Aero- and hydrodynamics with wind propulsion

Rogier Eggers (MARIN)

Natural Propulsion Conference, Webb, 16-11-2021

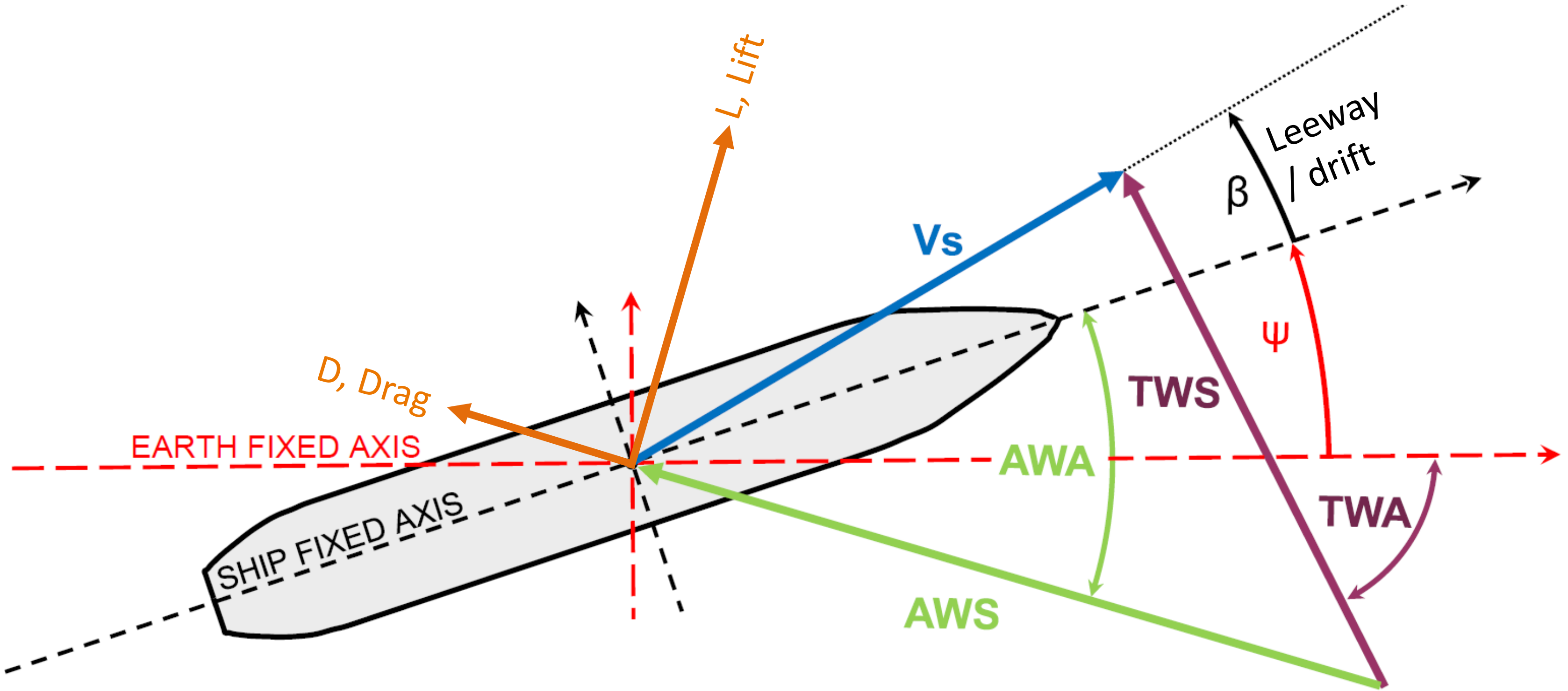
Outline

- Aerodynamics
- What changes in hydrodynamics?
- How to design (and operate)?
- Modelling and measurements

BETTER SHIPS, BLUE OCEANS

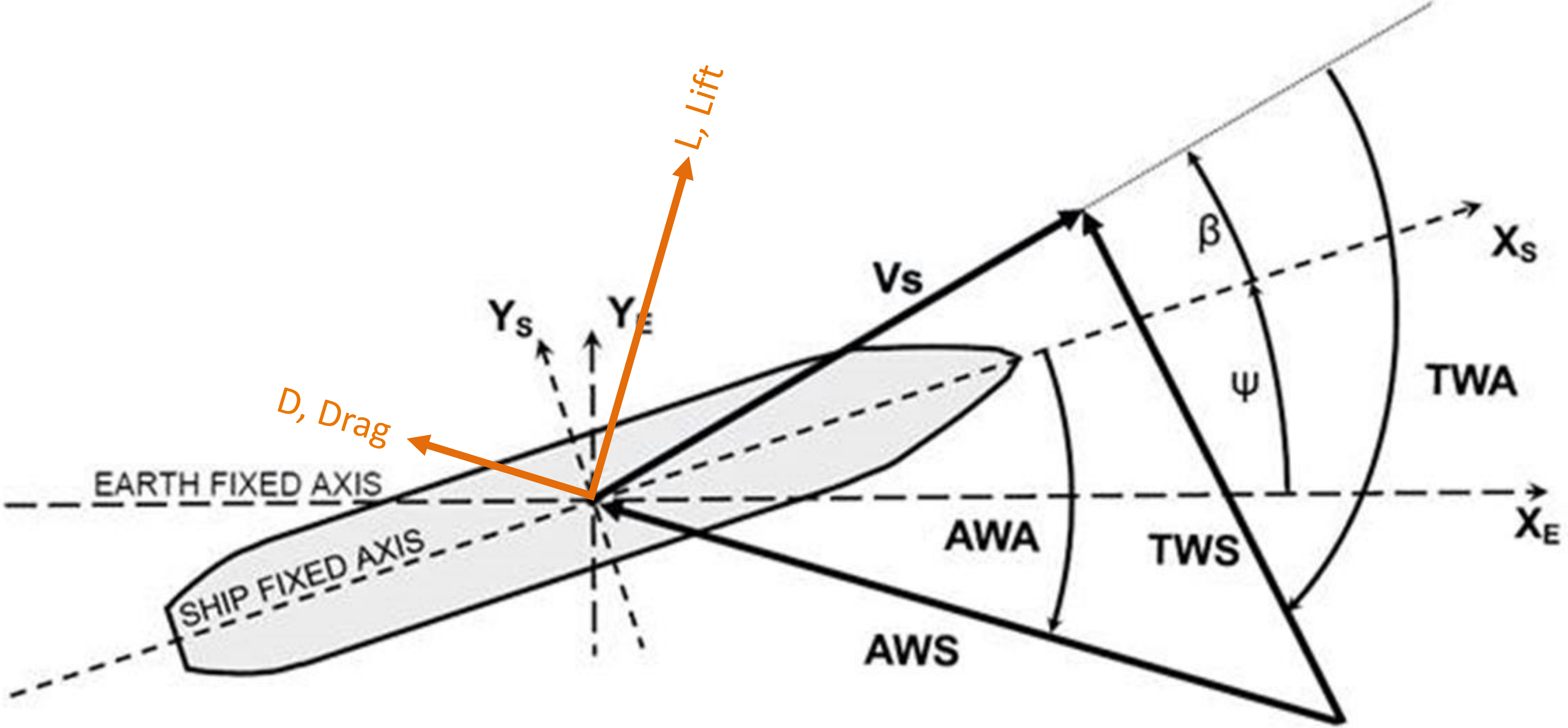
Aerodynamics

Wind definitions

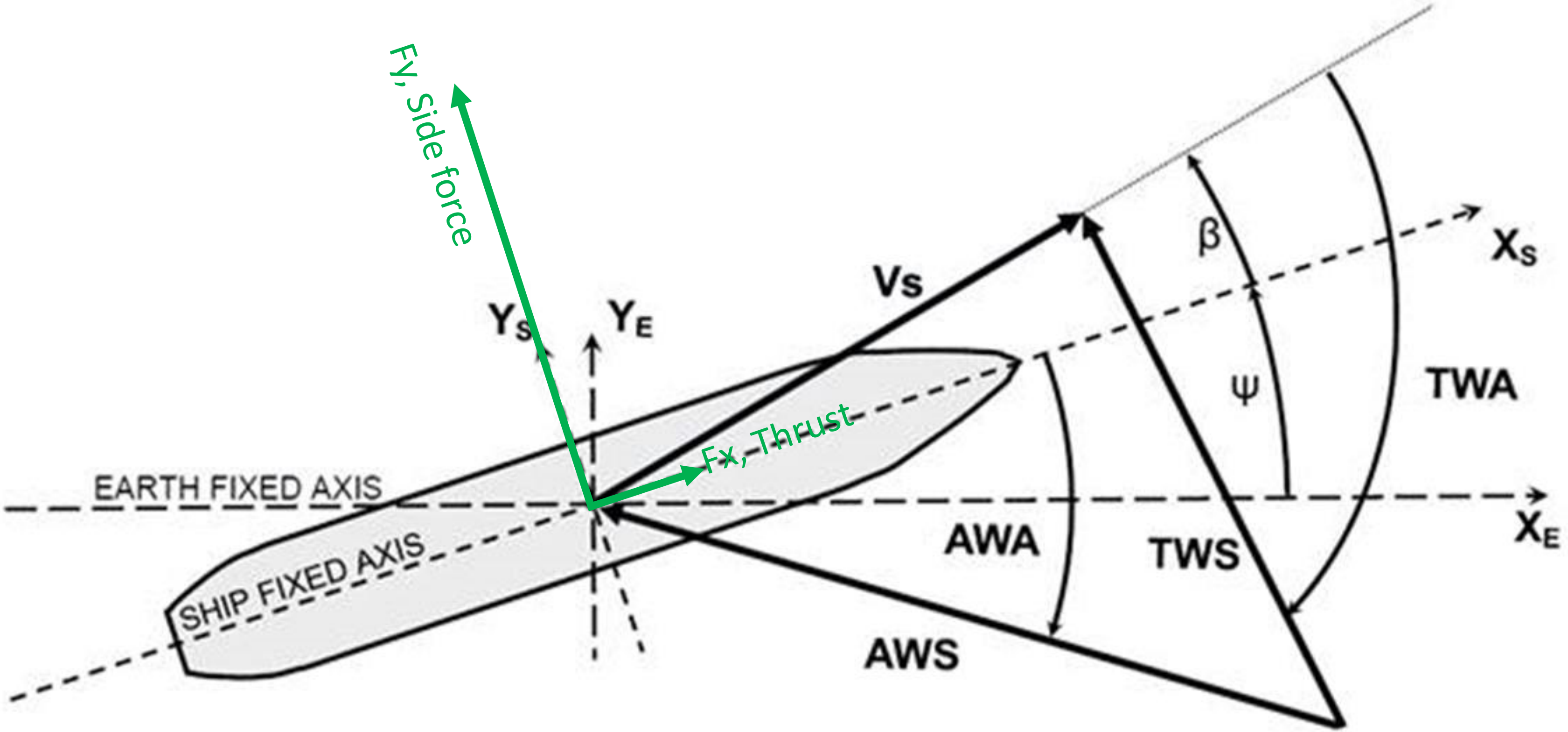


TWS: True Wind Speed
TWA: True Wind Angle
AWS: Apparent Wind Speed
AWA: Apparent Wind Angle

Lift and drag



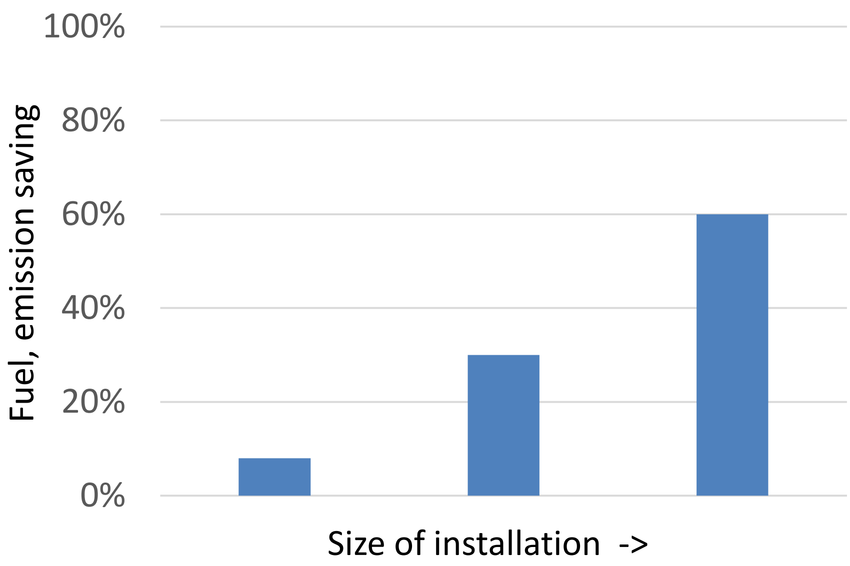
Thrust (and side force)



Thrust (and side force)

- The thrust is what we're after, leading to savings (or complete replacement of ship propulsion)

- The side force has some knock-on effects (discussed later)



Dimensionless numbers

Discarding influence of wind speed (AWS), projected area (A) and air density (ρ):
Allows a "fair" comparison of device types

Lift coefficient $$C_L = \frac{L}{\frac{1}{2} \cdot \rho \cdot AWS^2 \cdot A}$$

Drag coefficient $$C_D = \frac{D}{\frac{1}{2} \cdot \rho \cdot AWS^2 \cdot A}$$

Thrust, driving force coefficient $$C_X = \frac{F_X}{\frac{1}{2} \cdot \rho \cdot AWS^2 \cdot A}$$

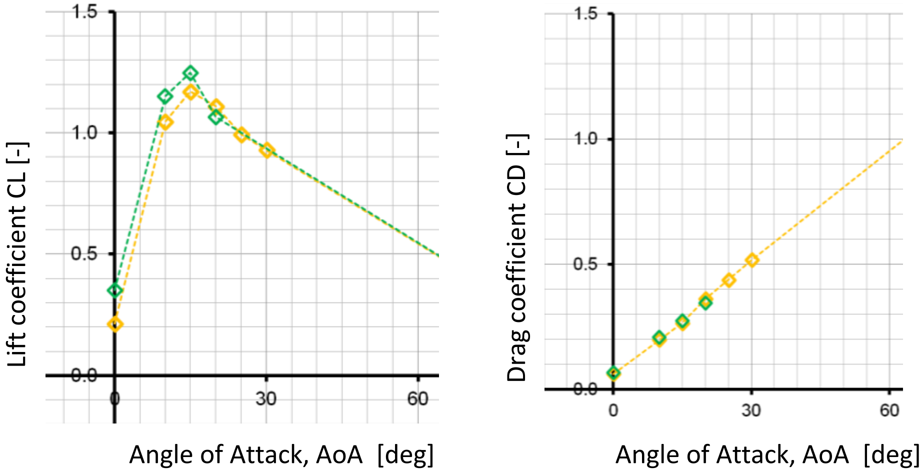
Side force coefficient $$C_Y = \frac{F_Y}{\frac{1}{2} \cdot \rho \cdot AWS^2 \cdot A}$$

Lift and drag curves (sails and wing sails)

Dependent on:

- Angle of attack
- (Reef/Retract)
- (Flap angle/ Camber

MARIN WindLab Project

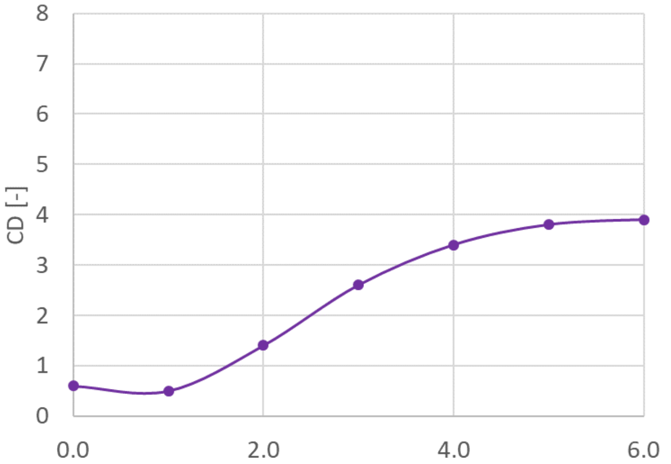


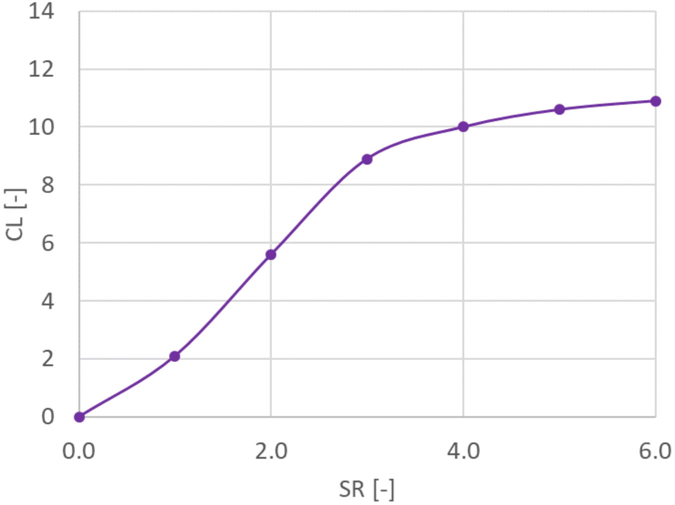
Lift and drag curves (Flettner rotor)

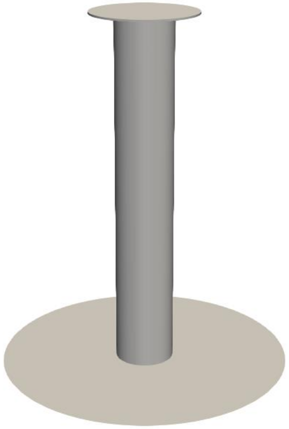
Dependent on:

- Spin ratio, $SR = \frac{n \cdot \pi \cdot D}{AWS}$ $[-]$

Average over several "full-scale" datasets

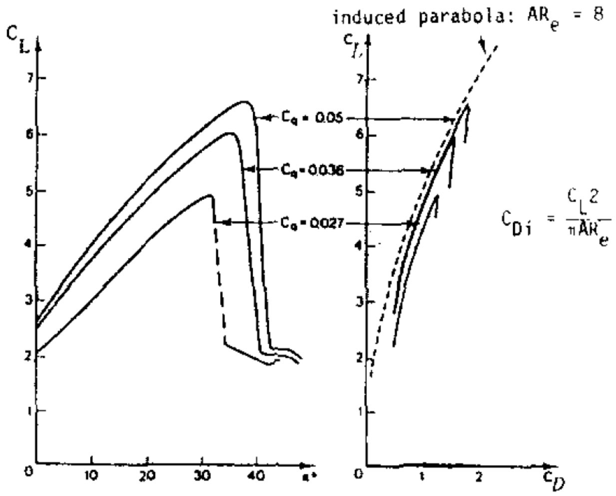






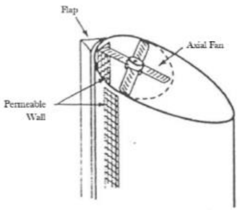
Lift and drag curves (suction sail)

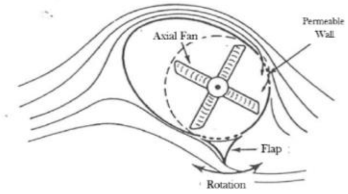
L. Malavard, “Un nouveau propulseur éolien de navire, La vie des sciences,” CR Ser. Générale, 1984



Dependent on:

- Angle of attack
- Aspiration (suction), $C_Q = \frac{Q}{AWS \cdot A}$
- Flap angle

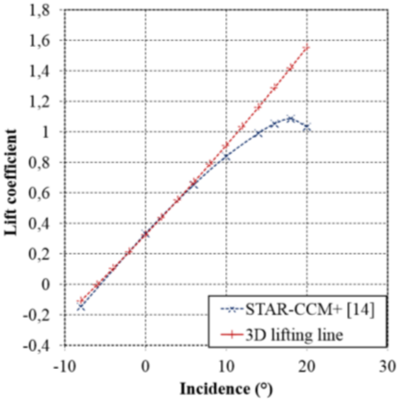


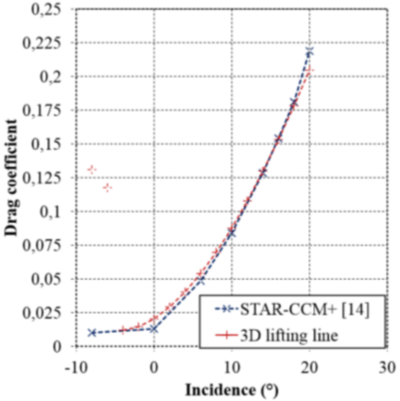


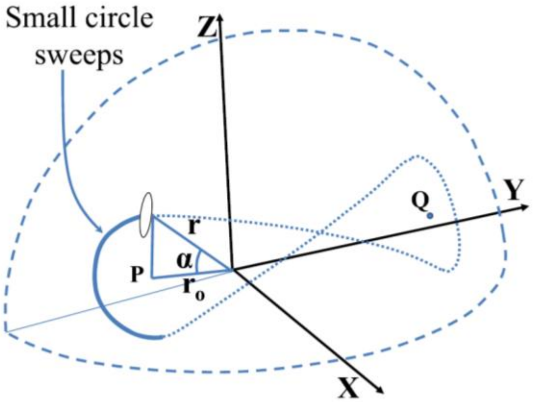
Lift and drag curves (kite)

- Dependent on:
  - Height (wind speed and angle)
  - Angle of Attack
  - Flight pattern (can magnify forces by factor ~25)

Leloup, Richard, et al. "Estimation of the lift-to-drag ratio using the lifting line method: Application to a leading edge inflatable kite." Airborne wind energy, 2013.



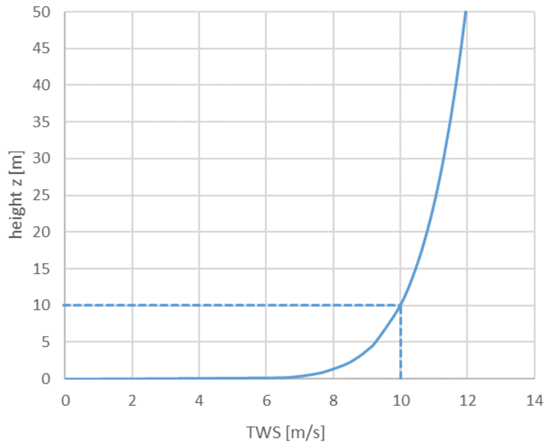




G. M. Dadd, D. A. Hudson, and R. A. Shenoi, “Determination of kite forces using three-dimensional flight trajectories for ship propulsion,” Renewable Energy, vol. 36, no. 10,

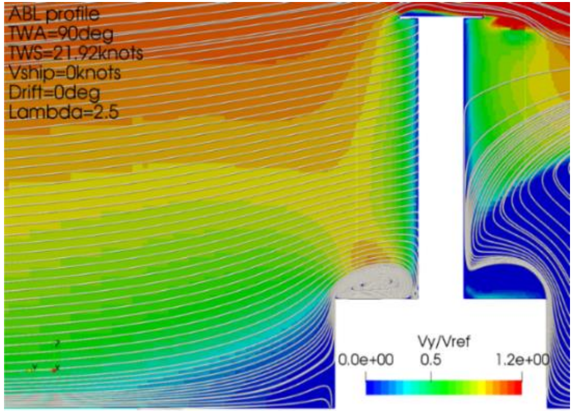
Incoming air flow

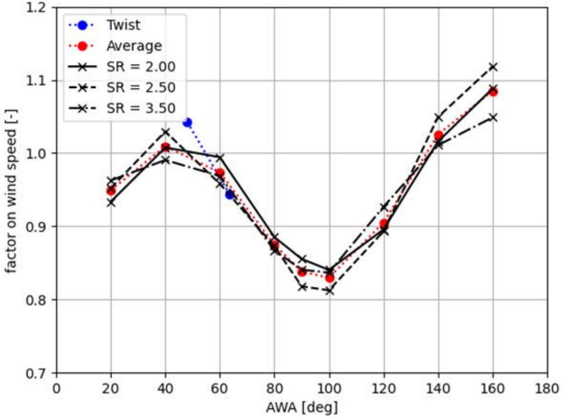
- Wind speed lower at sea surface than higher above: Atmospheric Boundary Layer (ABL)
- Common reference for wind speed at 10m height
- Combined with ship speed, as you go higher:
  - The apparent wind speed increases (“shear”)
  - The apparent wind angle moves aft (“twist”)

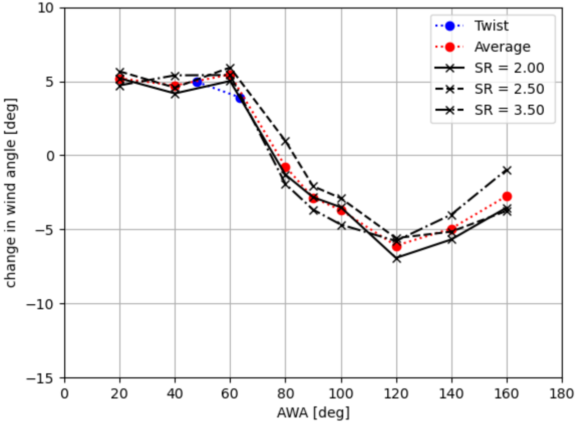


Disturbance of ship

- Ship hull and superstructures affect the flow
- Dependent on apparent wind angle
- Dependent on position on board







M. Garenaux and J. J. A. Schot, “Flettner rotors performance and interaction effects on the MARIN Hybrid Transition Coaster,” 2021.

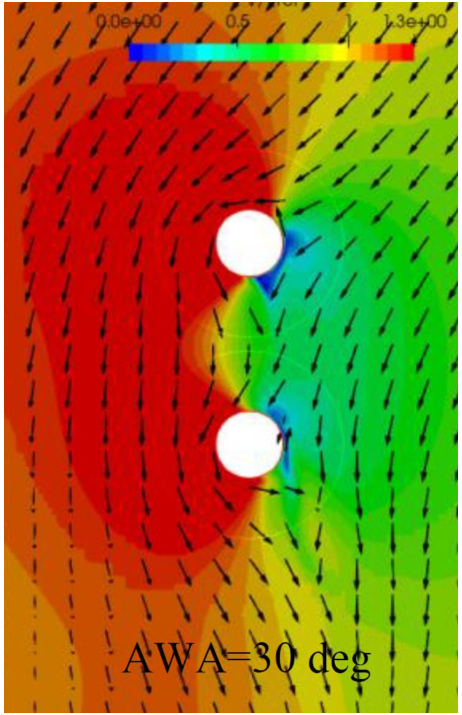
Interaction effects

With wind propulsors closely positioned together

(~ < 12 times chord or diameter):

- Mutual influence on each other's performance due to change in flow speed and angle
- Generally a reduction of overall thrust

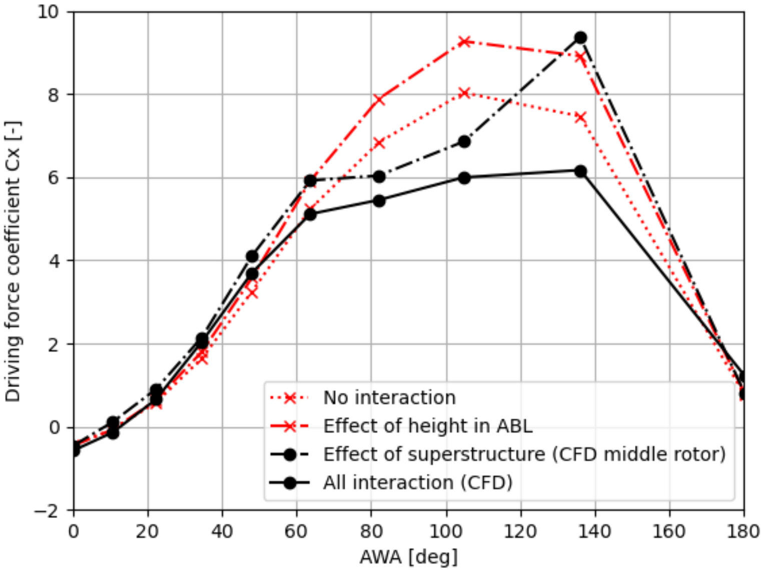
  (some exceptions with closely positioned wings/sails)



M. Garenaux and J. J. A. Schot, "Flettner rotors performance and interaction effects on the MARIN Hybrid Transition Coaster," 2021.

Full (interaction) scenario

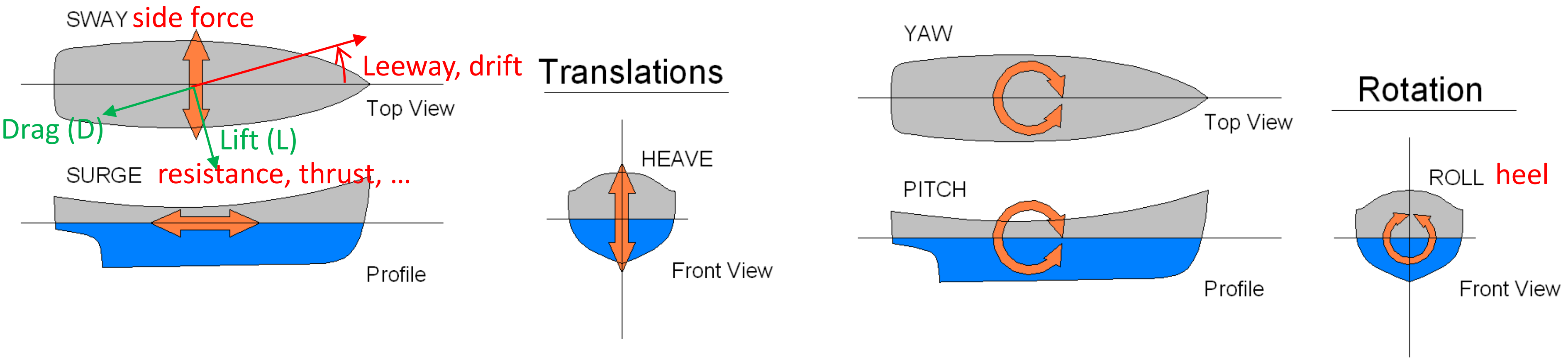
- Combined interaction effects can yield overall forces significantly different from just the wind propulsor in “clean” wind



M. Garenaux and J. J. A. Schot, “Flettner rotors performance and interaction effects on the MARIN Hybrid Transition Coaster,” 2021.

What changes (in hydrodynamics) with wind propulsion?

Definitions



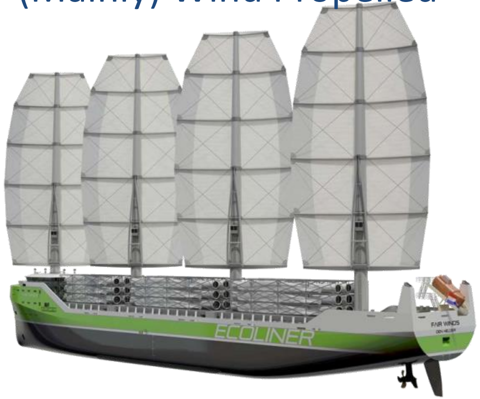
How much wind propulsion?

Not only dependent on design, but also operations (speed) and routes (wind) !

Reference:
Conventionally propelled

Fully sailing

Wind Assisted <-> (Mainly) Wind Propelled



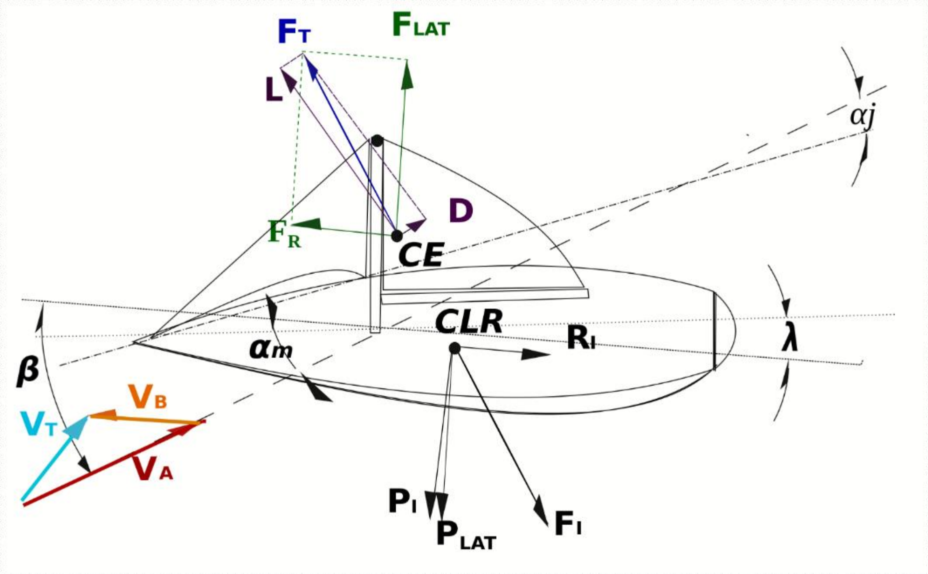
Reference without wind propulsion

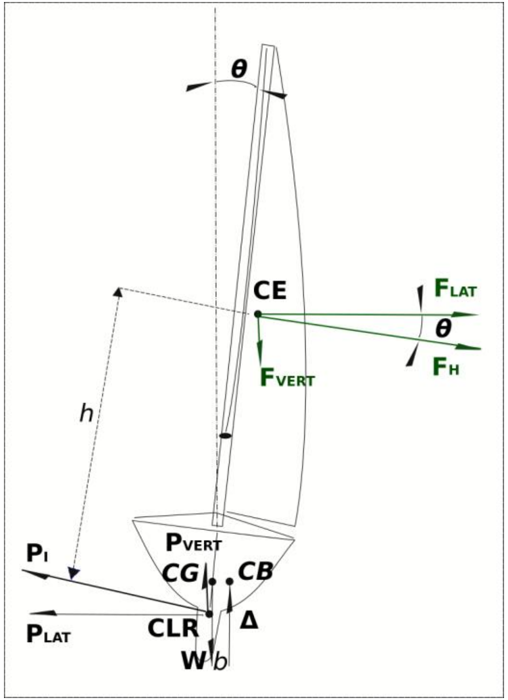
- Calm water
- Resistance – a force as function of speed
- (Propeller) propulsion – function of propeller rotation rate

➢ All of that only in **longitudinal direction, wind normally discarded**

What changes with wind propulsion?

What changes?

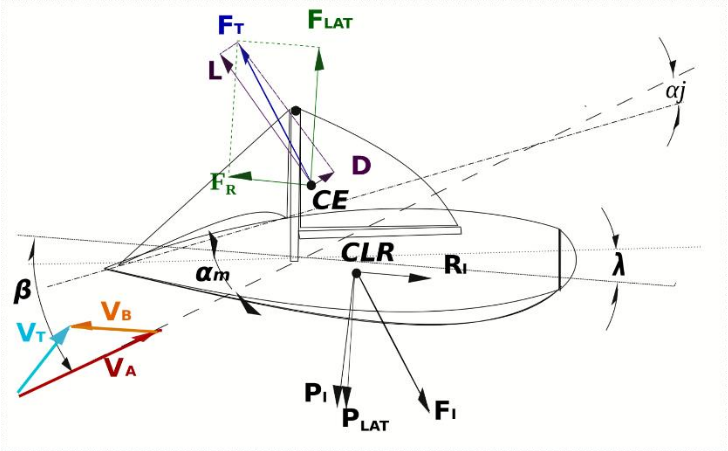


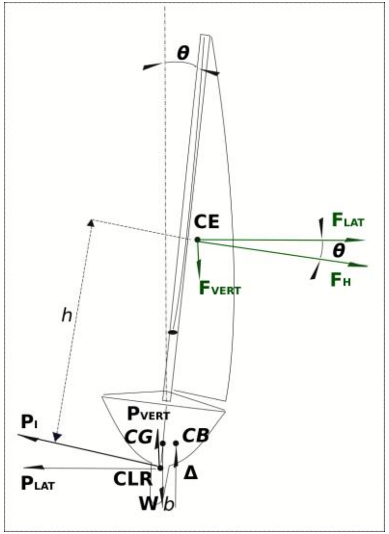


Source: Bcebul / Wikipedia

What changes?

- Aerodynamic thrust -> Savings on fuel consumptions & emissions
- Side force - > Leeway
- Rolling moment -> Heel
- Yawing moment -> Non-zero rudder angle
- Aerodynamic thrust -> Lower loading on propeller and engine

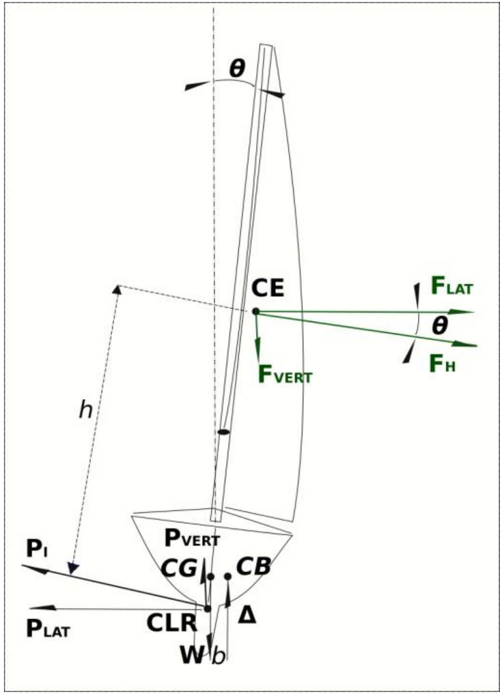




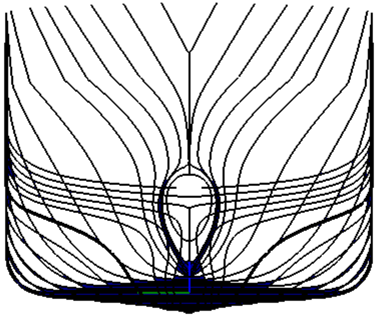
Heel

How much heel?

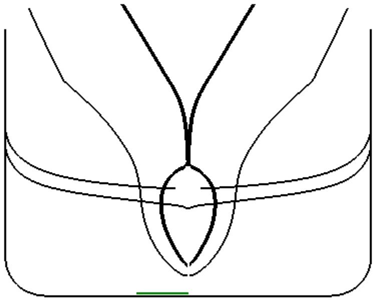
What is acceptable? No common reference yet. But published maxima vary between 5 to 10 degrees.



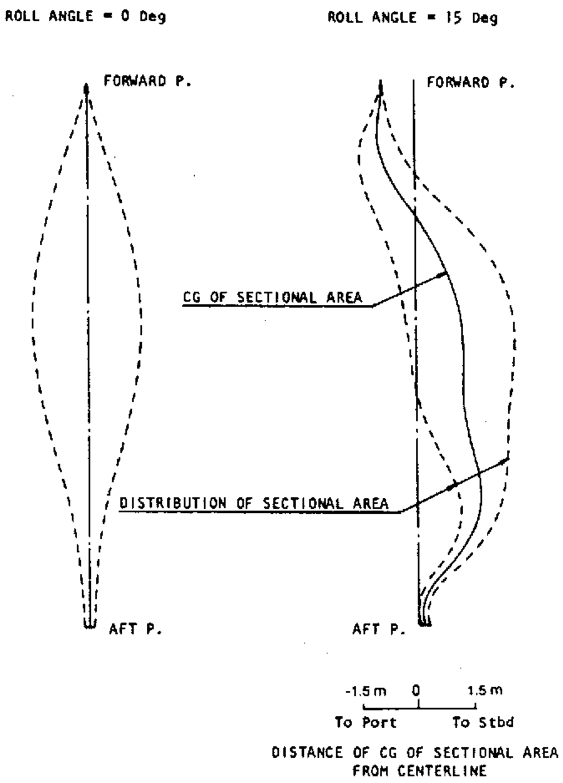
Heel

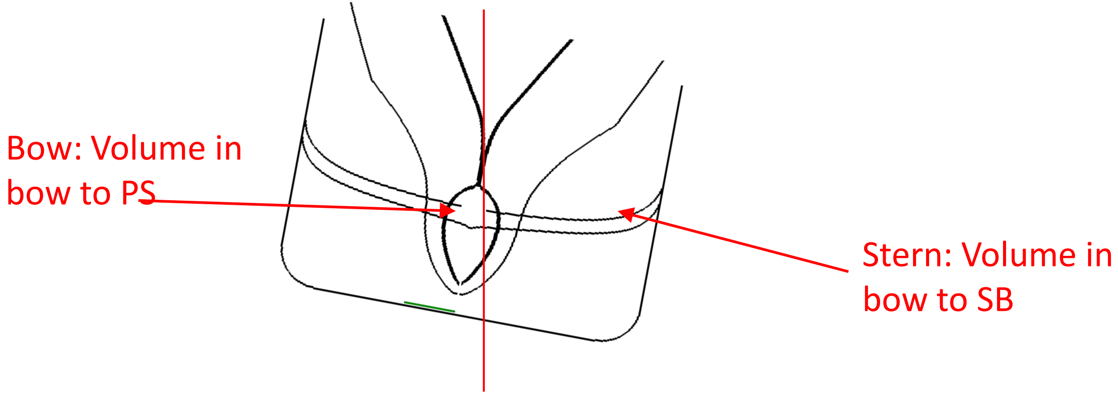


KCS reference hull



Heel

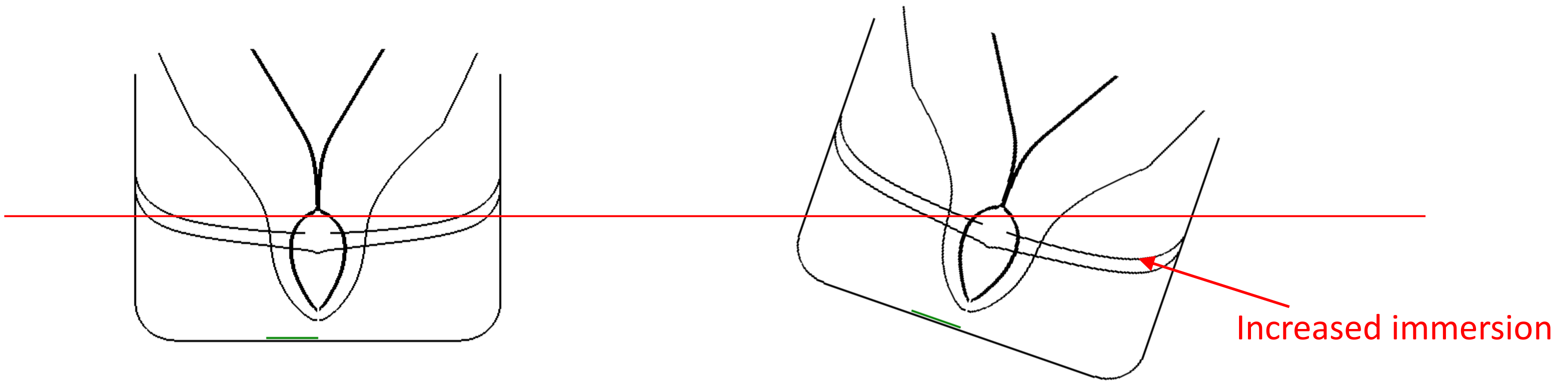




- Underwater shape becomes asymmetric
  - Angle of attack introduced
  - Resulting side force and yaw moment

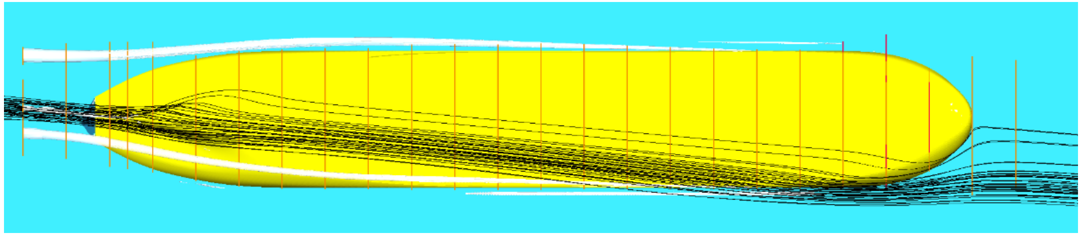
Heel

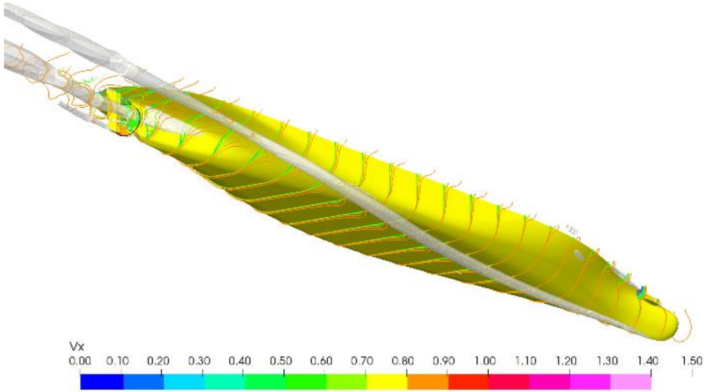
- Change of wetted surface
  - Change in drag
- Transom may locally immerse (more)
  - Increased drag



Leeway

- Change in flow, pressures, waves; starboard and port side different
- Generates required side force
- But comes with consequences
  - Increased resistance
  - Changed flow (and vortices) through propeller



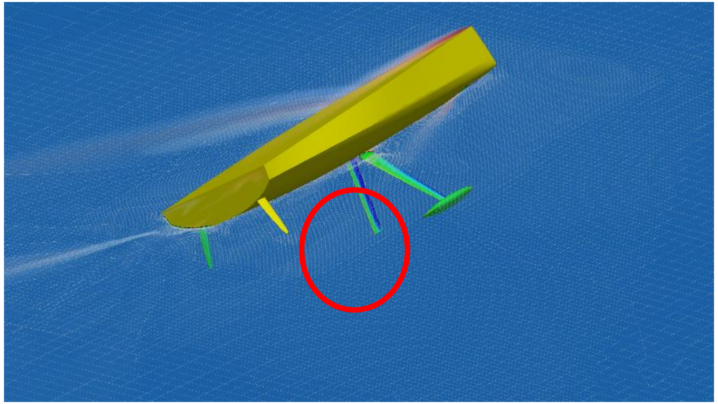


J. J. A. Schot and R. Eggers, “The Effect of Leeway Angle on the Propeller Performance,” London, United Kingdom, 2019.

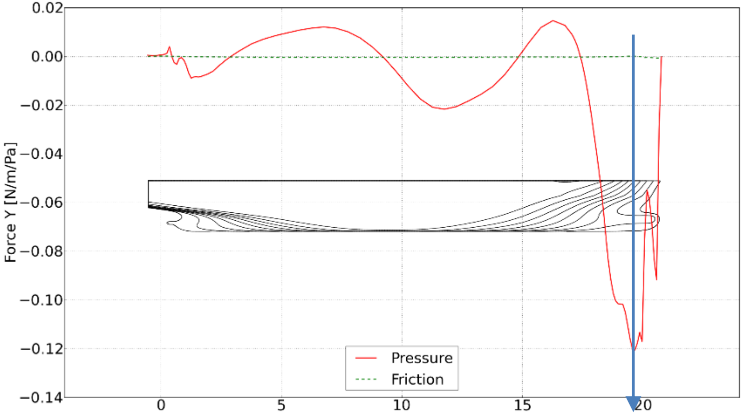
Yaw balance

- Side force on vessel without keel or *boards applies far forward !

Yacht: Keel carries majority of side force close to mid ship



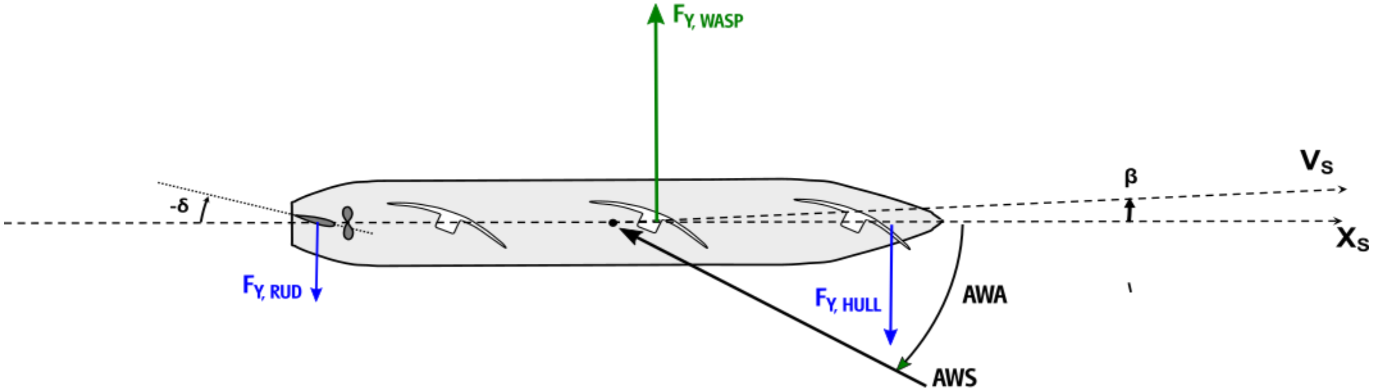
Merchant vessel: Majority of side force close to bow



R. Eggers, “Prediction Methods for Team Akzonobel in the Volvo Ocean Race and Wind Assisted Ship Propulsion for Merchant Vessels,” 2018.

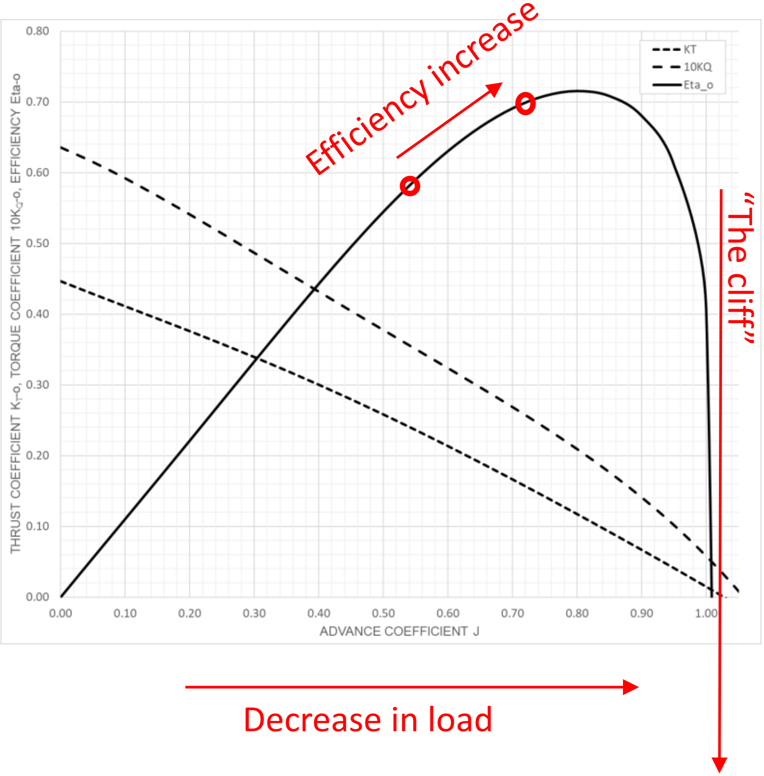
Yaw balance

- A rudder angle is generally required
- Rudder can easily be overloaded (excessive drag)
- Demanding for vessels without additional appendages



Propeller load

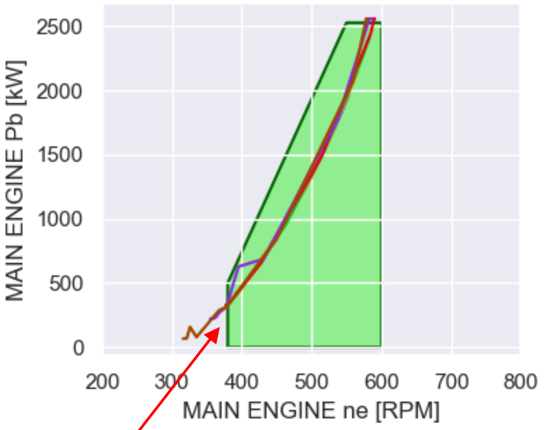
- Propeller is *generally* overloaded from efficiency perspective
- Wind propulsion can improve effiency by reducing load
- But don't fall of "the cliff"!
  - Windmilling/retract/feather
  - Power generation (with



Engine load

- When using a (single) combustion engine:
  - On edges of common operational conditions
  - Wear and tear
  - Poor **specific** fuel consumption (g/kWh)

WiSP Joint Industry Project



Outside operational region

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How to design (and operate)?

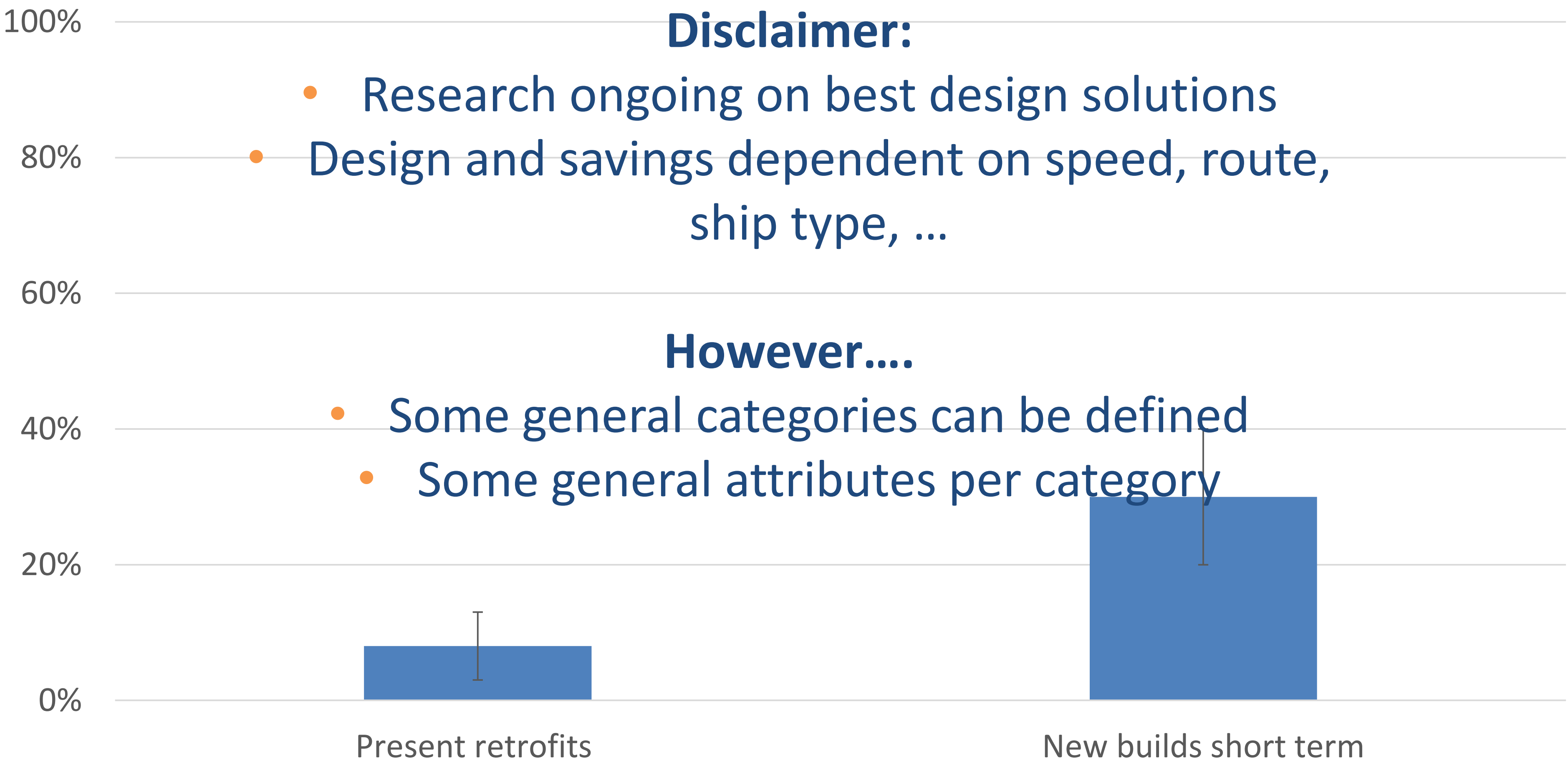
Design

Disclaimer:

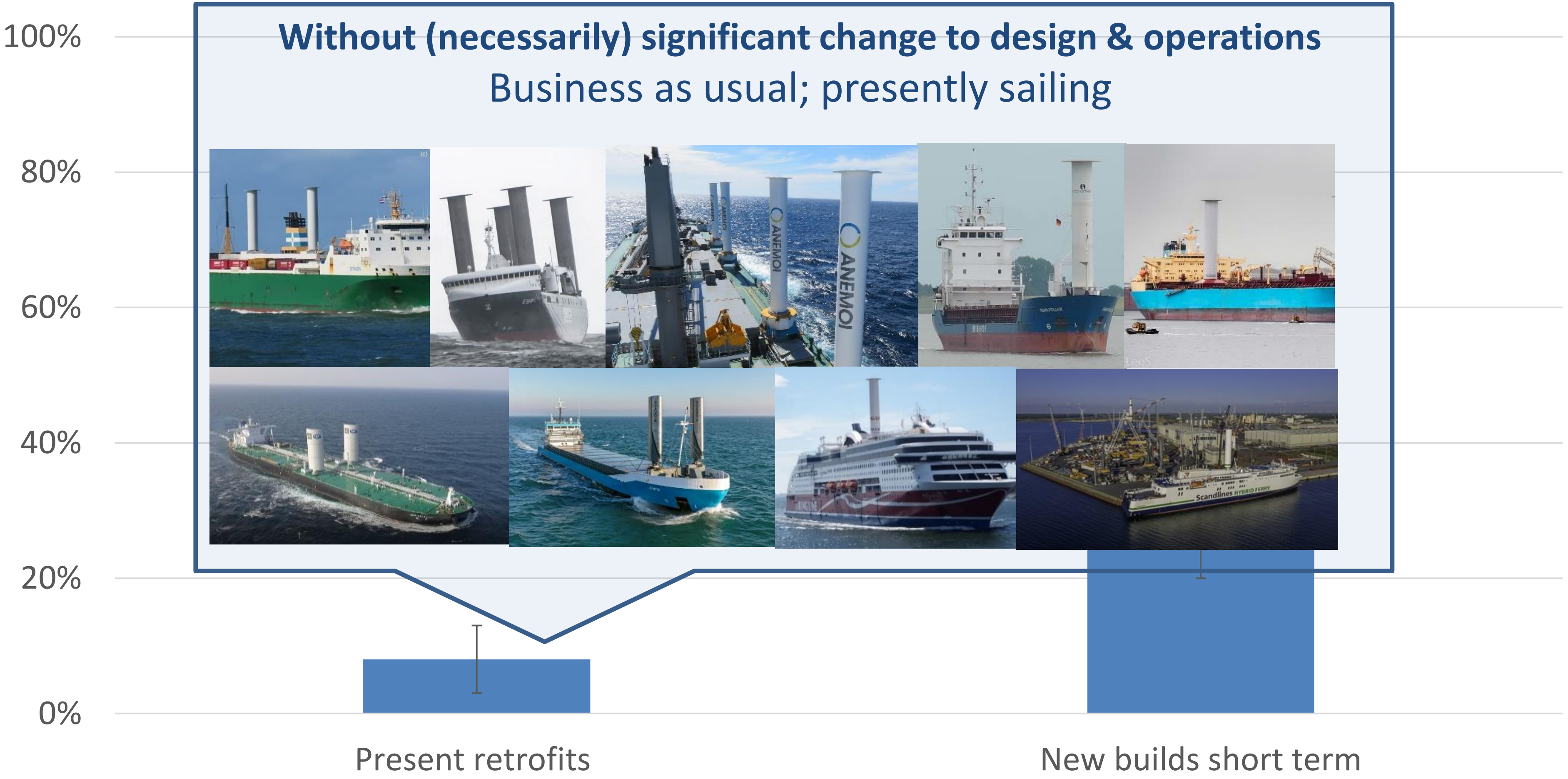
- Research ongoing on best design solutions
- Design and savings dependent on speed, route, ship type, …

However….

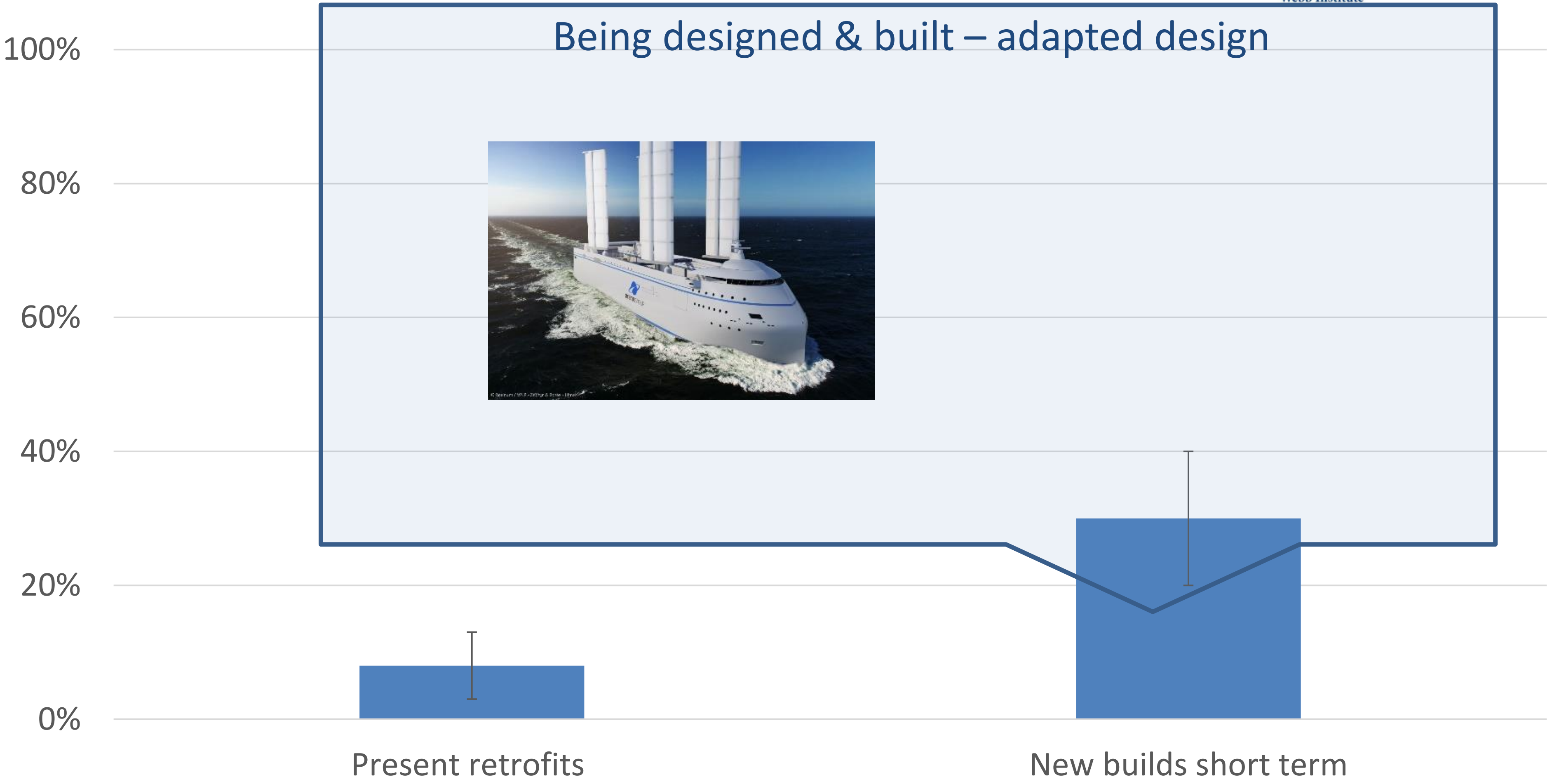
- Some general categories can be defined
- Some general attributes per category



Design – retrofits / business as usual

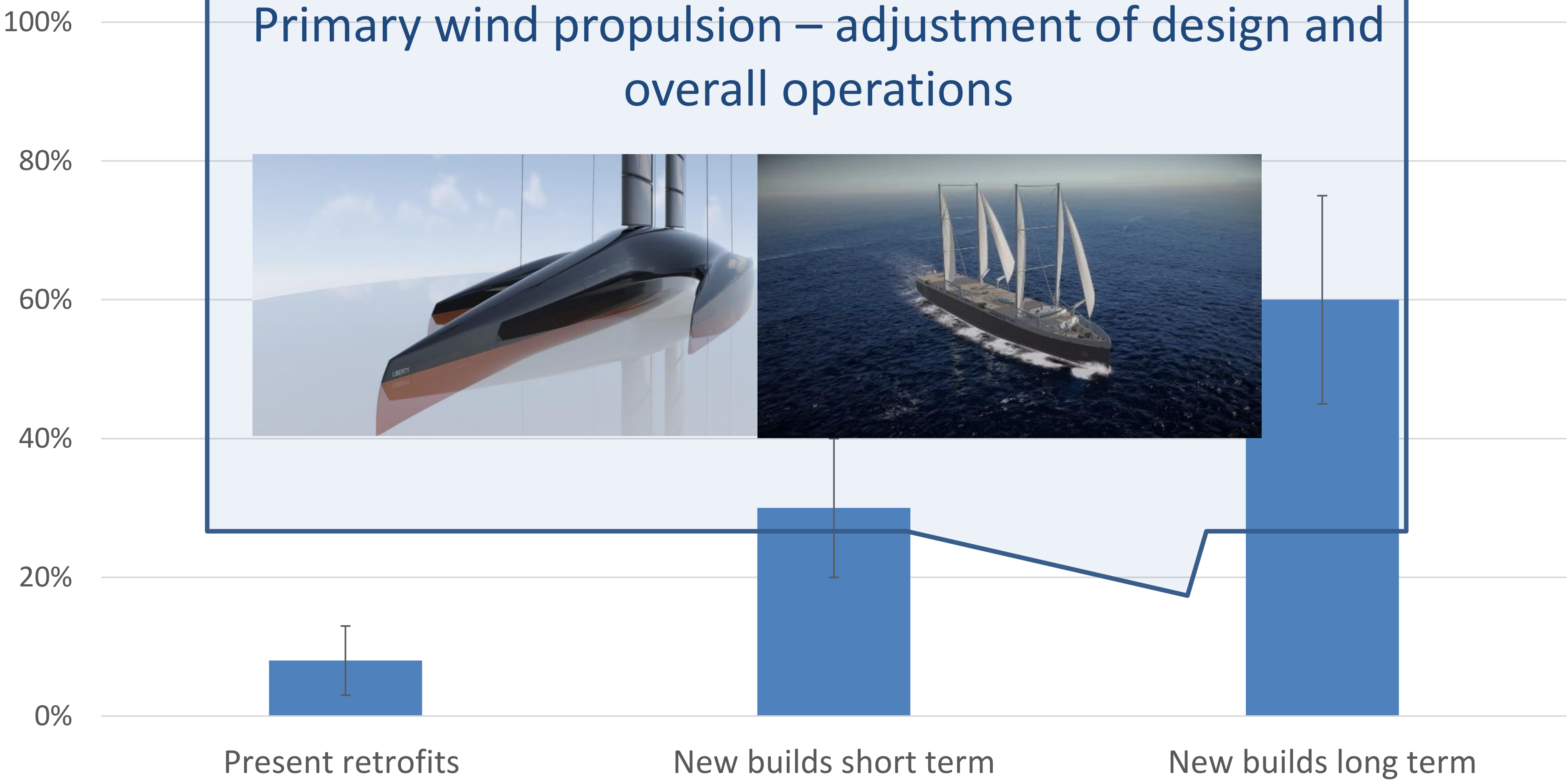


Design – new builds short term



Design – new builds long term

Primary wind propulsion – adjustment of design and overall operations



Aerodynamics - Design

- Select suitable type of wind propulsor !
- Clear area on deck with substantial separation between wind propulsors and superstructures
- New frontier: flow optimisation for drag reduction and good inflow
  - Adjusted deck edges, coamings
  - Fairing / end plates

Aerodynamics - Operation

- Local wind conditions at each wind propulsors not trivial !
- May specifically affect wind propulsors with a stall angle
- Dedicated measurements and/or ship specific corrections can help
- Direct force measurement can also help (but not trivial)

Hull & rudder

- For better ultimate sailing performance:
  - Aim for best lift-to-drag ratio
  - Bring the hydrodynamics side force aft (to reduce the rudder angle)

Hull & rudder

- The toolbox:
  - Change hull dimensions (more draught, …)
  - Use V-shaped sections or box keels (in stern area)
  - Avoid wide flat transom
  - Enlarge skegs and bilge keels
  - Use appendages (like keels or dagger boards)
  - High-lift/multiple rudders
- Most of these modifications come with performance degradation when sailing straight, in low wind.
- Find best compromise considering operational profile.

Propeller

Propeller characteristics and design to be updated for overall wind assistance profile.

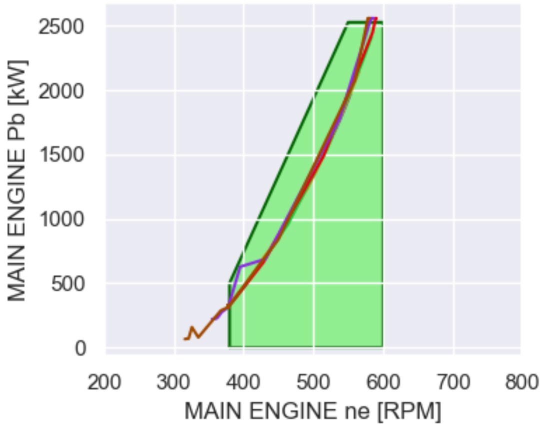
Two strategies when the ship sails only on wind power:

1. Fold, retract or weathervane propeller to reduce drag
2. Keep propeller in place; use propeller as turbine (regeneration)

Development required to optimize and verify performance at the scale of common commercial ships

Power generation - engines

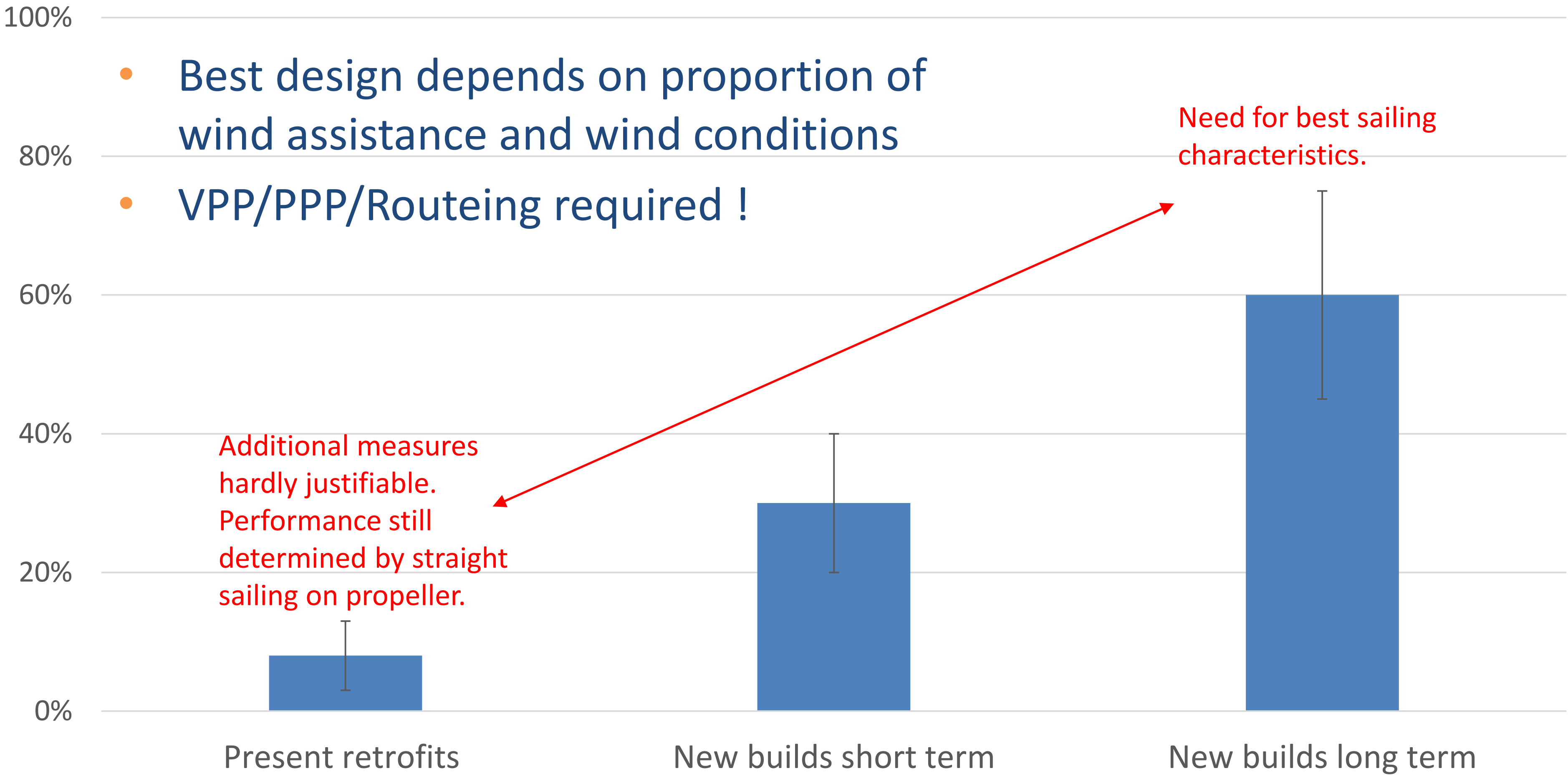
- A single combustion engine is *still* most cost effective (and directly available at scale)
- But larger load variations cannot be handled, so
  - Multiple engines mechanically coupled
  - Generator sets and electric drive
  - Fuel cell
  - ….
  - Hybrids !



- Of course dependent on general ambitions in project ! Diesel still acceptable?

Trade-off

- Best design depends on proportion of wind assistance and wind conditions
- VPP/PPP/Routeing required !



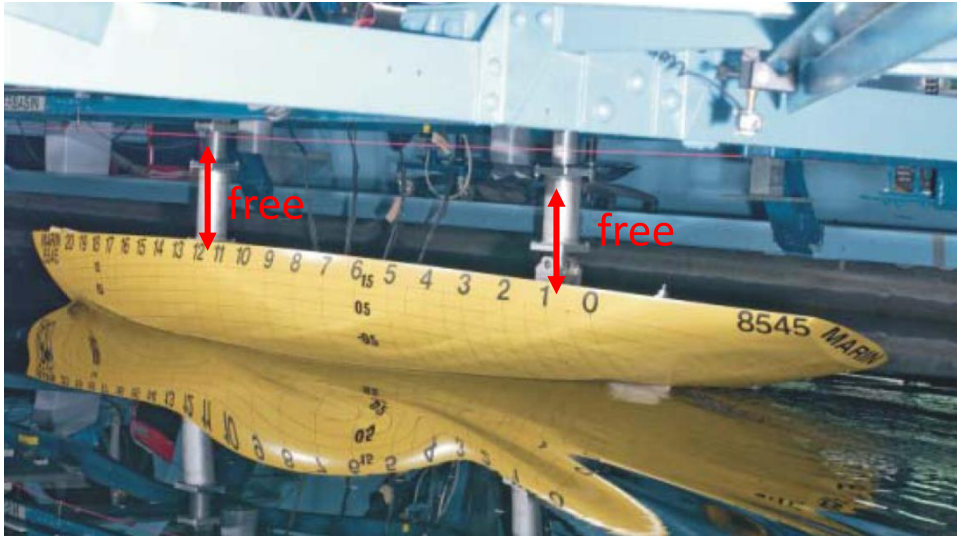
Modeling and measurements

Steps in performance prediction

1. Initial performance prediction (estimates)
2. Derivation of expected equilibrium conditions
3. Predict aero- and hydro forces
4. Refined (final) performance

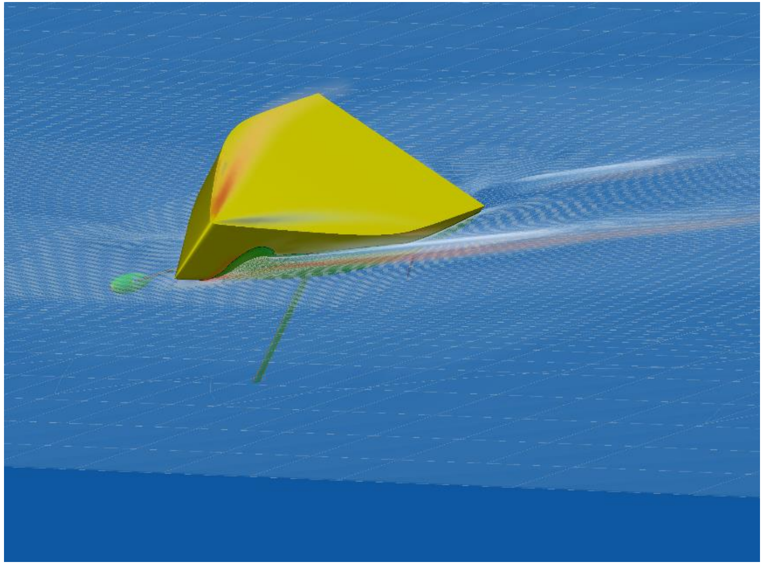
Model tests – a traditional "towing tank"

- Set-up:
  - Fixed in surge, sway roll and yaw
  - Free in heave and pitch
- Tests
  - Speeds
  - Heel angles
  - Leeway angles
  - Rudder angles
- Measured
  - Forces in surge, sway, roll and yaw
  - Forces in rudders, keels, …
  - Heave and pitch
  - Video
  - ….
- "Extrapolation" required for move from "model scale" to "full scale"
- But size of model should not be too small !
- Physics happens "automatically"



Computational Fluid Dynamics (CFD)

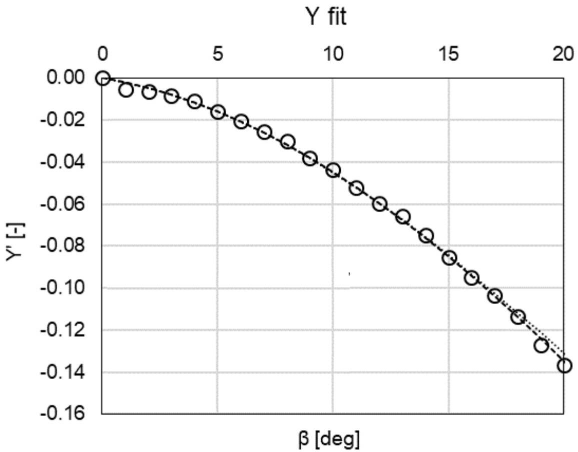
- Same approach as tests!
- However:
  - Directly at “full scale” (no extrapolation)
  - Insight in flow
  - (Start-up) cost lower
  - But, still sensitive to the right assumptions and methods (turbulence modesl, grids, …) to get the physics right!



Numerical model – "fitting"

Performance prediction needs "smooth" curves, for instance:

(Modular) forces in **surge, sway, roll and yaw** (4 outputs)
as function of
speed, leeway, heel, rudder angle (4 inputs)



Example fit of side force (Y)
versus leeway (β)

Composition of performance prediction

Aerodynamic forces

\+

Hydrodynamic forces

→

Equilibrium

Force equilibrium:
- Speed
- Leeway (drift)
- Heel
- Rudder angle

- Result of final prediction
- But already required for hydro prediction
- Chicken and egg problem!

Optimize, e.g.
- Flettner rotor rotation rate
- Suction wing ventilation
- Sail trim, reefing
- Propeller pitch
- …

Summary

Wind propulsion is already proven to work and provide substantial savings!

However, to get the most out of it:

- Aerodynamics critical to get right
- Hydrodynamics can be influenced by substantial WASP
- Best design for substantial WASP
  - General trends known
  - Elaboration for specific ships ongoing
- Prediction methods available (but validation & standardisation ongoing)

THANK YOU - ANY QUESTIONS ?

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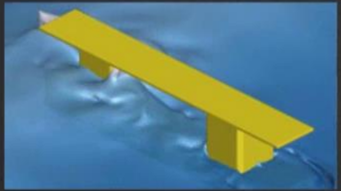

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