Using physics for monitoring autonomous rigid-wing sailing robots

Mälardalens Högskola, november 2021

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INTRODUCTION

Arcada University of Applied Sciences (since 2021)
Cornell University (2019)
Åland University of Applied Sciences (2002->)
Åbo Akademi University (1992-2002)
University of New South Wales (2000-2001)

Research: Nonlinear system identification, identification for control, models for supervision and control, process control. Nonlinear dynamical systems.

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UNDERSTANDING EVOLVES SLOWLY: SAILING

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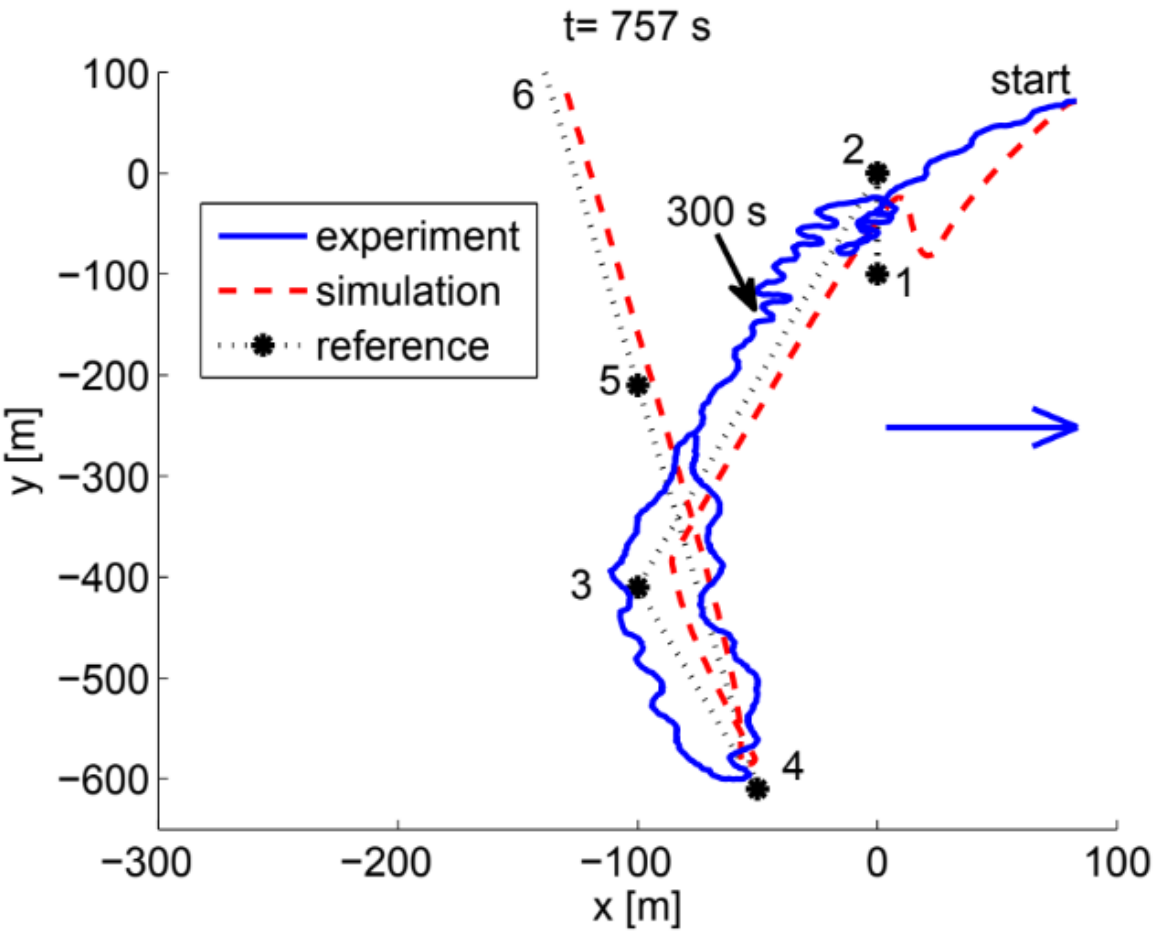
May 2015



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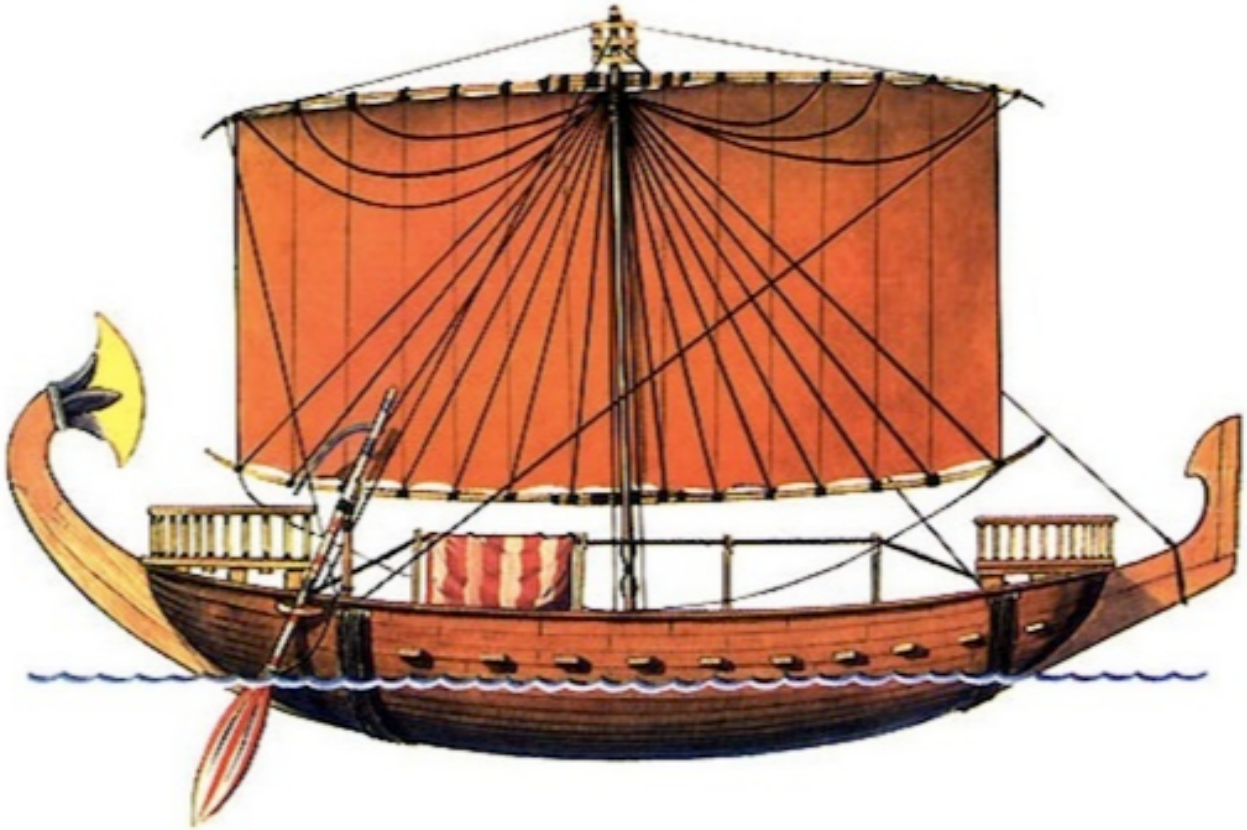
HISTORY OF SAILING?



Egyptian merchant ship. 2550 B.C.E.

Picture: Armament history

Wind and Hydro(nonelectric) Power

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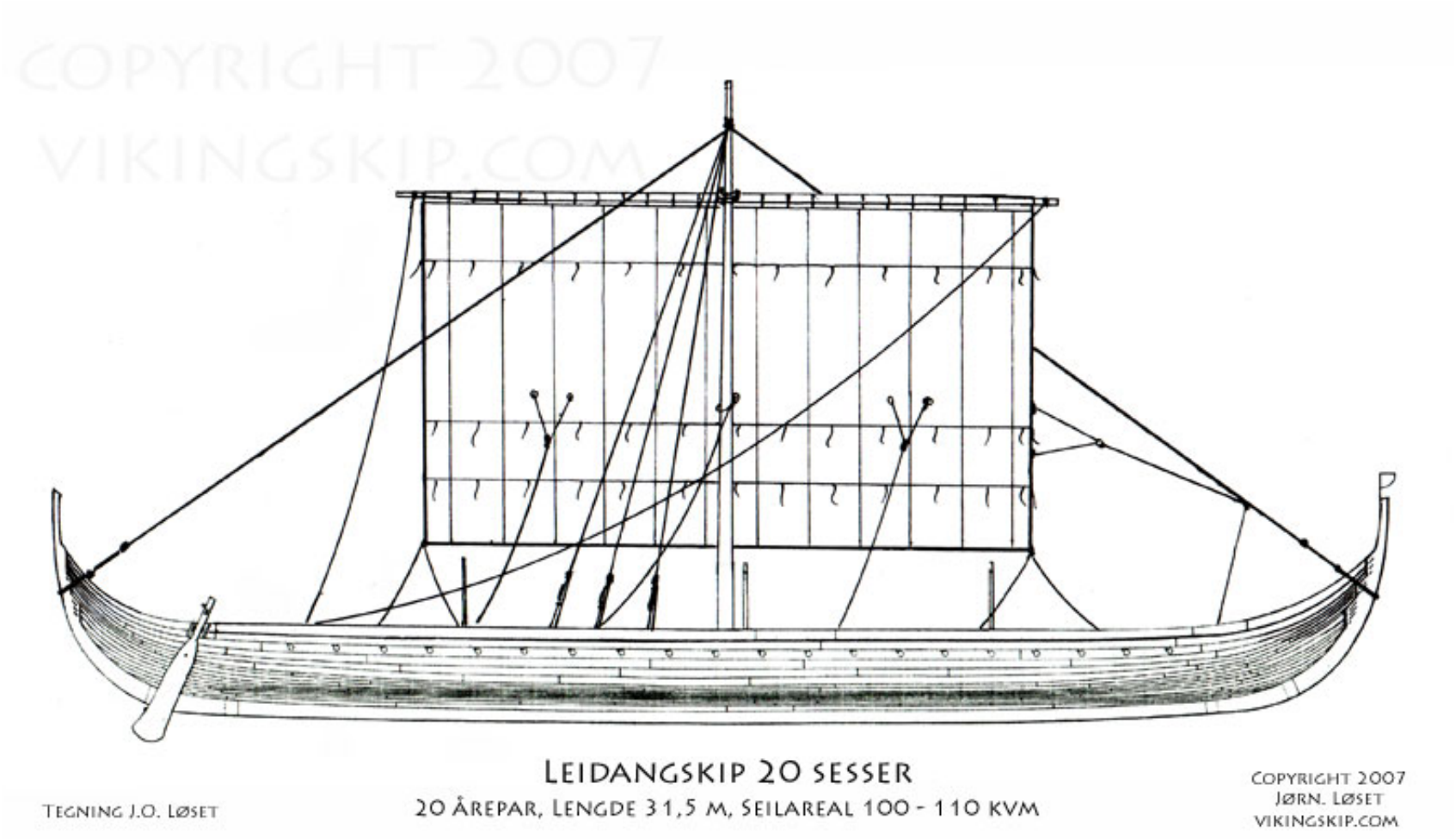
NORDIC SAILING



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Sailing Arabian Dhow

Sailing Chinese Junk

Hong Kong's last authentic junk boat is struggling to stay afloat due to a lack of overseas tourists.

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SAILING

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ROMANTICIZING SAILING?

"A large piece of canvas flapping in a storm is like a thing possessed and totally uncontrollable. Fear of the damage that a sail can and will do, and the hurry to reduce its size or to put it away altogether are still as much a part of the mental makeup of most yachtsmen today as they were of the poor souls who manned the square riggers that look so pretty in a moderate wind on a smooth sea, or even better as a picture on the wall. I have very little patience with the romanticising that goes on about these vessels. To me their very design made superhuman demands on the crew which led inevitably to the brutality that characterized the maintenance of discipline on long voyages. It is no surprise that they are no longer in use for carrying any type of cargo anywhere in the world"

Venkatraman Radhakrishnan—space scientist and member of the Royal Swedish Academy of Sciences.

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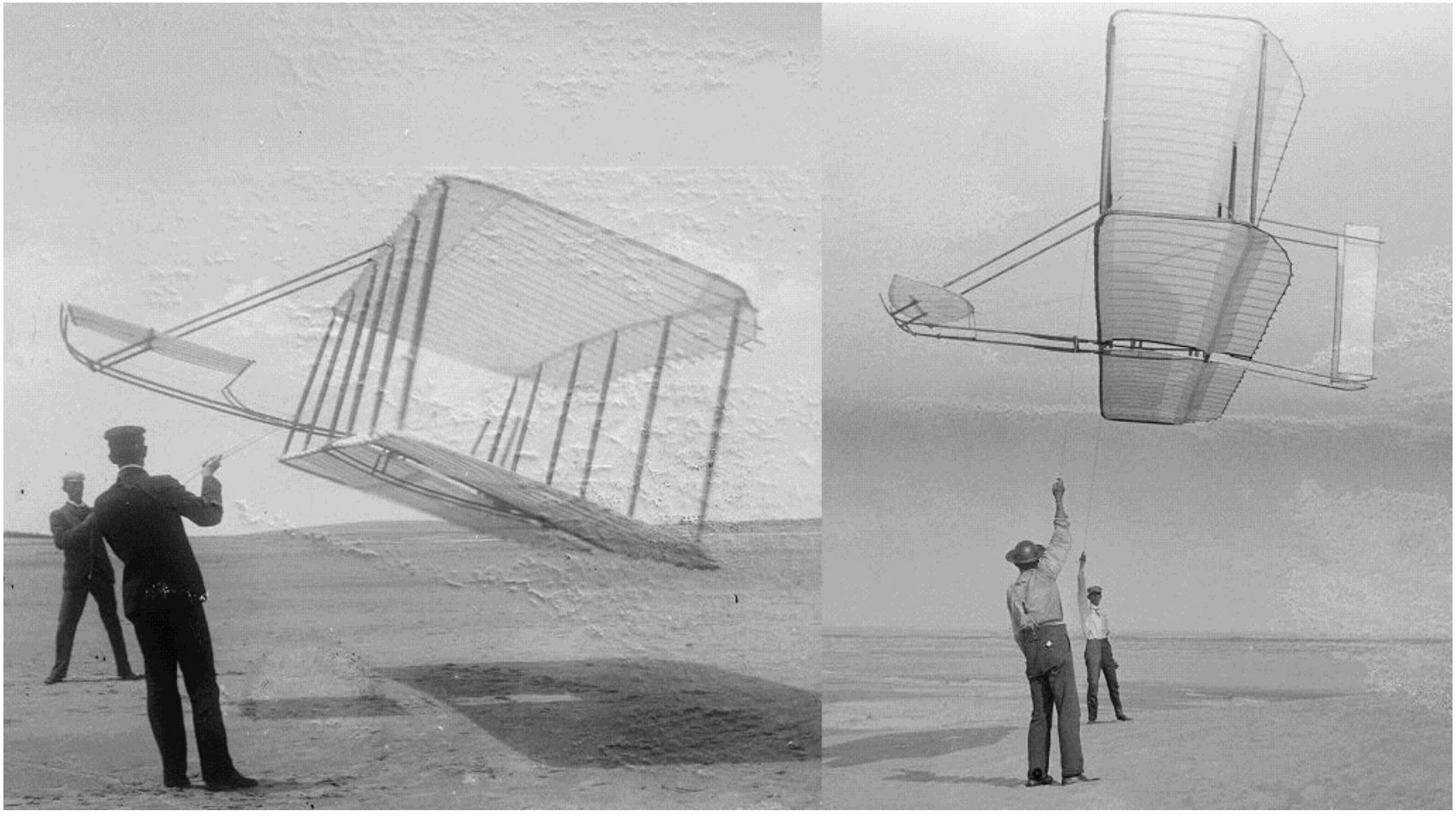
SAILING?



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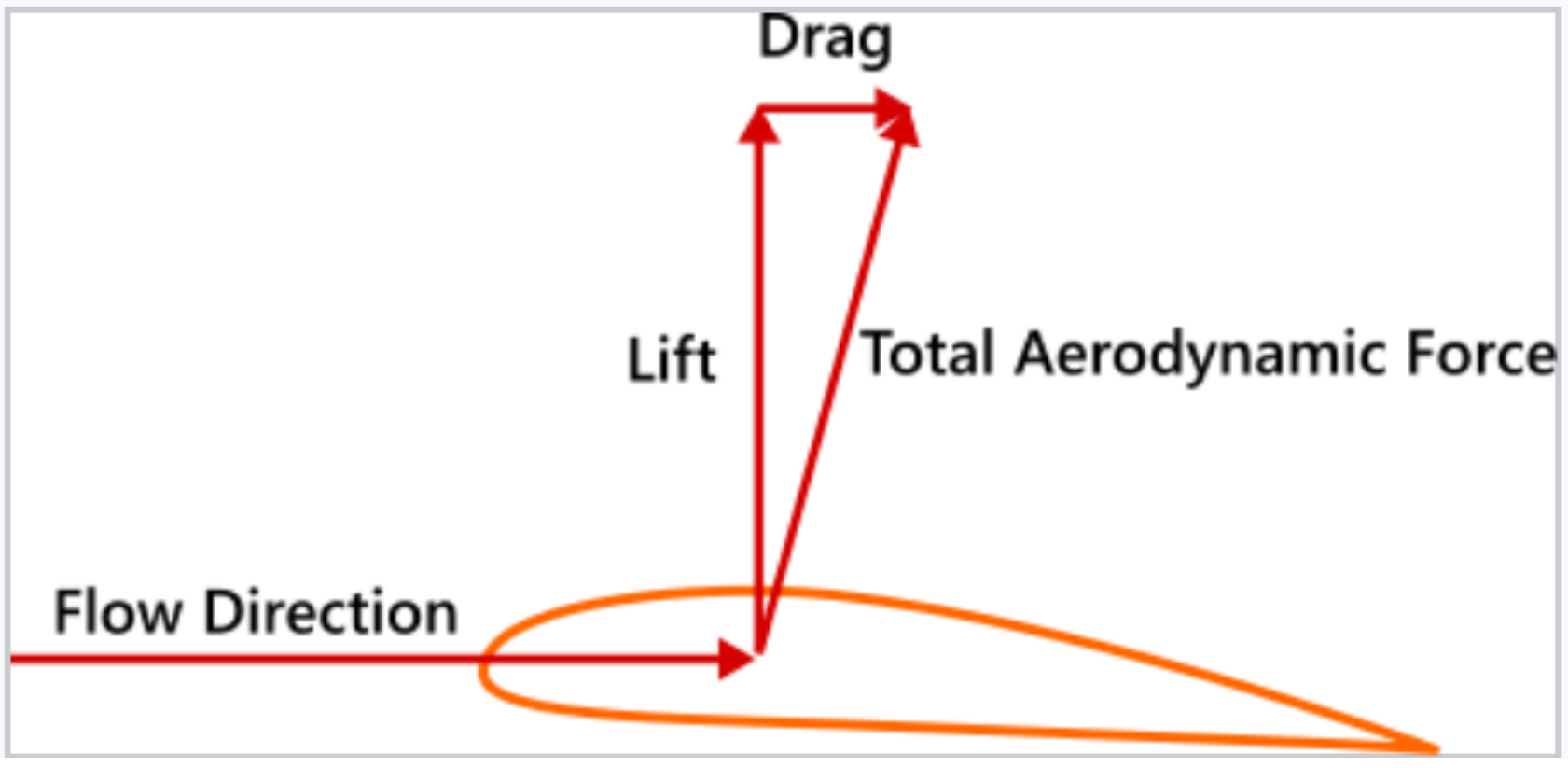
SAILING?



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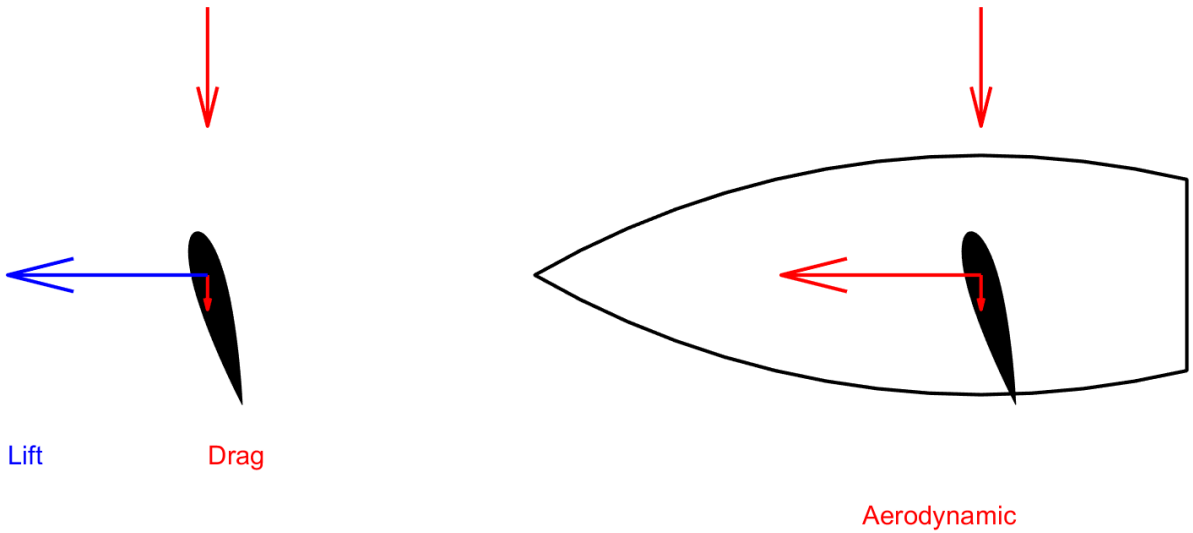
BACK TO SAILING



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CAN YOU USE A SYMMETRIC WING FOR SAILING?

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GOOD COMPANY

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KTH: MARIBOT VANE

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WALLENIUS MARINE

▸ OceanBirdKTH

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SAILING

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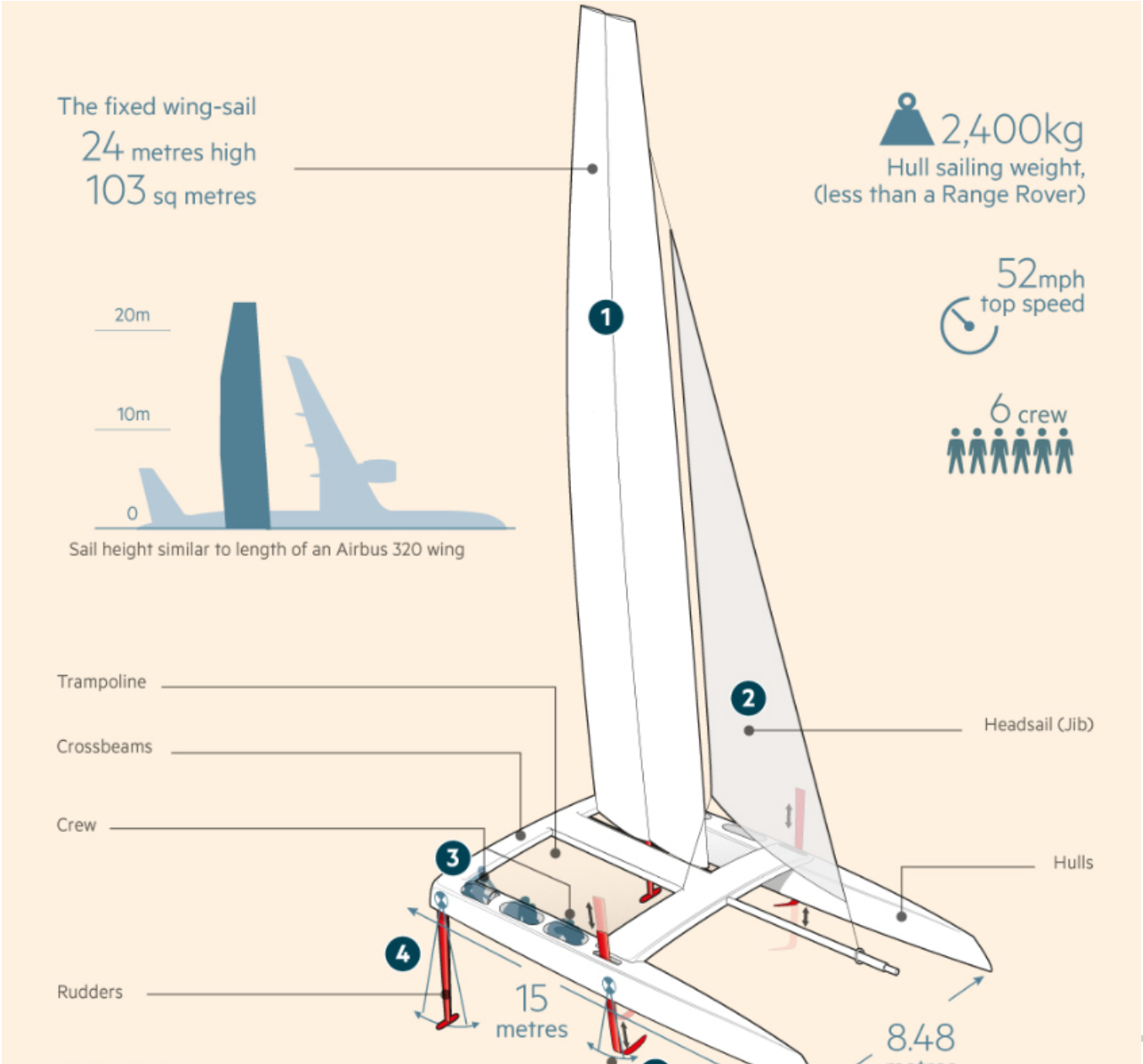
SAILING



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SAILING

Luna Rossa approaches Mark 3 - Race 1 - Prada Cup Final - Day 1 - February 13, - America's Cup 36 - photo © Richard Gladwell / Sail-World.com

▸ America's Cup 2021

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THINKING EVOLVES SLOWLY

Ludwig Wittgenstein: “If people never did anything stupid, nothing intelligent would ever get done.”
Lars Hertzberg: “Galenskapen tänker i räta linjer och logiska system, det sunda förnuftet böjer sig för verklighetens okontrollerbara mångfald.”
“Insanity/Madness works in straight lines and logical systems, common sense bends for the uncontrollable diversity of reality”
Personal reflection: In the midst of scientific work, things can seem incomprehensible one day and trivial the next.

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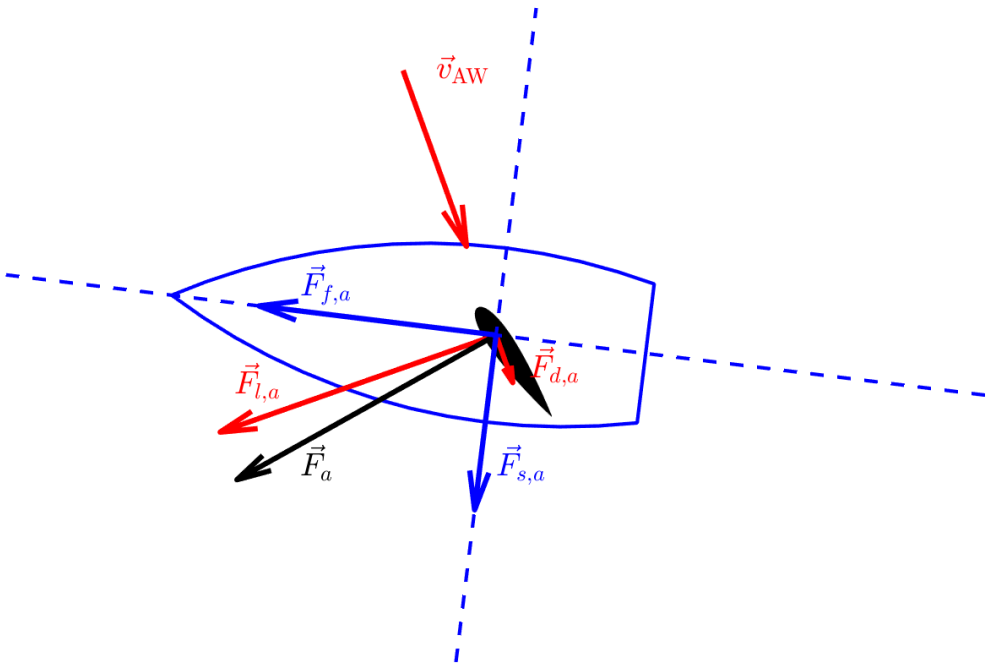
THE PHYSICS BEHIND SAILING-AERODYNAMICS



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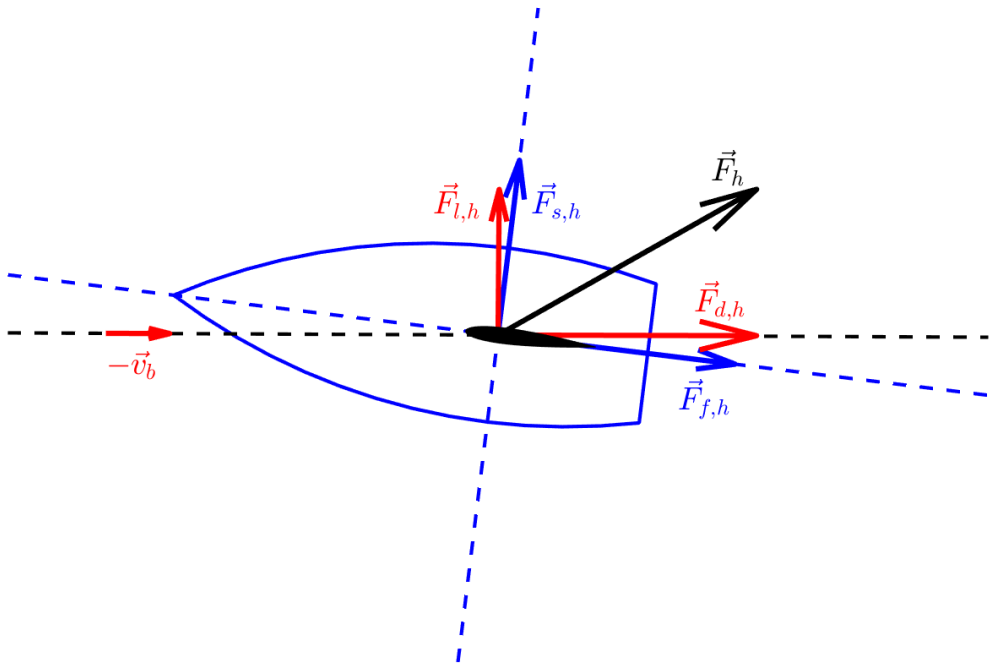
THE PHYSICS BEHIND SAILING-HYDRODYNAMICS



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THE PHYSICS BEHIND SAILING-VARIABLES

- apparent wind angle, β_{AWA}
- apparent wind speed, v_{AW}
- angle of attack (wingsail), α
- leeway, λ
- boat speed (over water), v_b

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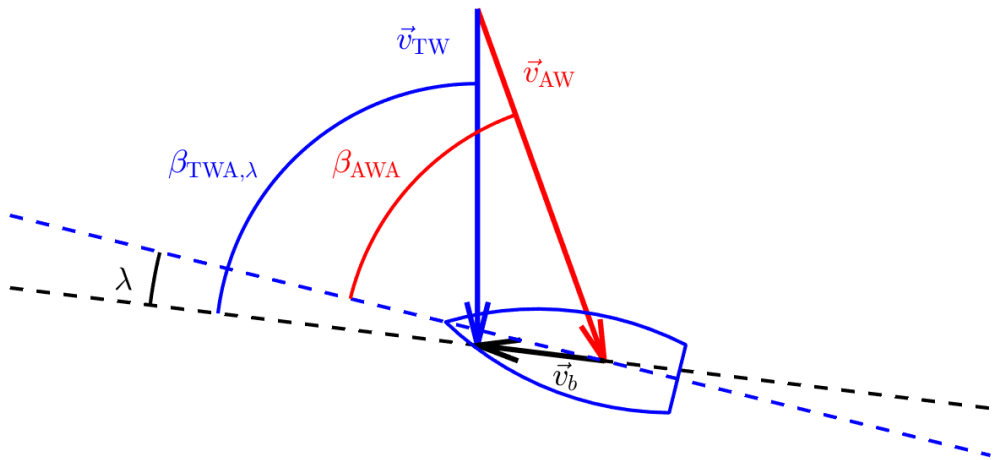
THE GEOMETRY BEHIND SAILING—DIFFERENT PERSPECTIVES



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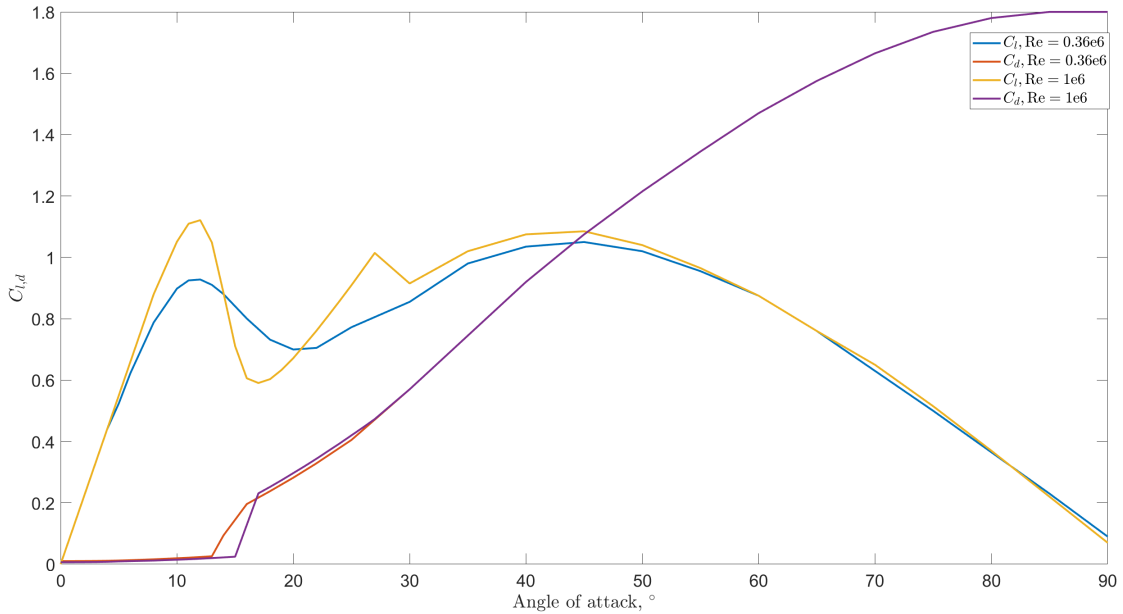
THE PHYSICS BEHIND SAILING—AERODYNAMICS

$$F_{l,a} = \frac{1}{2}\rho_a C_l A_s v_{\mathrm{AW}}^2 \tag{1}$$

$$F_{d,a} = \frac{1}{2}\rho_a C_d A_s v_{\mathrm{AW}}^2 \tag{2}$$



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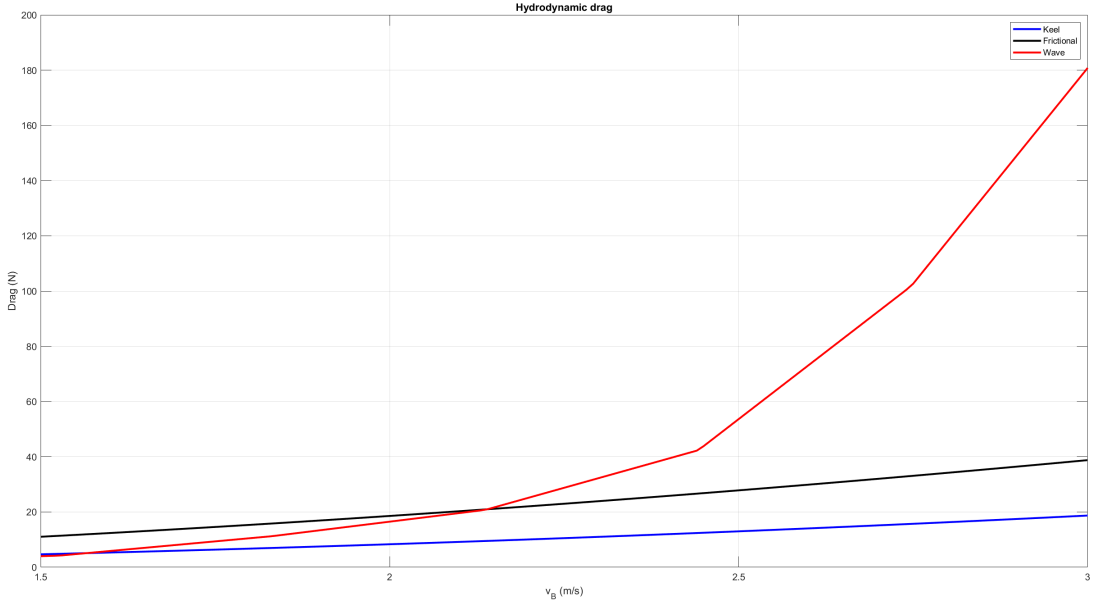
THE PHYSICS BEHIND SAILING—HYDRODYNAMICS

$$F_{l,h} = \frac{1}{2}\rho_w C_{l,k} A_k v_b^2 \tag{3}$$

$$F_{d,h} = F_{\text{wave}} + \frac{1}{2}\rho_w (C_R A_w + C_{d,k} A_k) v_b^2 \tag{4}$$



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THE PHYSICS BEHIND SAILING—BASIC MODEL

$$\begin{aligned} F_{f,a} &= \operatorname{sgn}(\beta_{\text{AWA}}) \sin(\beta_{\text{AWA}}) F_{l,a} - \cos(\beta_{\text{AWA}}) F_{d,a} \\ F_{s,a} &= -\left(\operatorname{sgn}(\beta_{\text{AWA}}) \cos(\beta_{\text{AWA}}) F_{l,a} + \sin(\beta_{\text{AWA}}) F_{d,a}\right) \end{aligned} \tag{5}$$

$$\begin{aligned} F_{f,h} &= \sin(\lambda) F_{l,h} - \cos(\lambda) F_{d,h} \\ F_{s,h} &= \cos(\lambda) F_{l,h} + \sin(\lambda) F_{d,h} \end{aligned} \tag{6}$$

$$\begin{aligned} F_{f,a} + F_{f,h} &= 0 \\ F_{s,a} + F_{s,h} &= 0 \end{aligned} \tag{7}$$

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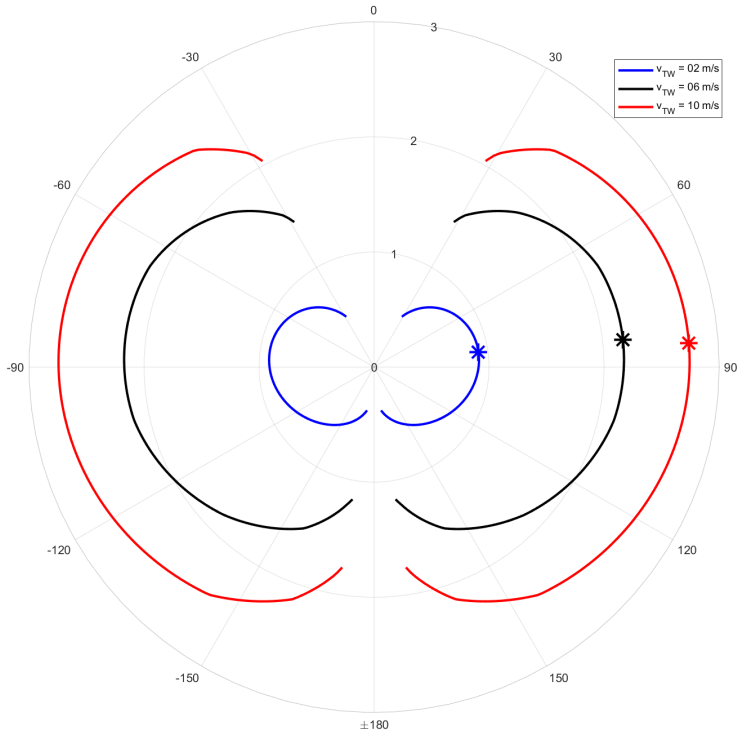
CRASH COURSE IN SAILING PHYSICS: ANIMATION



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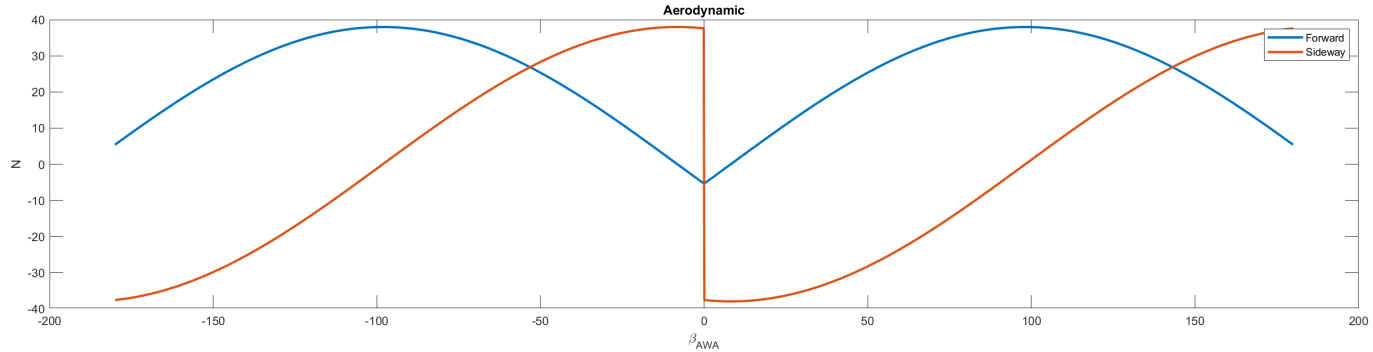
NUMERICAL EXPLORATION



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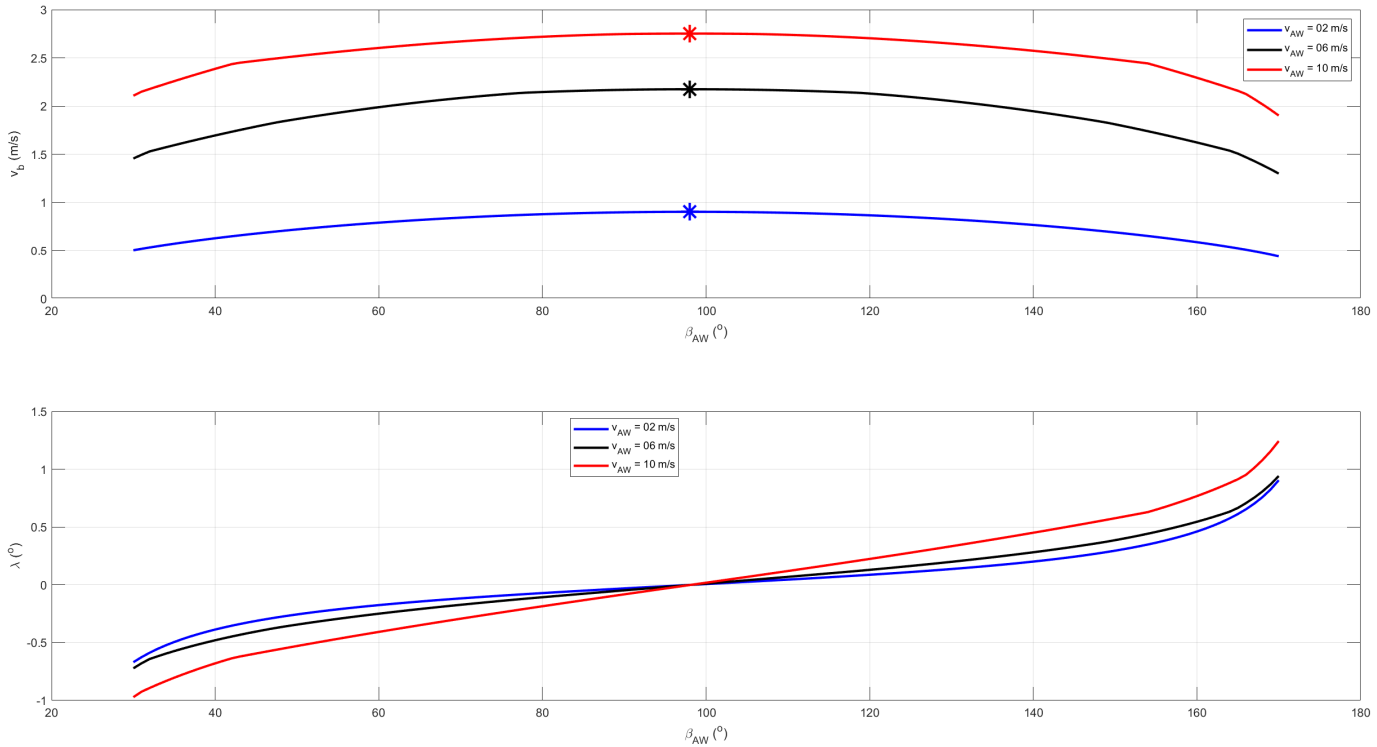

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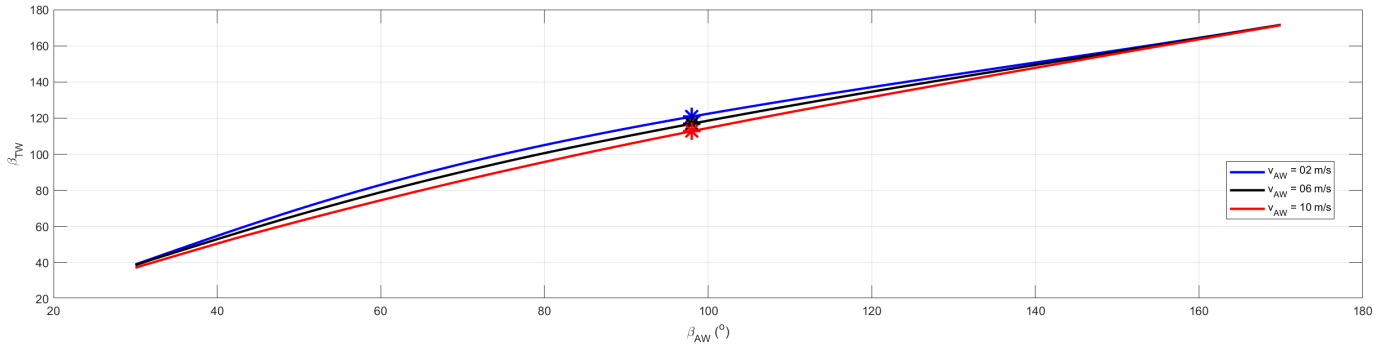

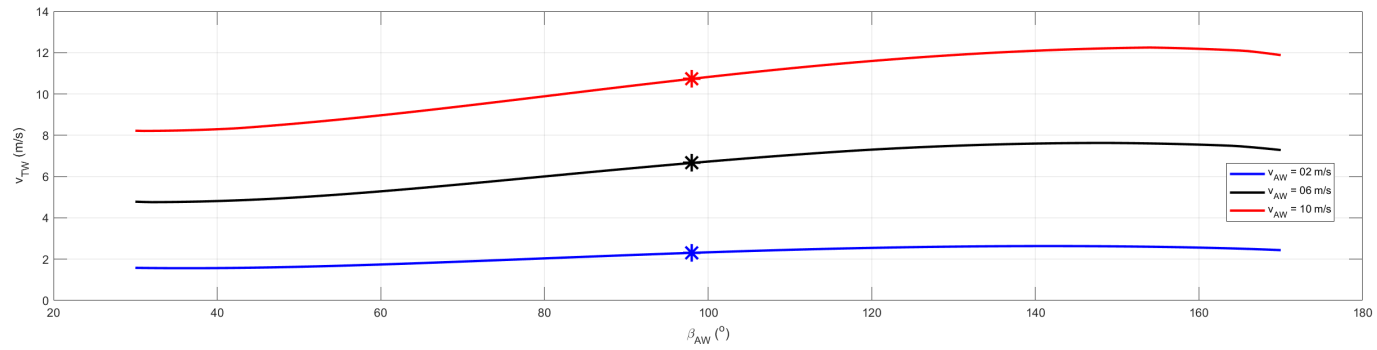

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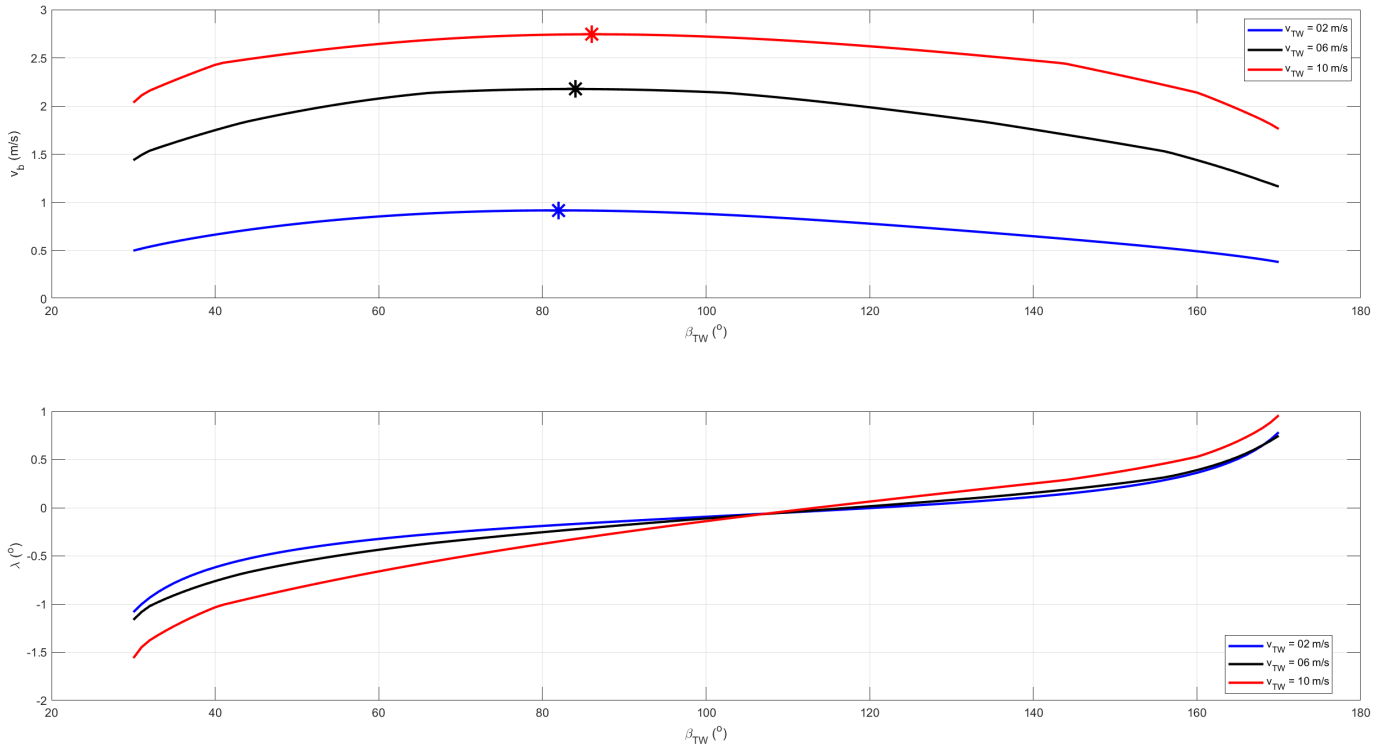
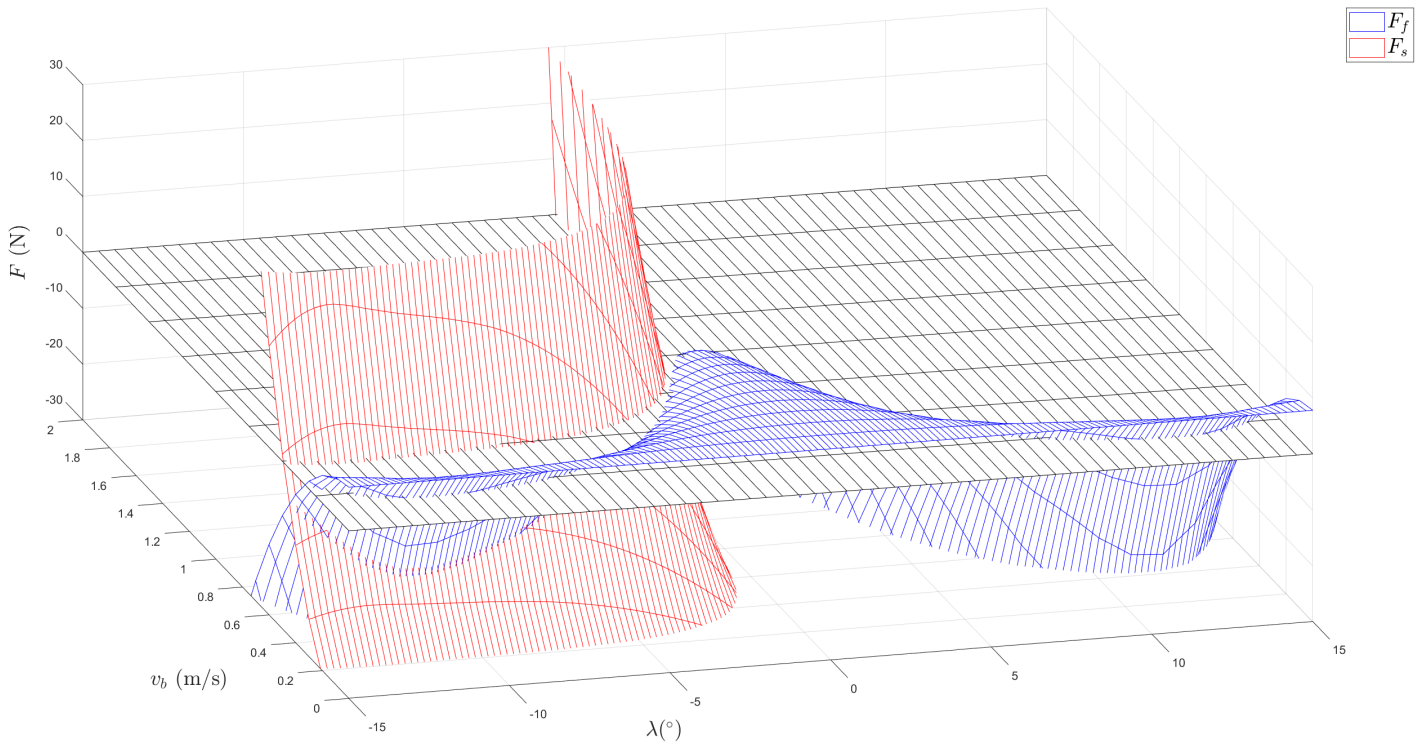


NUMERICAL CHALLENGES: $\beta_{\text{AWA}} = 20°$



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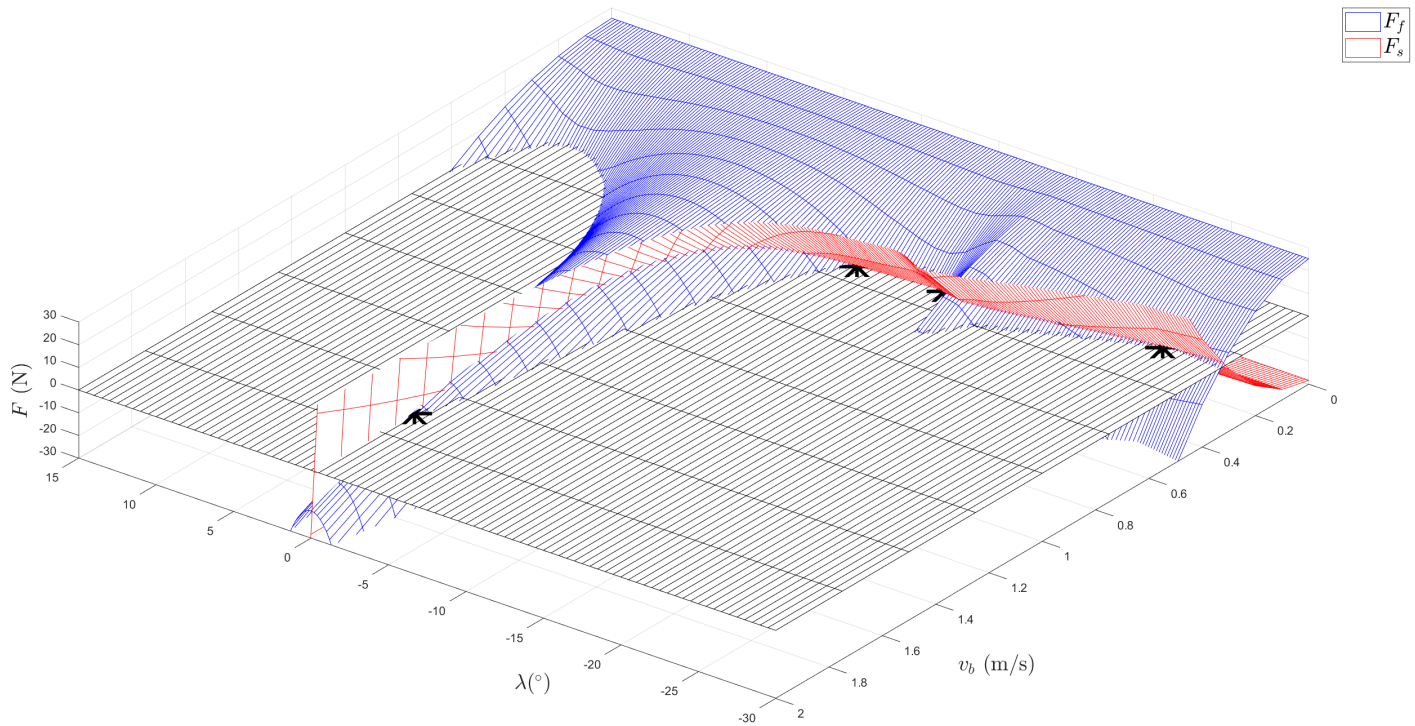
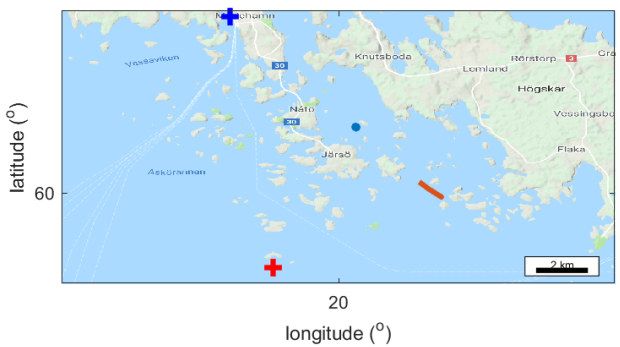
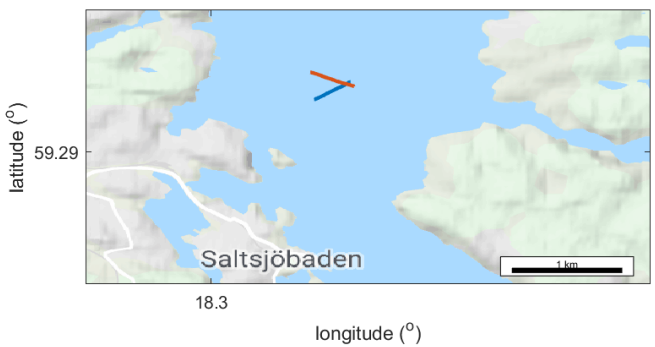
NUMERICAL CHALLENGES: $\beta_{\text{AWA}} = 50°$



EXPERIMENTS





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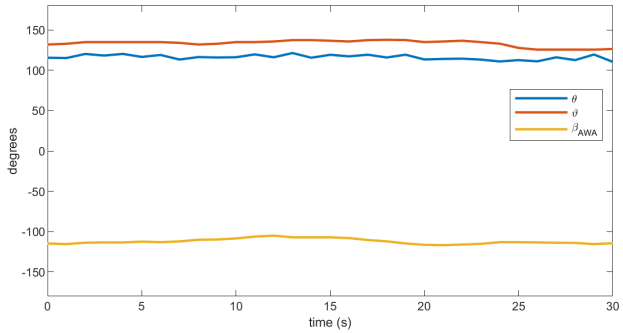
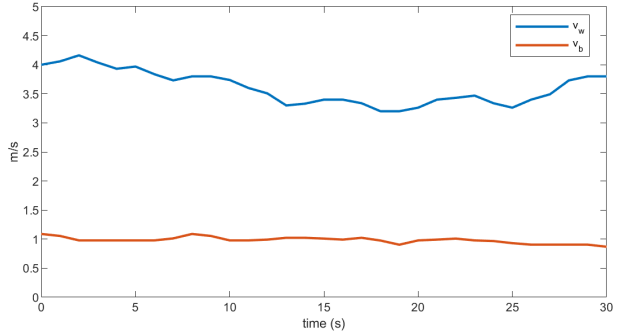
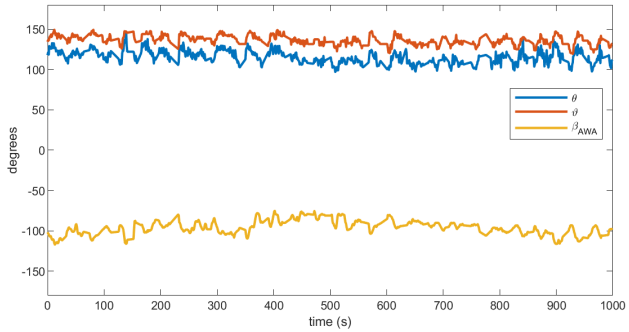
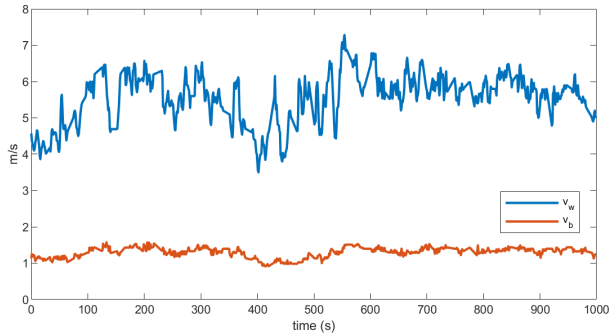
ASPIRE DATA









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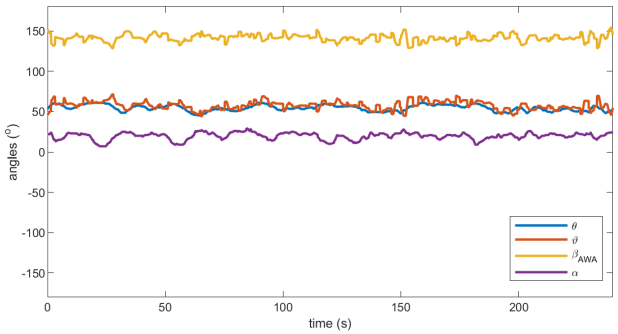
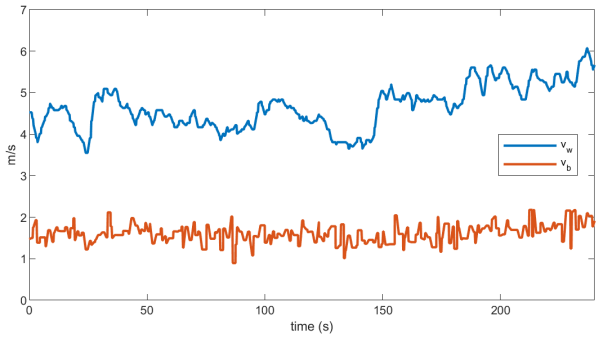
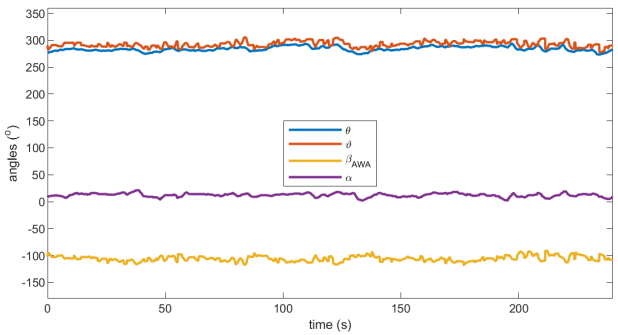
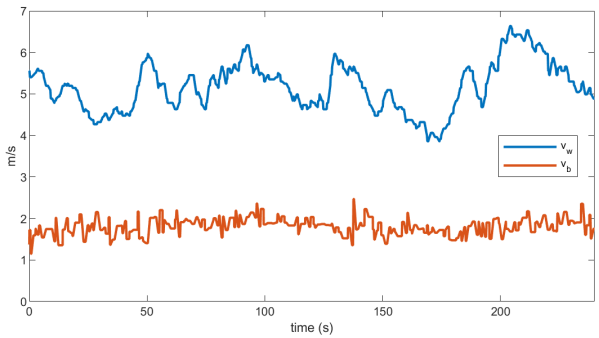
MARIBOT VANE DATA









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SOLVING

$\theta(^\circ)$	$\vartheta(^\circ)$	$\beta_{\text{AWA}}(^\circ)$	v_{AW} (m/s)	$\alpha(^\circ)$	v_b (m/s)	$\hat{v}_b$ (m/s)	$\lambda(^\circ)$	$\hat{\lambda}(^\circ)$	R_F (N)
116.0	133.3	-112.0	3.6	15.0	1.0	*1.5*	-17.3	*-0.0*	9.8
114.9	136.3	-95.8	5.5	15.0	1.3	*2.0*	-21.4	*0.1*	9.4
248.2	258.4	-63.8	5.4	10.7	1.6	*1.9*	-10.2	*0.2*	15.1
54.4	57.7	141.3	4.7	15.0	1.6	*1.6*	-3.3	*0.2*	7.9
154.7	161.8	35.8	6.2	15.0	1.0	*1.3*	-7.1	*-0.9*	3.4
283.9	292.5	-105.8	5.2	12.2	1.8	*1.9*	-8.6	*-0.0*	17.6
113.0	119.4	80.6	6.6	15.0	1.8	*2.2*	-6.4	*-0.2*	8.9
321.9	327.6	-142.0	3.9	10.3	1.2	*1.4*	-5.7	*-0.2*	9.2

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SOLVING

$\lambda(^\circ)$	v_b (m/s)	$\beta_{\text{AWA}}(^\circ)$	v_{AW} (m/s)	$\alpha(^\circ)$
-17.3	*0.0002*	-112.0	*0.0028*	15.0
-21.4	*0.0001*	-95.8	*0.0019*	15.0
-10.2	*0.0001*	-63.8	*0.0020*	10.7
-3.3	*0.0002*	141.3	*0.0048*	15.0
-7.1	*0.0000*	35.8	*0.0034*	15.0
-8.6	*0.0001*	-105.8	*0.0023*	12.2
-6.4	*0.0004*	80.6	*0.0045*	15.0
-5.7	*0.0009*	-142.0	*0.0098*	10.3

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SOLVING

$\lambda(^\circ)$	v_b (m/s)	$\beta_{\text{AWA}}(^\circ)$	v_{AW} (m/s)	$\alpha(^\circ)$
-17.3	1.0	*49.9469*	*11.2544*	15.0
-21.4	1.3	*53.7785*	*17.0194*	15.0
-10.2	1.6	*-137.5566*	*21.1565*	10.7
-3.3	1.6	*34.4756*	*13.1014*	15.0
-7.1	1.0	*52.5021*	*11.3502*	15.0
-8.6	1.8	*-144.1916*	*21.6750*	12.2
-6.4	1.8	*49.5053*	*19.6090*	15.0
-5.7	1.2	*-160.0588*	*12.0018*	10.3

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Optimizing

$$V(x) = c(F_{f,a} + F_{f,h})^2 + (1-c)(F_{s,a} + F_{s,h})^2 \tag{8}$$

$\lambda(^\circ)$	v_b	$\hat{v}_b$ (m/s)	$\beta_{\text{AWA}}(^\circ)$	v_{AW} (m/s)	$\alpha(^\circ)$	$1 - V(x)/V_0(x)$	R_F
-17.3	1.0	*0.2*	-112.0	3.6	15.0	*0.9926*	*0.6*
-21.4	1.3	*0.3*	-95.8	5.5	15.0	*0.9900*	*0.4*
-10.2	1.6	*0.2*	-63.8	5.4	10.7	*0.9958*	*0.3*
-3.3	1.6	*0.0*	141.3	4.7	15.0	*0.9854*	*0.0*
-7.1	1.0	*0.5*	35.8	6.2	15.0	*0.9861*	*1.0*
-8.6	1.8	*0.4*	-105.8	5.2	12.2	*0.9986*	*0.8*
-6.4	1.8	*0.6*	80.6	6.6	15.0	*0.9957*	*0.8*
-5.7	1.2	*0.4*	-142.0	3.9	10.3	*0.9986*	*0.9*

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OPTIMIZING

$\lambda(^\circ)$	v_b (m/s)	$\beta_{\text{AWA}}(^\circ)$	v_{AW} (m/s)	$\alpha(^\circ)$	$\hat{\alpha}(^\circ)$	$1 - V(x)/V_0(x)$	R_F
-17.3	1.0	-112.0	3.6	15.0	*11.3*	*0.0347*	*9.3*
-21.4	1.3	-95.8	5.5	15.0	*11.1*	*0.0372*	*9.0*
-10.2	1.6	-63.8	5.4	10.7	*10.7*	*0.0000*	*15.1*
-3.3	1.6	141.3	4.7	15.0	*90.0*	*0.4256*	*3.5*
-7.1	1.0	35.8	6.2	15.0	*11.6*	*0.0794*	*3.2*
-8.6	1.8	-105.8	5.2	12.2	*11.4*	*0.0001*	*17.6*
-6.4	1.8	80.6	6.6	15.0	*15.8*	*0.0014*	*9.1*
-5.7	1.2	-142.0	3.9	10.3	*11.6*	*0.0042*	*9.0*

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MODEL-BASED DIAGNOSTICS

1. Heading measurements are unreliable.
2. Measurements of course over ground are unreliable.
3. Measurements of course over ground do not correspond to course over water.
4. The model underestimates leeway.

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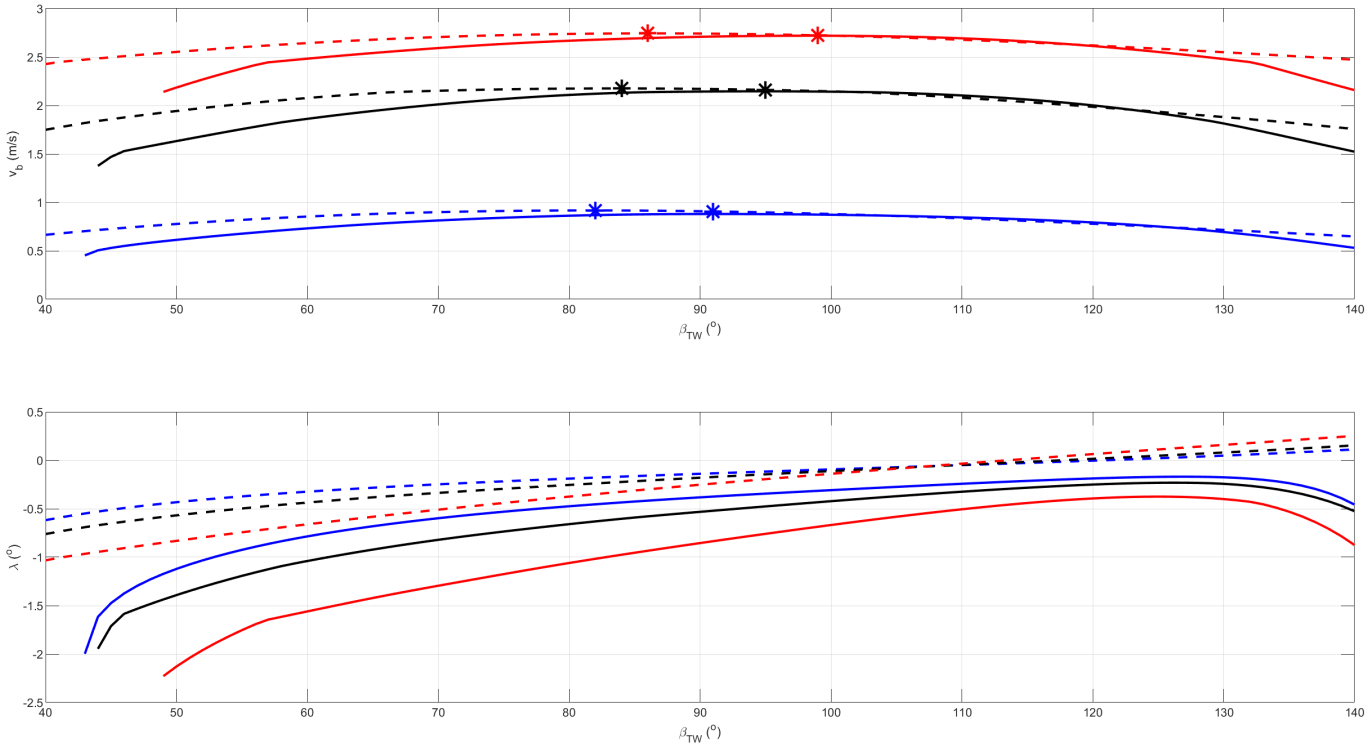
MODEL DEVELOPMENT



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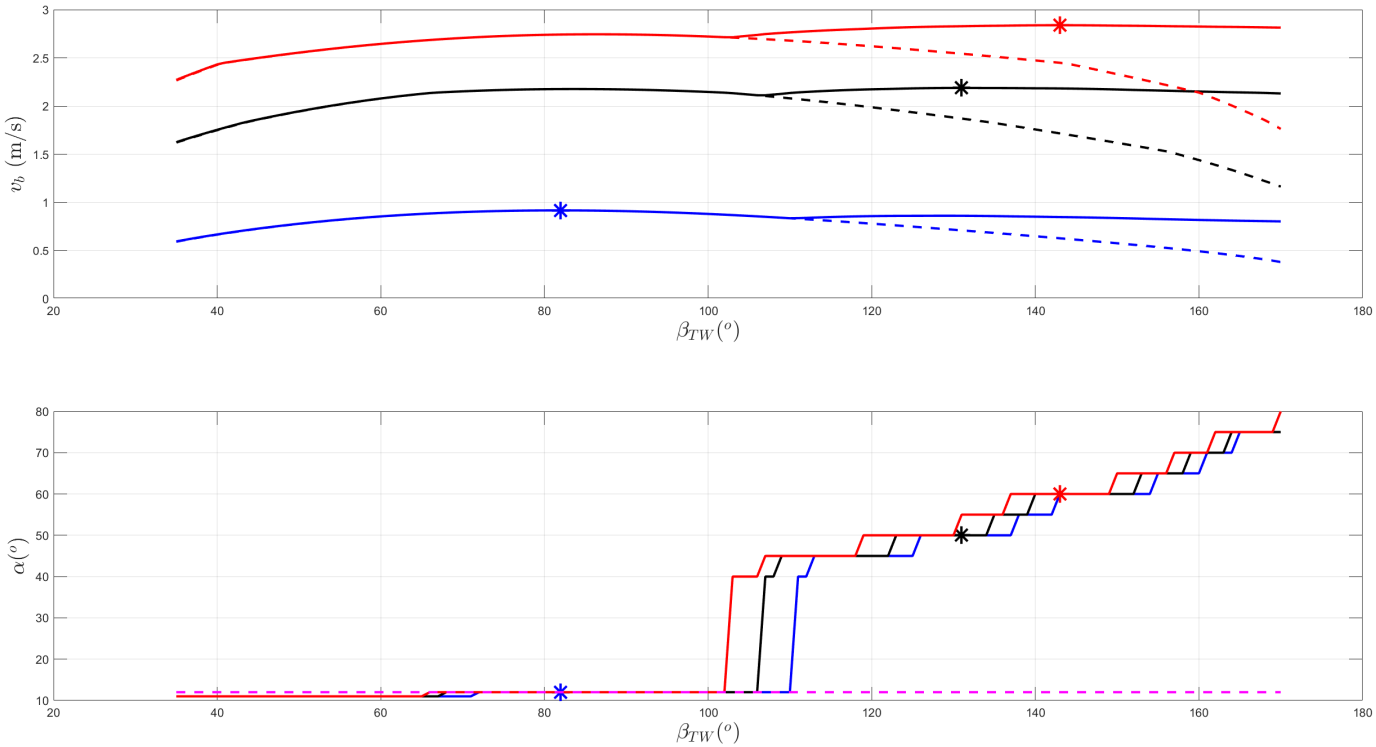
MODEL EXPLORATION



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What and Why?

- Basic physics, simple model, computational strategy.
- Differences in perspectives between on-shore planning and design on the one side, and on-board evaluation on the other.
- Predict sailing speed.
- A tool for monitoring performance, detecting unreliable sensors, evaluating changes in design and assessing model development.

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