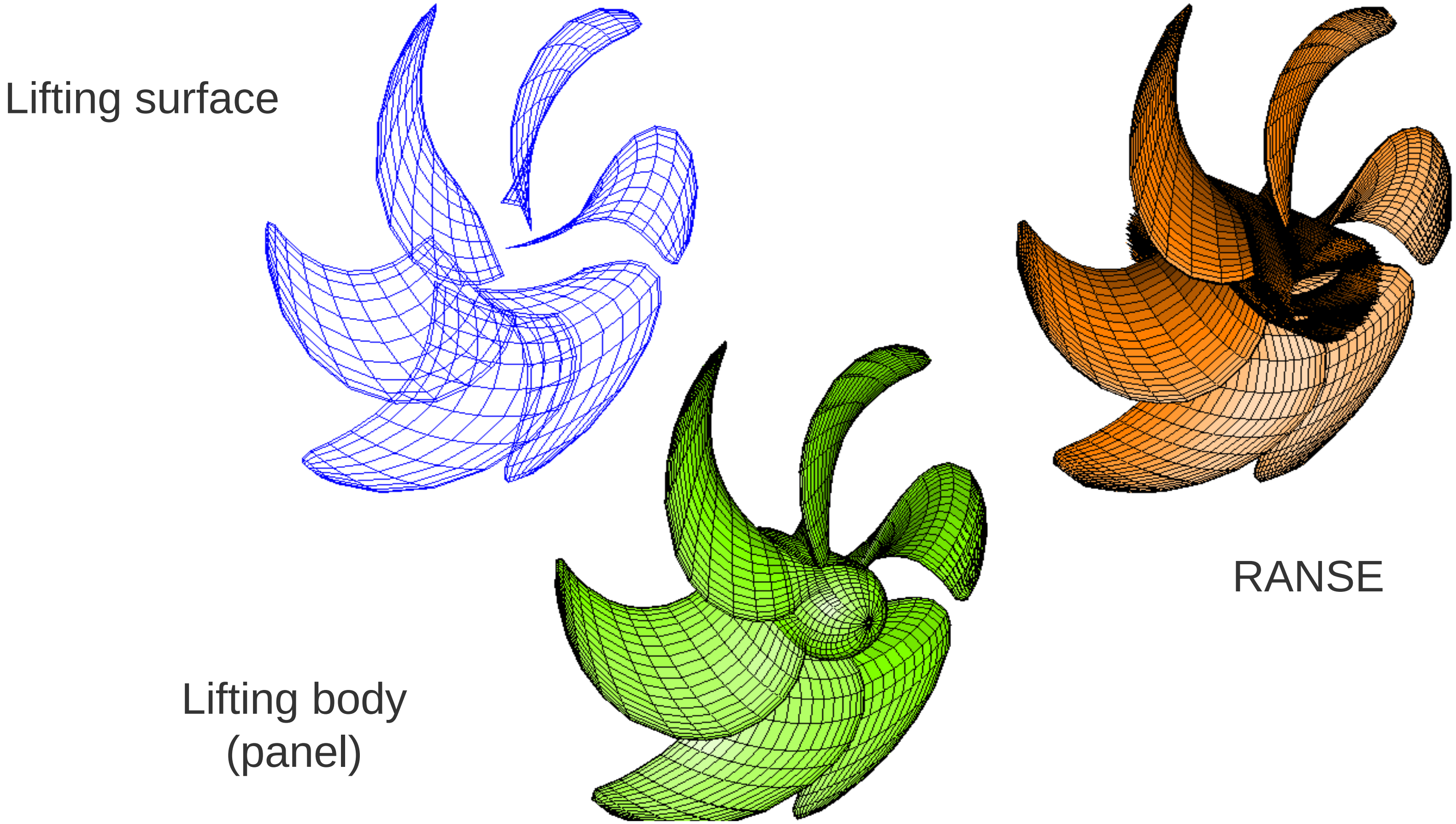




# Appendages & hull openings

- secure smooth curvature of hull surface in streamline direction
- avoid obstacles as far as possible
- for absolutely necessary appendages
    - streamline, or
    - make removable,
    - or make to drop flush with surface
- for absolutely necessary hull openings
    - minimize size
    - streamline (using CFD)

# Like propeller, like foil...




Source: HSVA

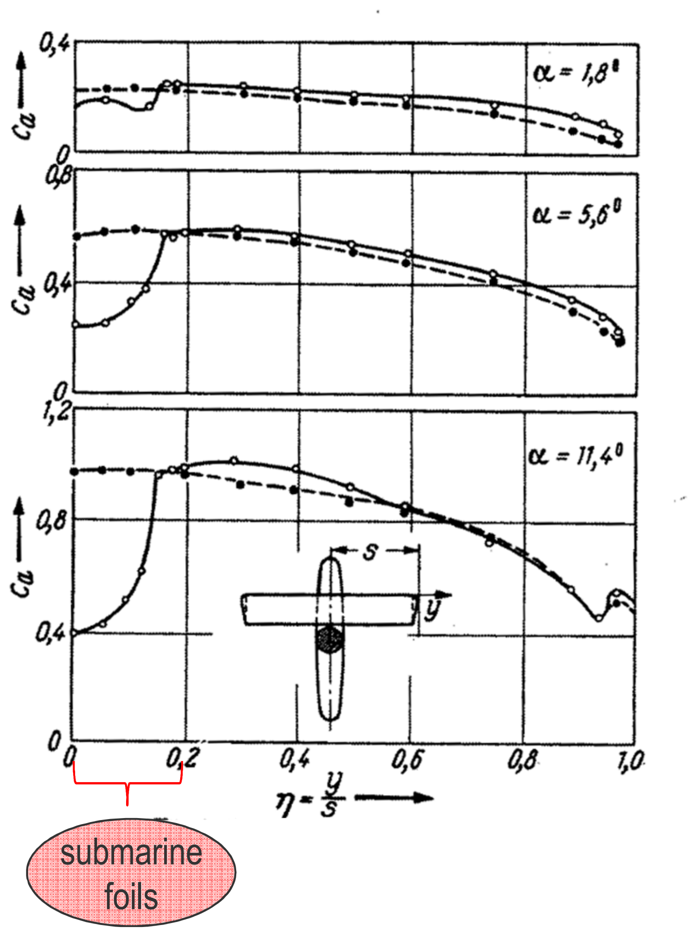
## Hull and foil interact

- boundary reduces velocity (20-50 cm in aftbody)
- hull changes velocity outside boundary layer
    - change in magnitude (increase)
    - change in direction

**Significant for foils of small aspect ratio**

## Some insight from wind tunnel tests

- extensive experiments for aerospace industry
- classical computations & experiments compiled into design curves
- not recommended for asymmetric configurations (use CFD instead)



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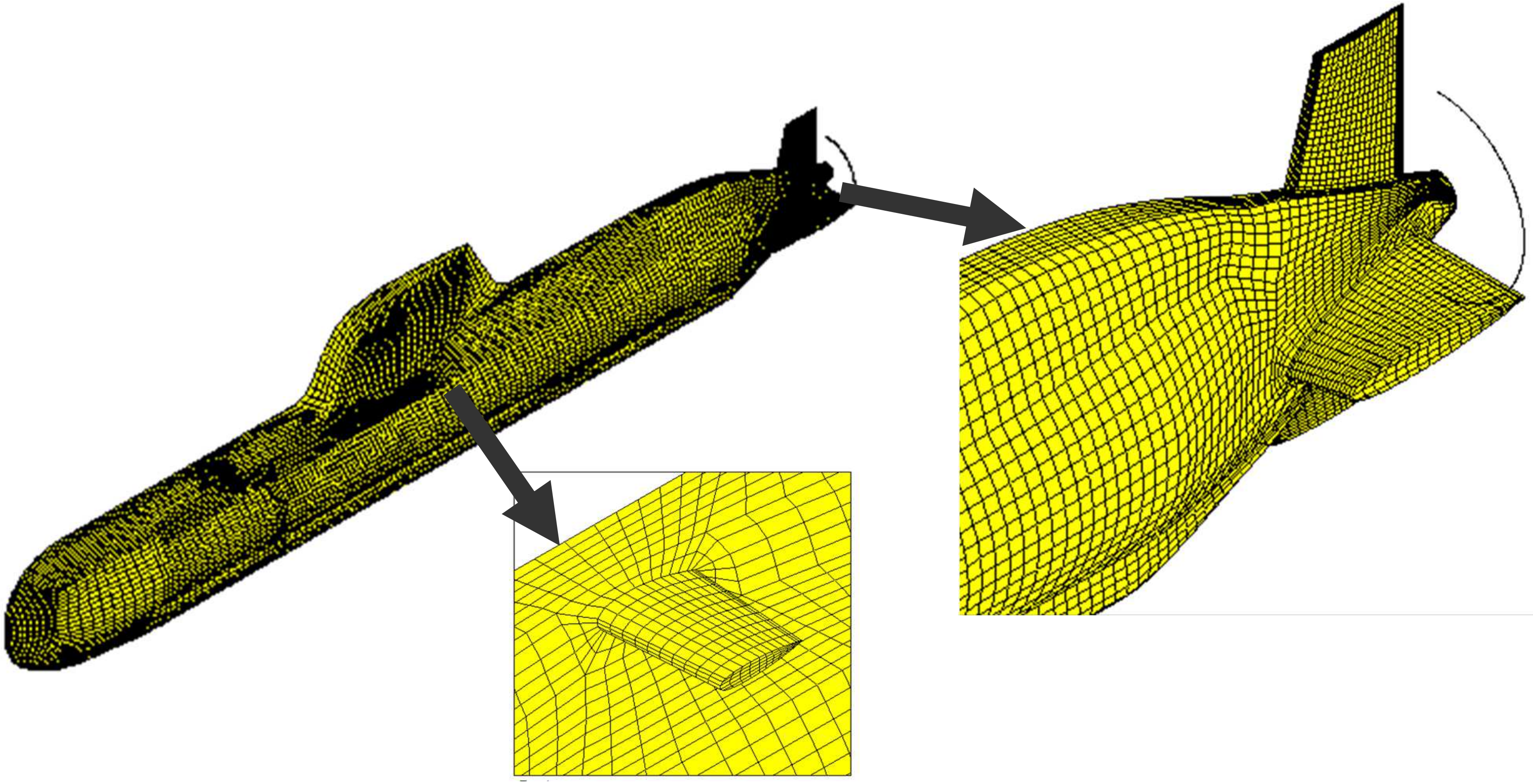
# CFD application to aft hydroplane

Submarine with foils



Source: HSVA

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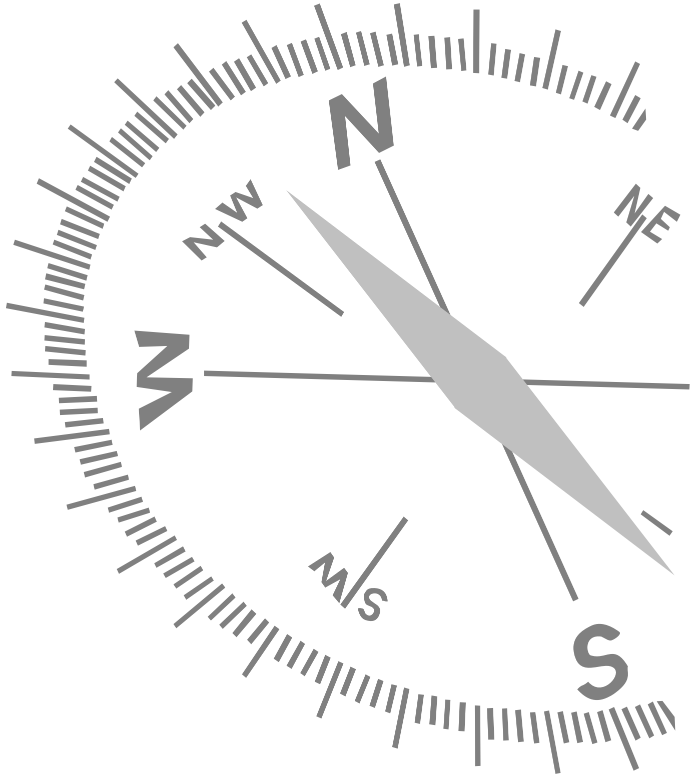
# Navigator



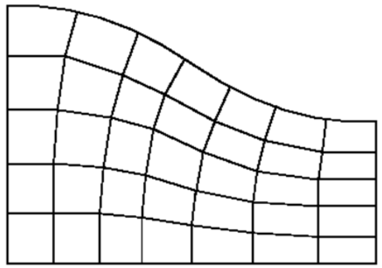


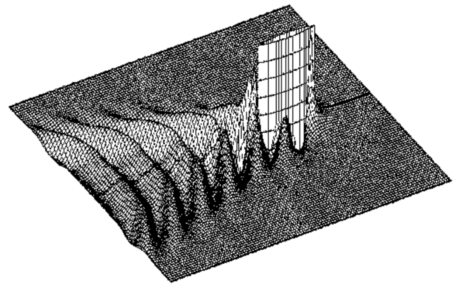

 

# Two approaches used for free-surface RANSE

## Interface tracking

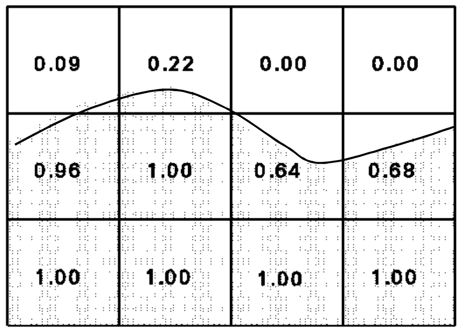
- Exact representation of free surface
- Unsuited for complex geometries

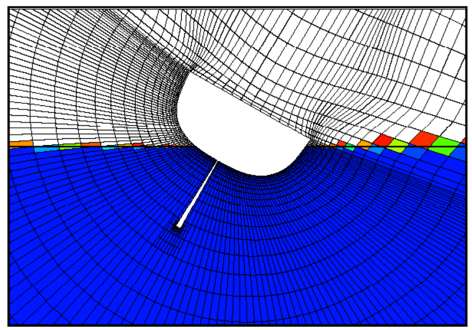




## Interface capturing

- Ability to handle wave breaking
- VOF, Level Set, Two-Phase



RANSE = Reynolds averaged Navier-Stokes equations
VOF = Volume of Fluid



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# Interface capturing allows complex wave breaking

$$\alpha = \begin{cases} 1 & \text{for cells inside fluid 1} \\ 0 & \text{for cells inside fluid 2} \\ 0 < \alpha_0 < 1 & \text{for transitional area} \end{cases}$$

$$\rho_{eff} = \alpha\,\rho_1 + (1-\alpha)\,\rho_2$$
$$\nu_{eff} = \alpha\,\nu_1 + (1-\alpha)\,\nu_2$$

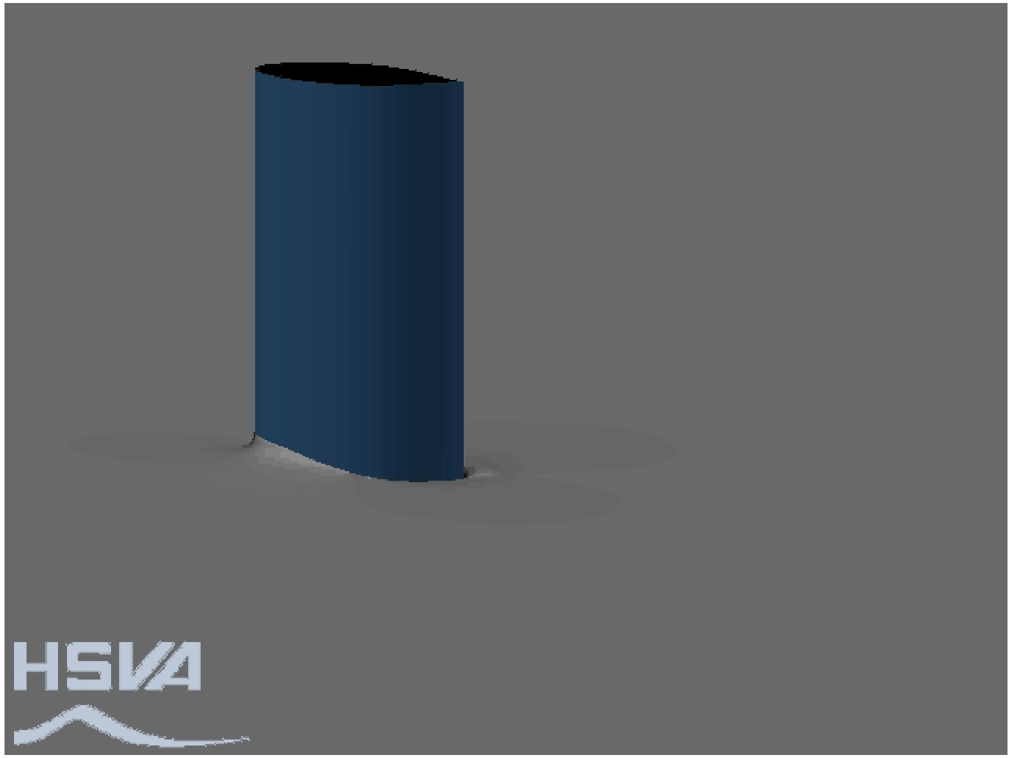
| | | | | |
|---|---|---|---|---|
| 1 | 1 | 1 | .68 | 0 |
| 1 | 1 | 1 | .42 | 0 |
| 1 | 1 | .92 | .09 | 0 |
| 1 | .85 | .35 | 0 | 0 |
| .31 | .09 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |

# High Froude numbers and breaking waves

# Also in struts for underwater model tests

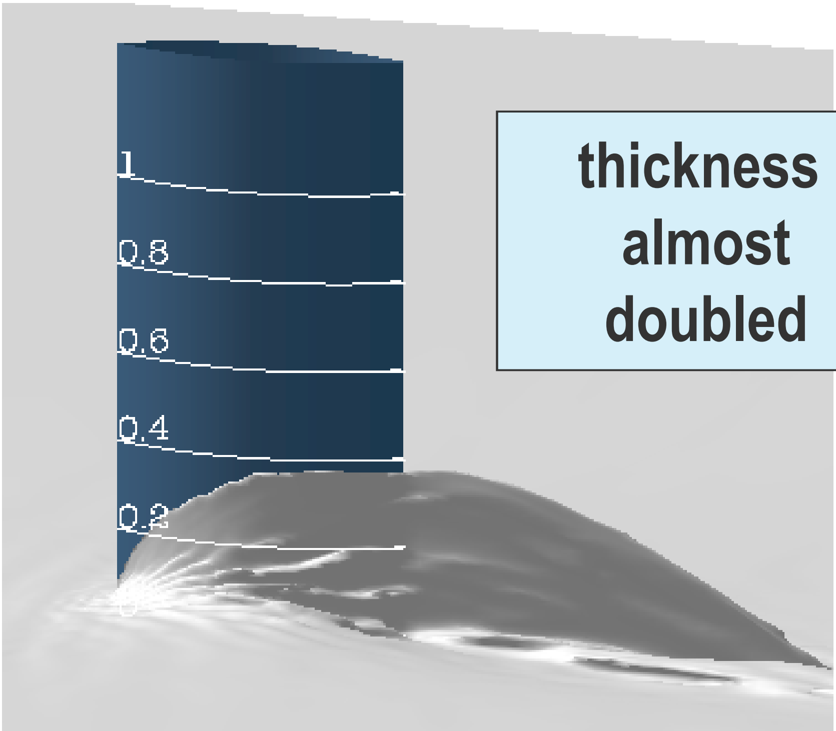
# Free-surface RANSE captures wave breaking

Circular section strut, $F_n$=2.03, $R_n$=3.35·$10^6$

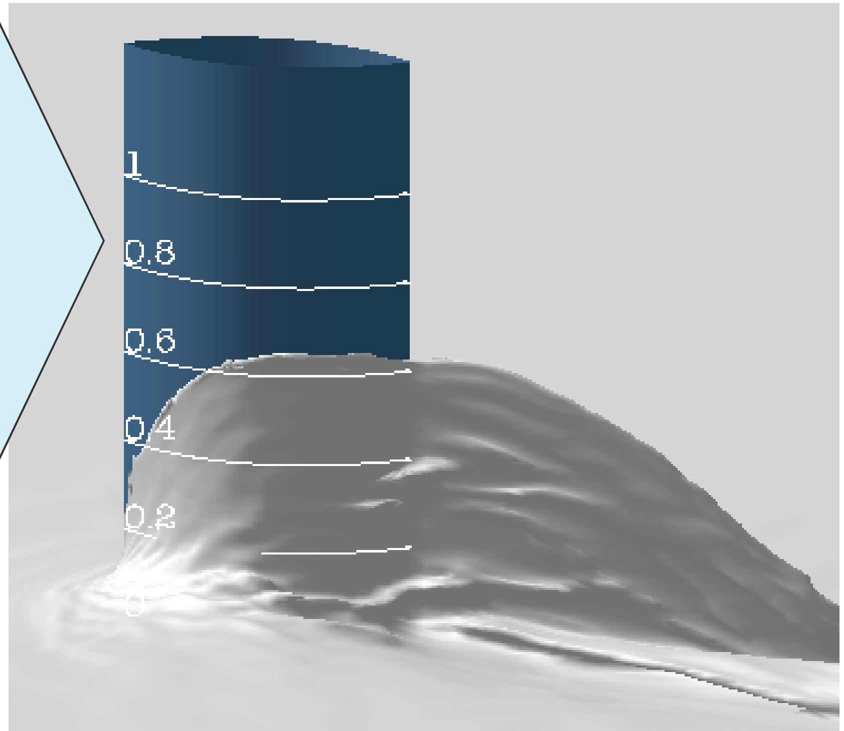



Source: HSVA

## Wave height increases with thickness of profile




**thickness almost doubled**




Thickness “60”

Thickness “100”



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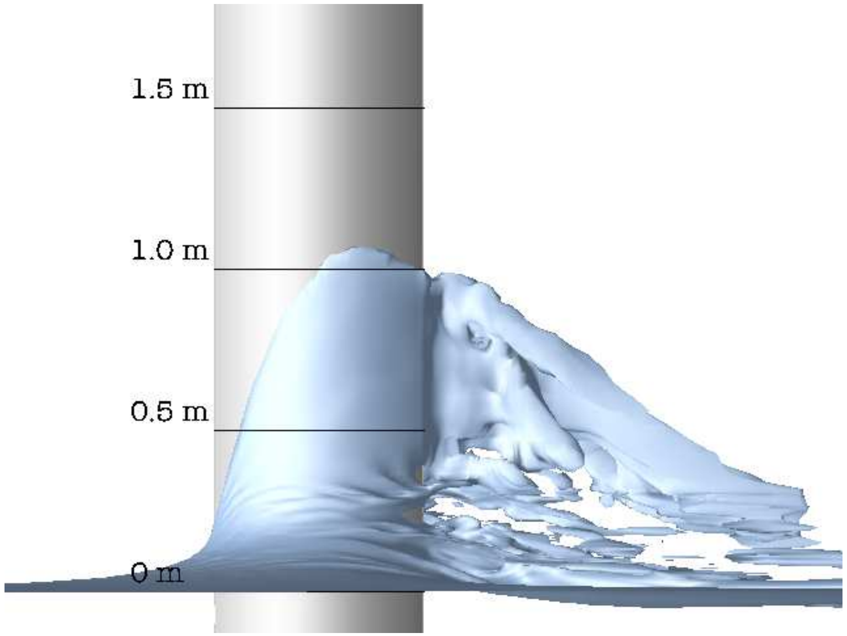
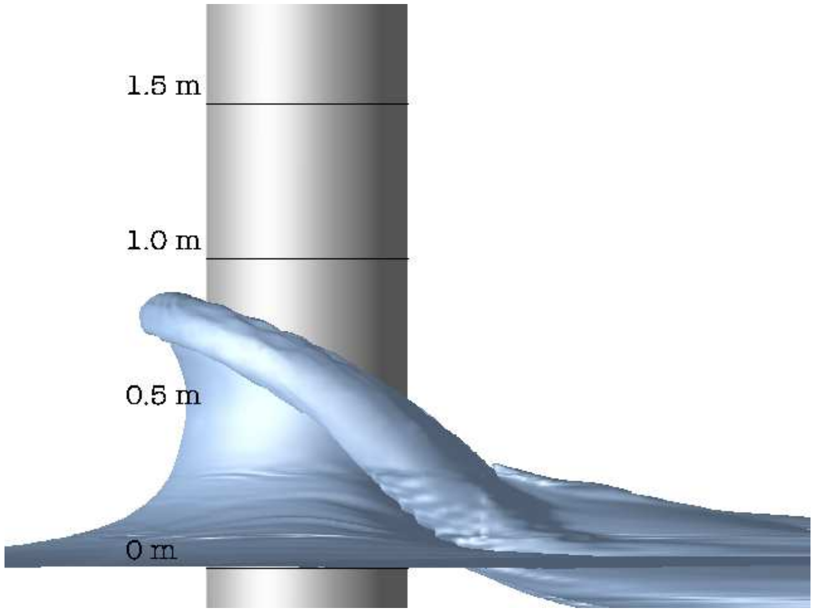
# Wave characteristics changed

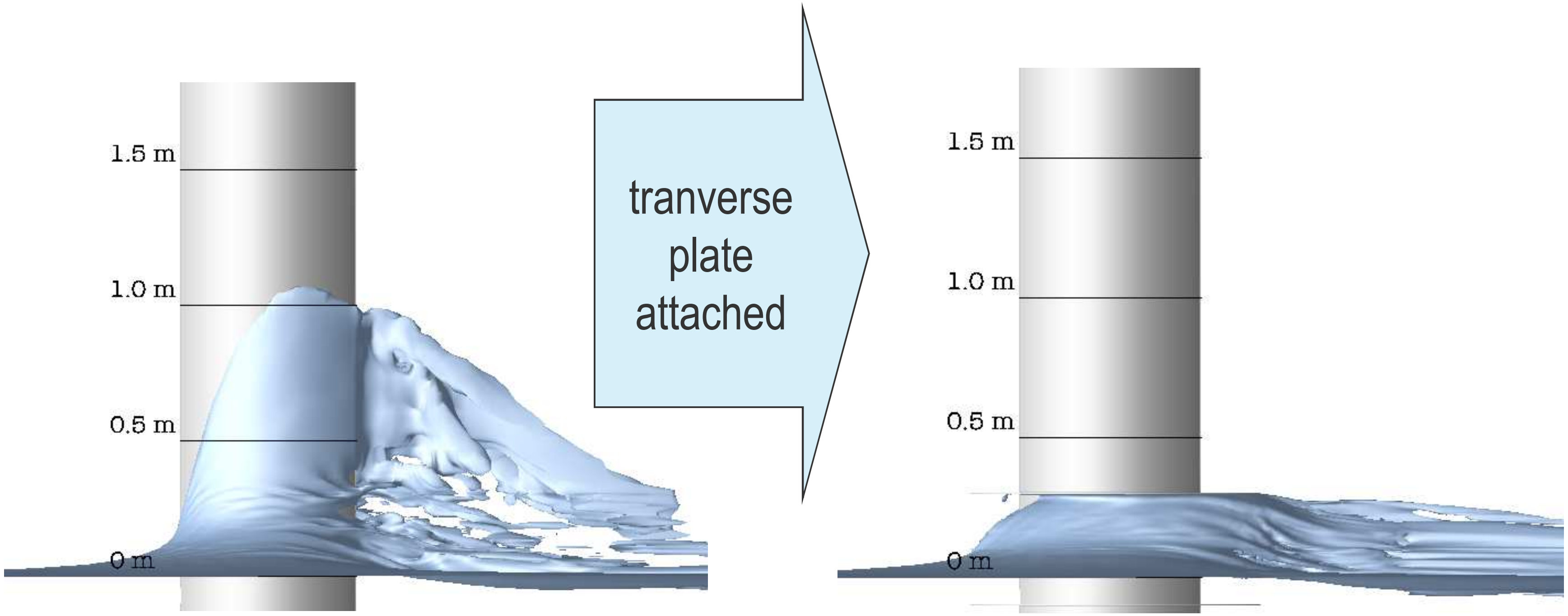



parabolic strut



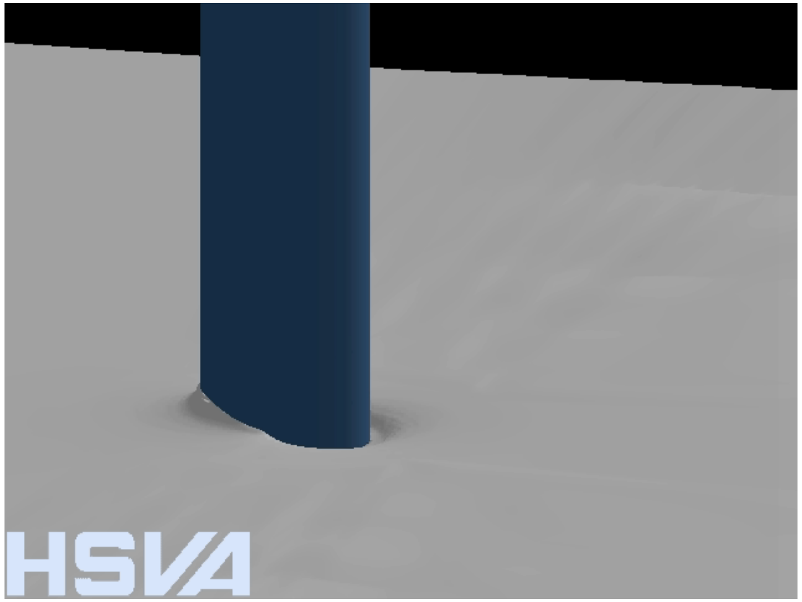

cylinder

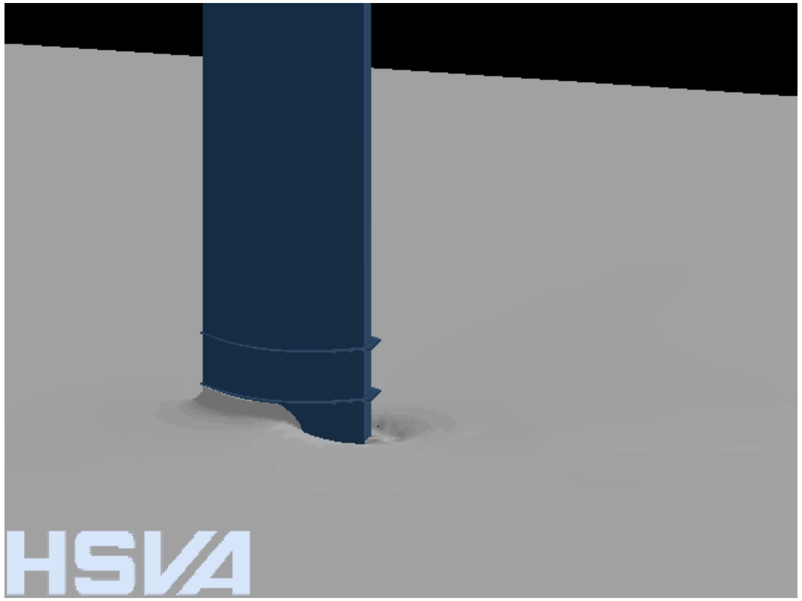
# Transverse plate reduces waves




Parabolic strut

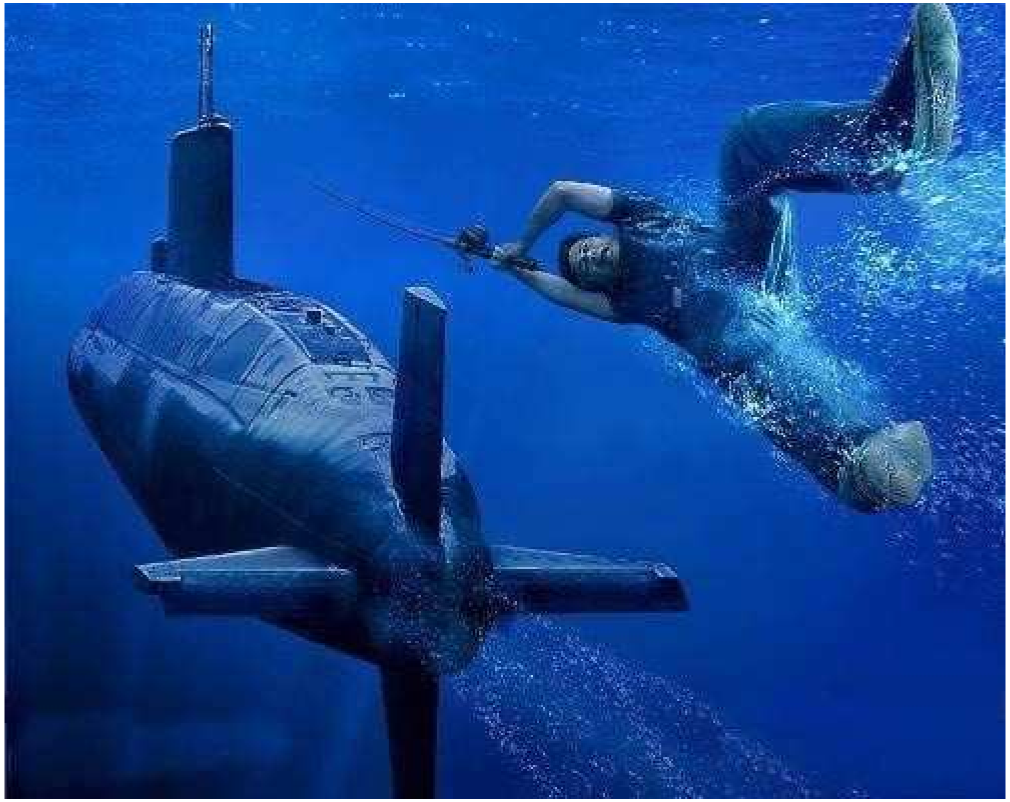
# Transverse plate reduces waves



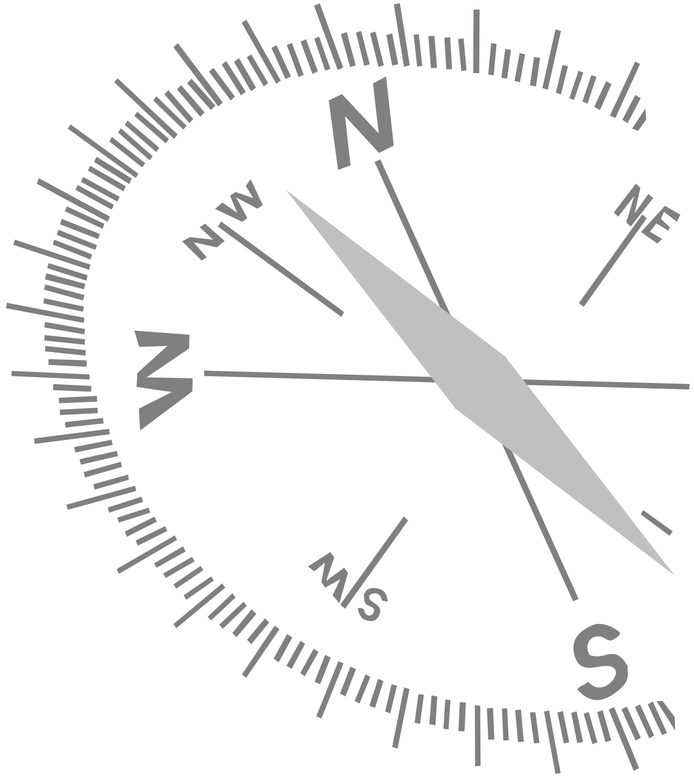




Source: HSVA

# Thank you for your attention – and now...

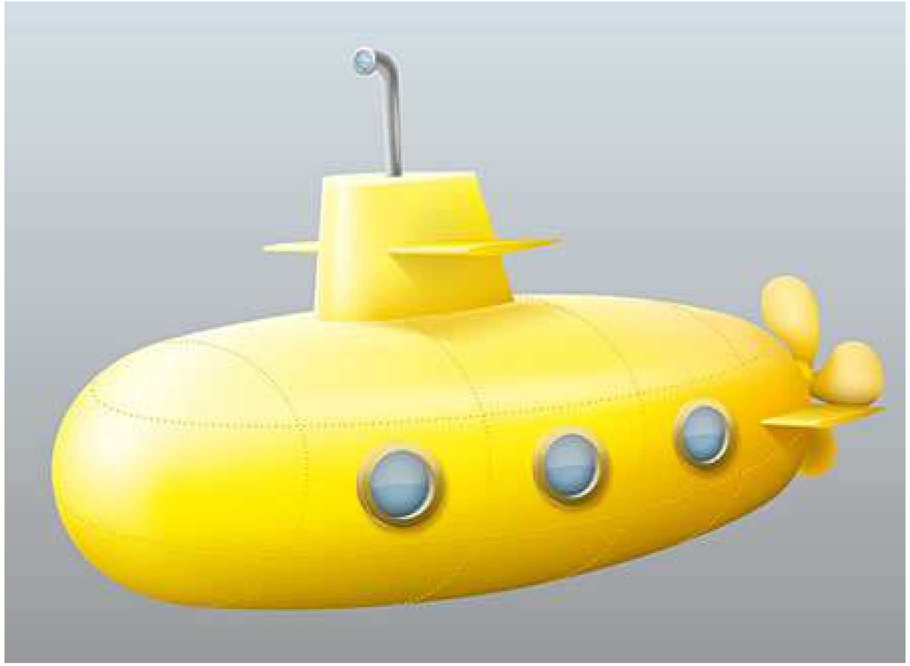


# Navigator

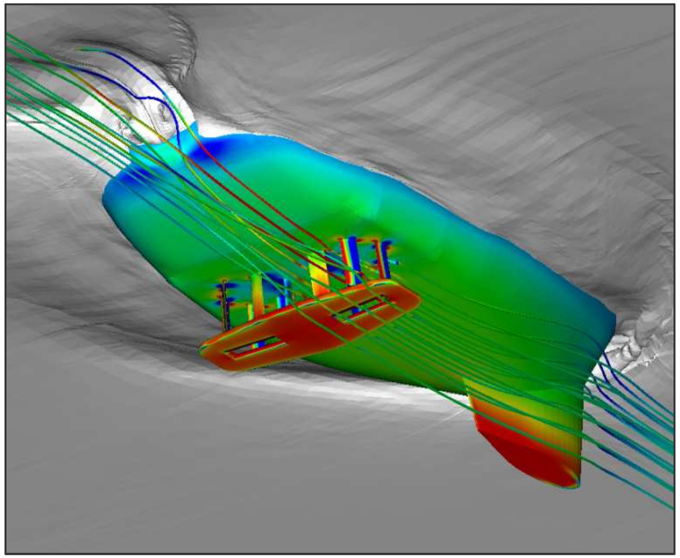



- Hull Design Aspects
- Quiz
- Hydrodynamic Assessment
- Hull-Appendages Interference
- Analysis Methods for Snorkels
- → **Quiz**

## Quiz: Do you know your design of submarines ?

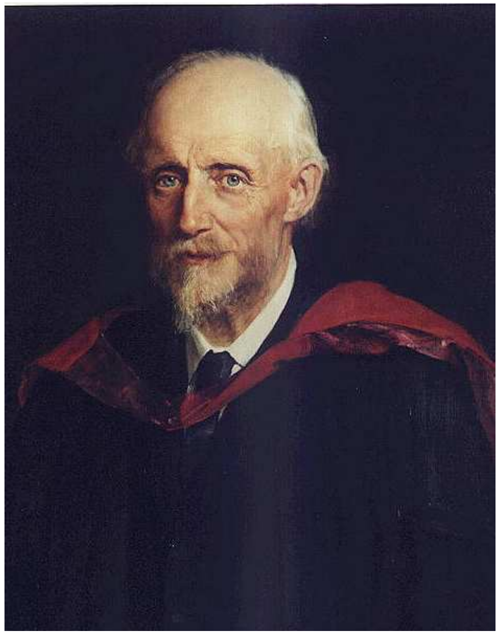



## What is definitely not a CFD method ?



a. Euler solver
b. Laplace solver
c. Paint solver
d. RANSE solver

## The Reynolds number …



a. ensures similarity of flow separation
b. ensures similarity of surface roughness
c. increases with length
d. is kept same on model and full scale in ship model basins

# What can<u>not</u> be captured by wave resistance codes ?

a. breaking waves
b. dynamic trim & sinkage
c. lifting surfaces
d. limited water depth



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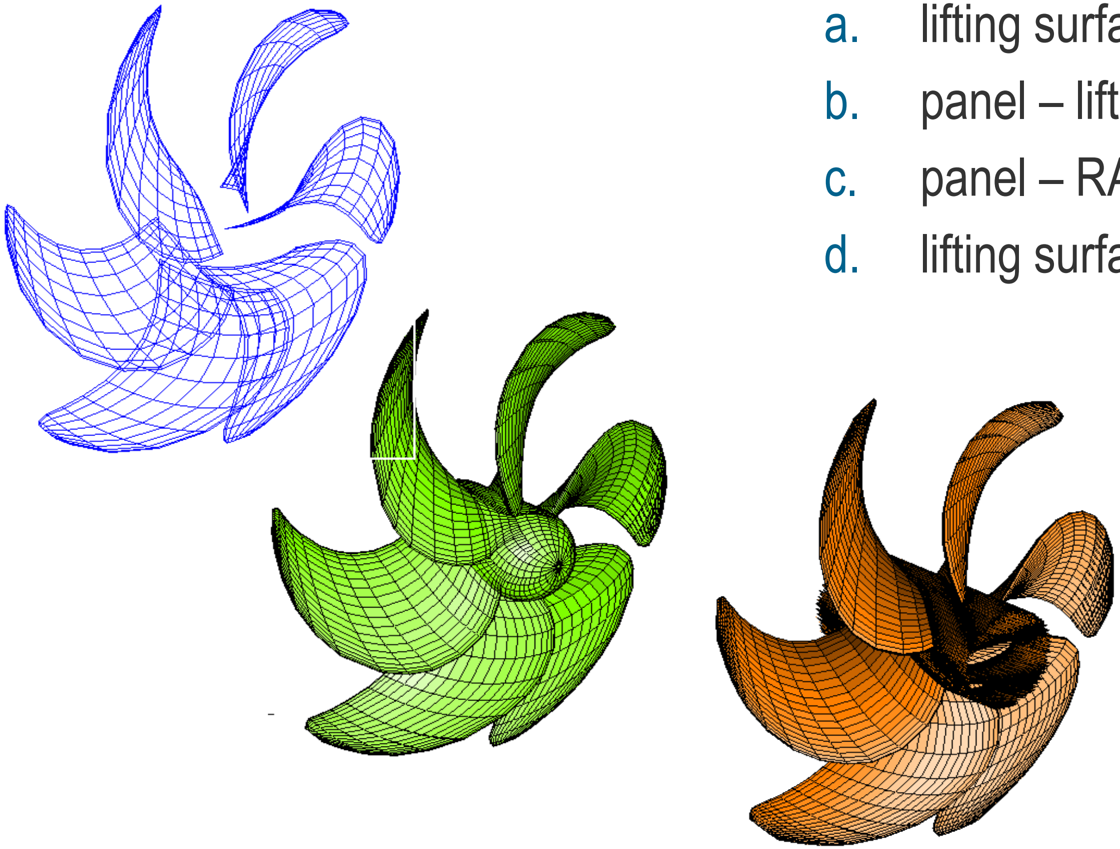
## Order computational methods in increasing complexity



a. lifting surface – panel – RANSE

b. panel – lifting surface – RANSE

c. panel – RANSE – lifting surface

d. lifting surface – RANSE – panel



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## Stroboscopic light is used...

a. for non-intrusive velocity measurements
b. to detect flow separation on hulls
c. to make blade and cavitation appear stationary in propeller tests
d. to measure unknown geometries (for CFD)

 

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## What is best for assessing flows on appendages ?

a. lifting surface method
b. model test
c. panel method
d. RANSE

## The Froude number is a ...

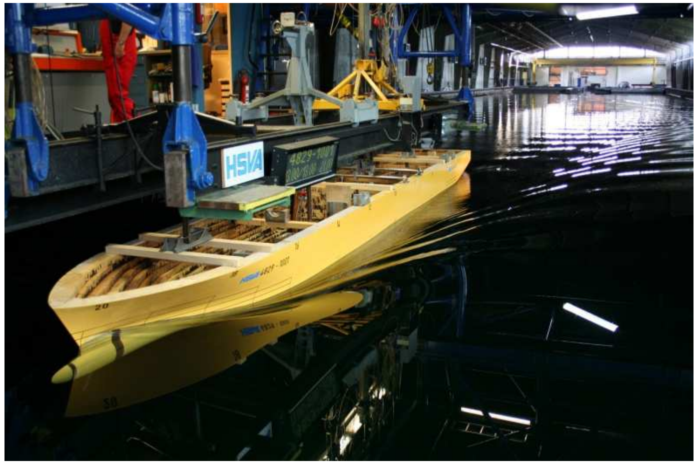
a. non-dimensional gravity force coefficient
b. non-dimensional parameter combining speed & viscosity
c. non-dimensional speed parameter
d. non-dimensional wave resistance coefficient

# Snorkels are best shaped like …

a. cylinders (circular)
b. lentils (parabolic)
c. reverse teardrop
d. teardrop (profile)

## Model tests in ship model basins …

a. are "wrong" for appendages
b. ensure similar friction forces by keeping Froude numbers constant
c. ensure similar wave breaking by keeping Froude numbers constant
d. keep Reynolds numbers constant



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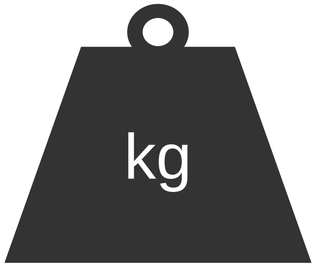
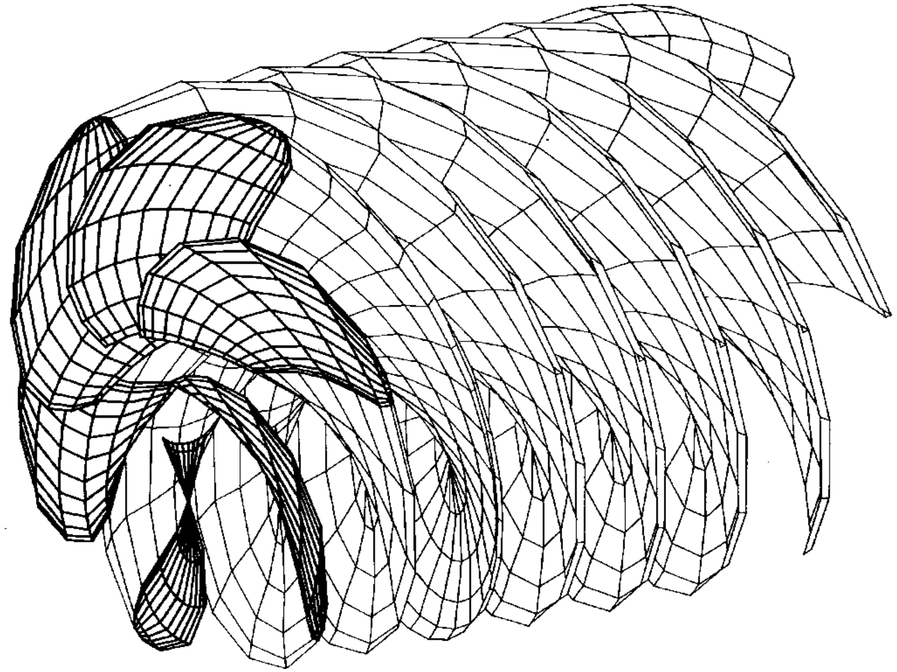
## Ship models in professional basins weigh …




a. 10 kg
b. 100 kg
c. 1000 kg
d. 10000 kg

## Propeller models are typically tested in…



a. cavitation tunnels
b. propulsion test basins
c. towing tanks
d. wind tunnels



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## Compared to condition in open water, a control foil ...

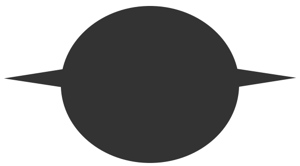
... attached to a submarine ...

a. has less lift (due to the lower velocity in the boundary layer)

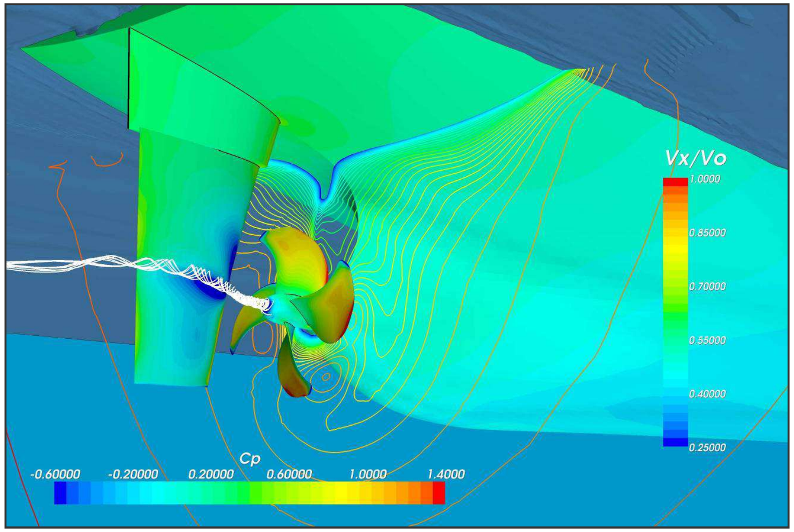
b. has more lift (due to the higher speed around the hull)

c. has same lift. That is why we generally work with open-flow diagrams...

d. is complicated due to spanwise changes both in magnitude and direction

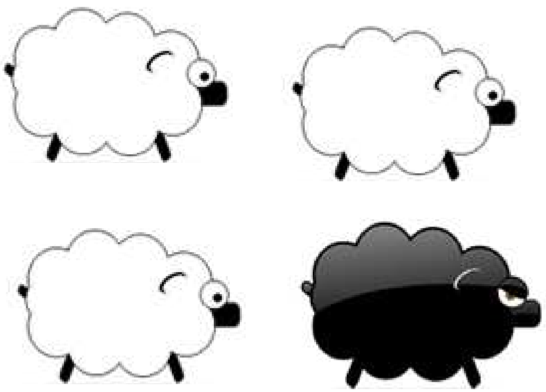


# Hull-propeller-rudder interaction best investigated by




a. lifting surface method
b. model test
c. panel method
d. RANSE

## What is <u>not</u> a recommendation for appendages?



a. make appendages flush with surface
b. make appendages large enough to create complete recirculation
c. minimize size of appendages
d. streamline appendages

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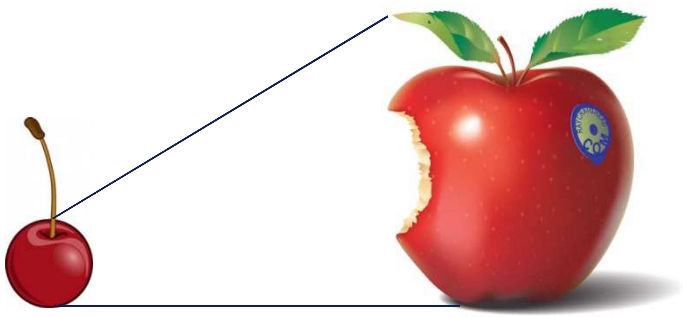
## Different physics between model test and real ship...

... are generally called...

a. "Applicability Issue"
b. "Model Problem"
c. "Scaling Errors"
d. "Size Matters"



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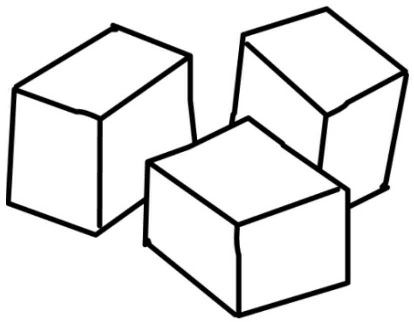
# Potential flow codes generally use…



a. Boundary element methods
b. Finite Difference Methods
c. Finite Element Methods
d. Finite Volume Methods

# Time for a break ?

# Thank you...

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**www.dnvgl.com**

SAFER, SMARTER, GREENER

 