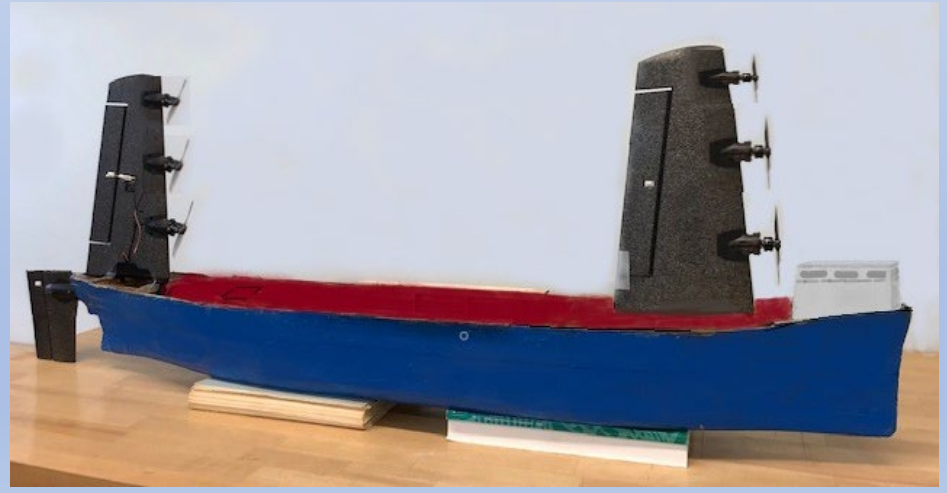
A second look at the Propeller Sail: a new high-lift wing for sailing cargo ships using distributed, wing-mounted propellers

Sergio E. Perez, Lubomir A. Ribarov

USMMA Department of Marine Engineering

perezs@usmma.edu



Huge sailing ships with huge sails ideal, but…

- Mast heights of 90 m+
- Sails can obstruct cargo operations
- Smaller sails as auxiliary propulsion to engine power will be important
- Powered high-lift devices (Flettners and suction sails) can produce lift coefficients much higher than conventional wings, permtting smaller wings
- BUT…….

But…: Penalty for high lift: **Induced drag goes through the roof at high lift coefficients:**

NASA Langley Public Domain photo

- $Cd_i = \frac{(\mathrm{Cl})^2}{\pi\ e\ AR}$

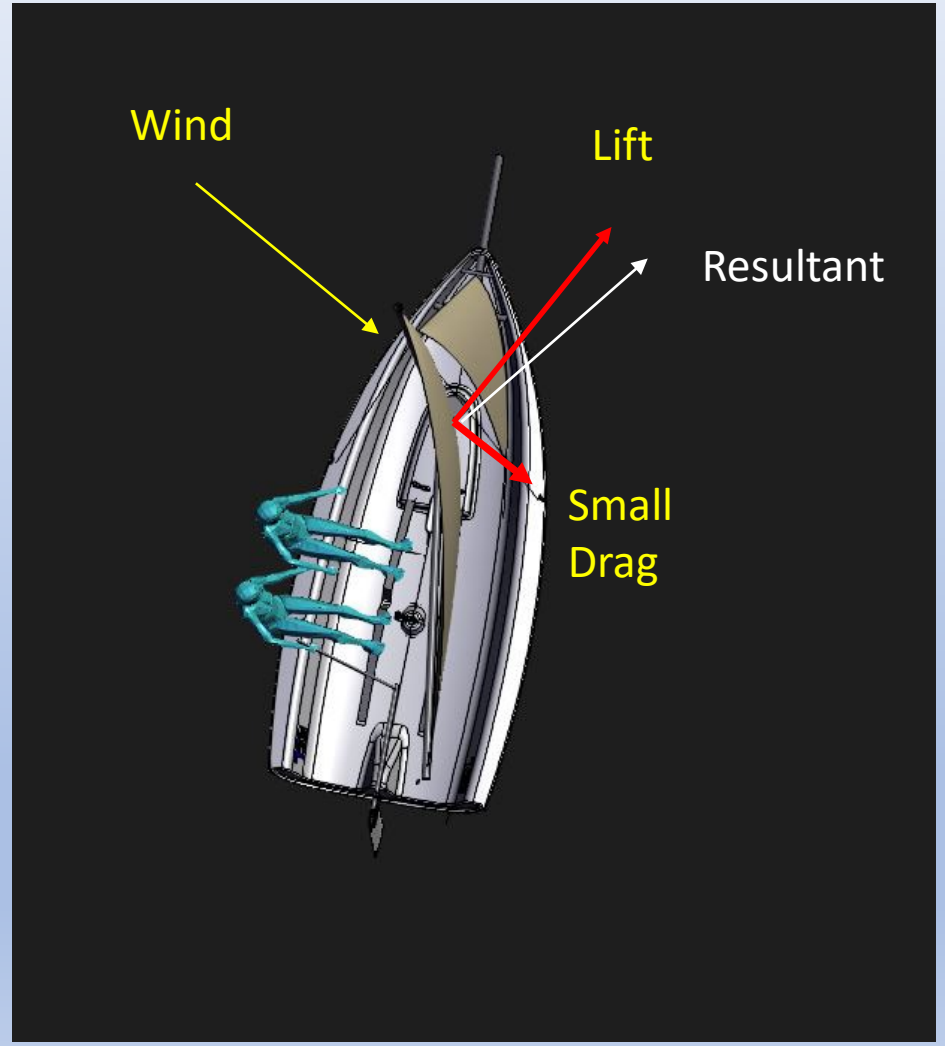
Lift coefficient

Induced drag coefficient

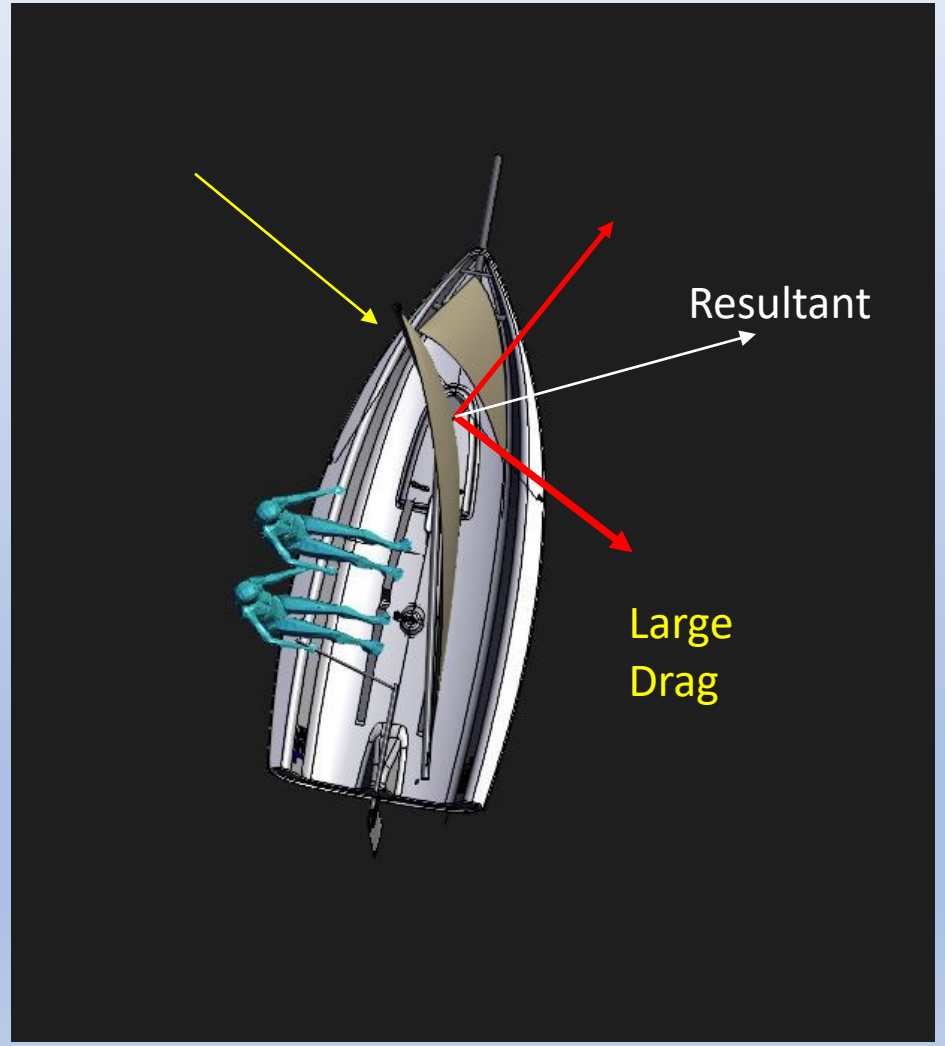
- When Cl goes from about 1 (normal sail) to 5 (or more with high-lift devices) Cd_i goes up by 25 times.

What's so bad about high drag?

Low Drag Sail



High Drag Sail



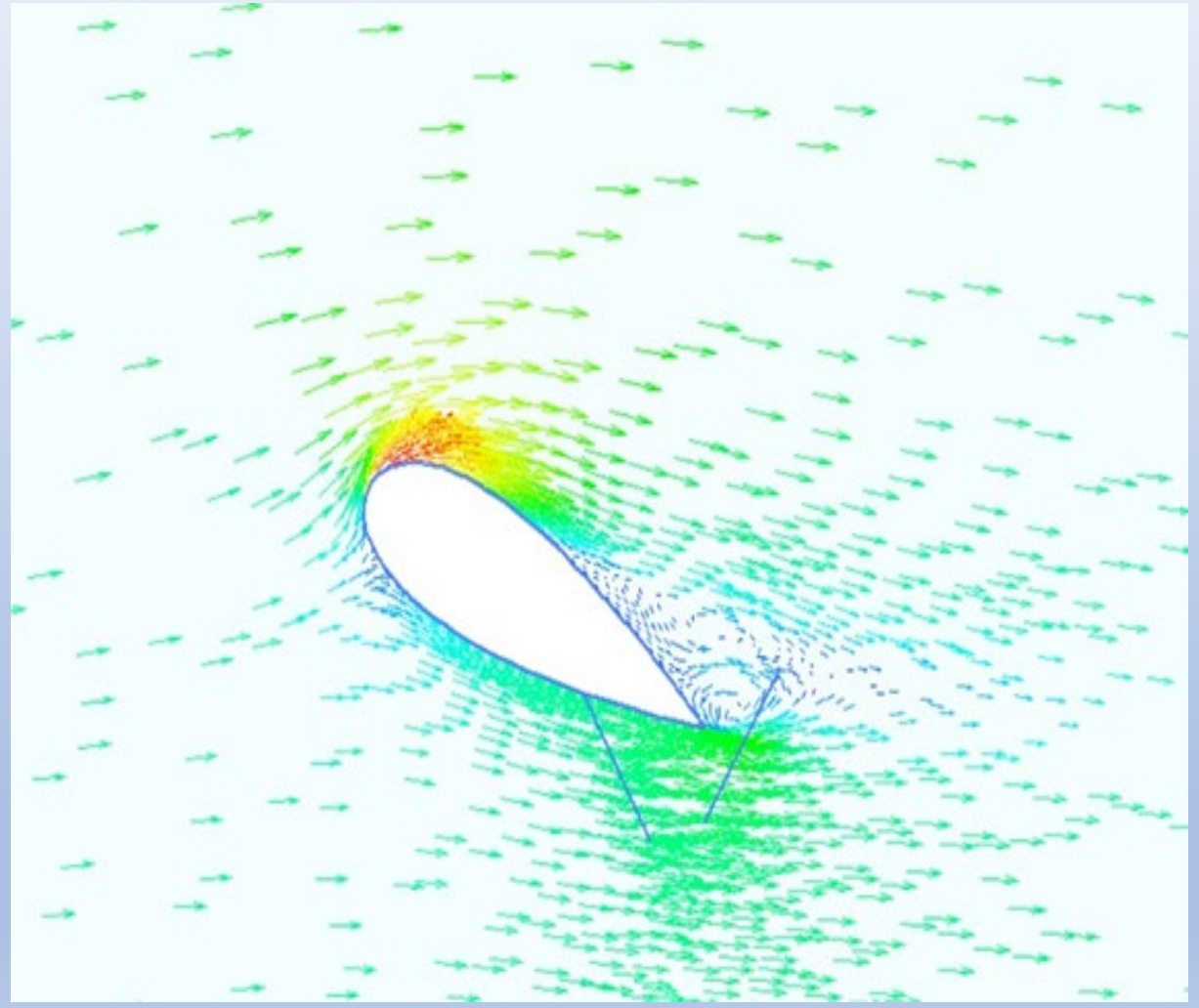
A possible solution:

- Snyder (1967), Sinnige (2018): mount propellers on wingtips (contra-vortex).
- 50% induced drag reduction at lift coefficients of 0.7, compared to mounting propellers more inboard

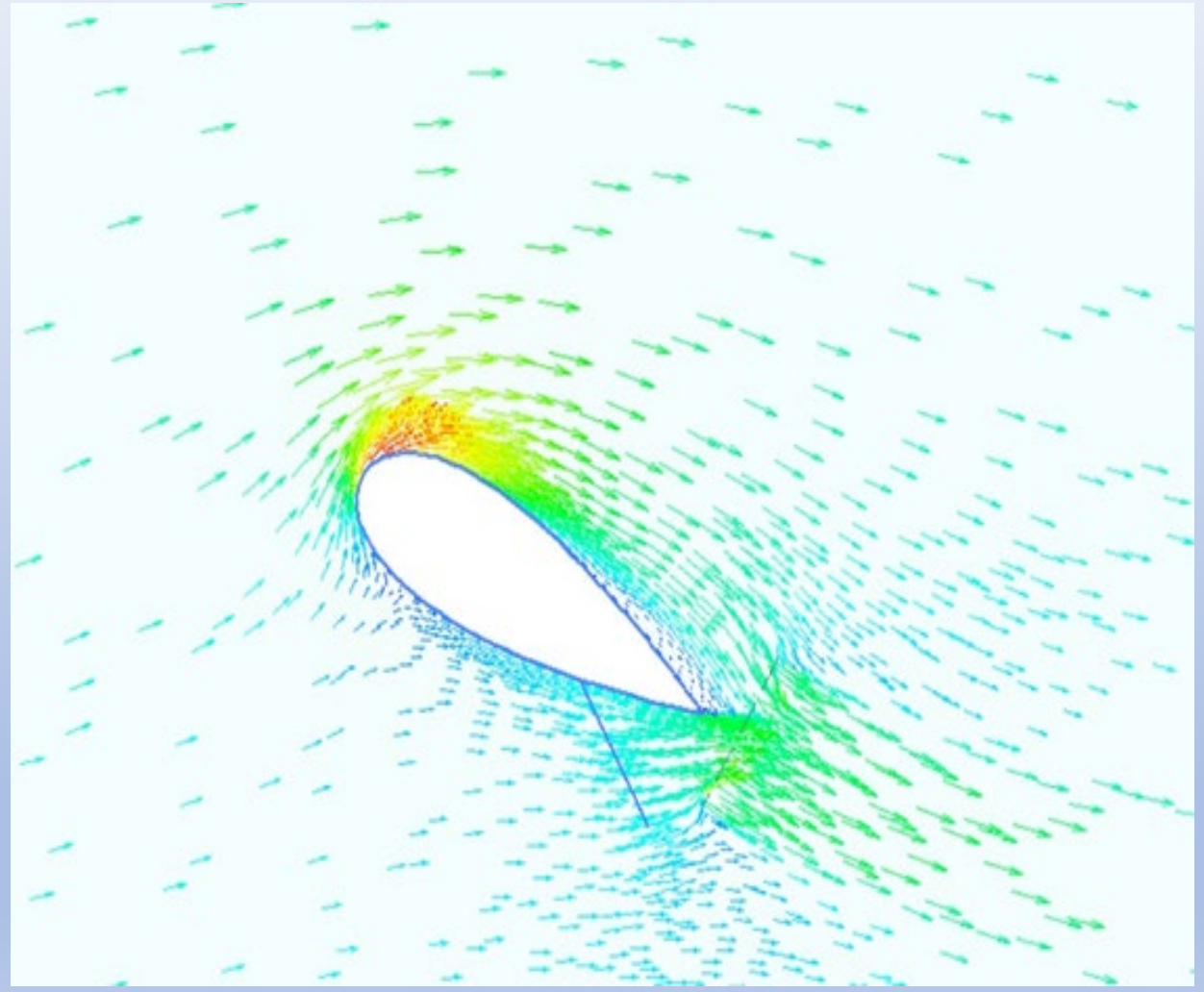
NASA X-57 with distributed electric motors and contra-vortex propellers on wingtips

How does the Propeller Sail work?

1) Propeller allows boundary layer to remain attached. Wing can be used at higher angles of attack.



Propeller not activated.. Note separation. Low lift.

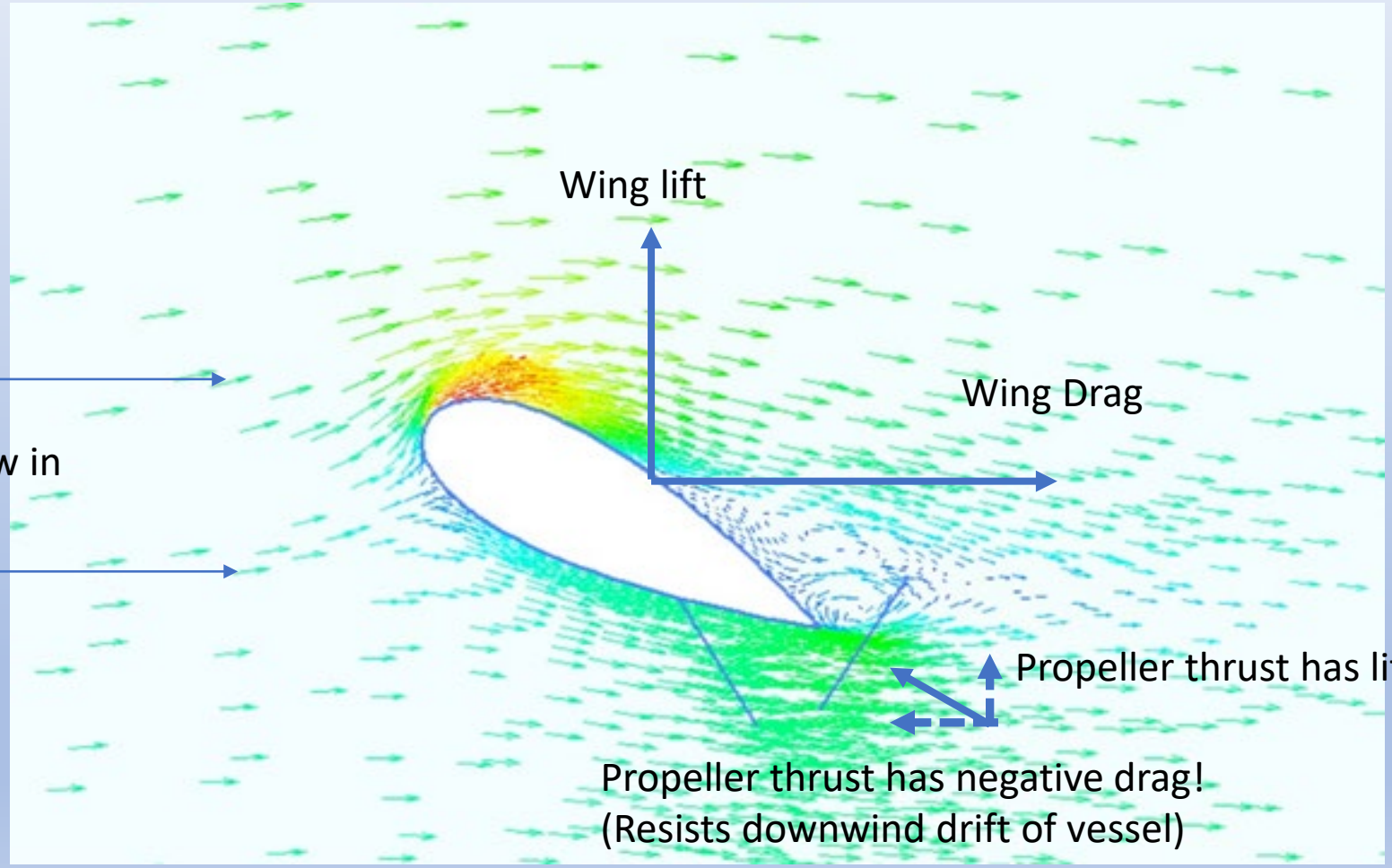


Propeller activated.. Separation greatly reduced. Higher lift.

How Propeller Sails work, continued

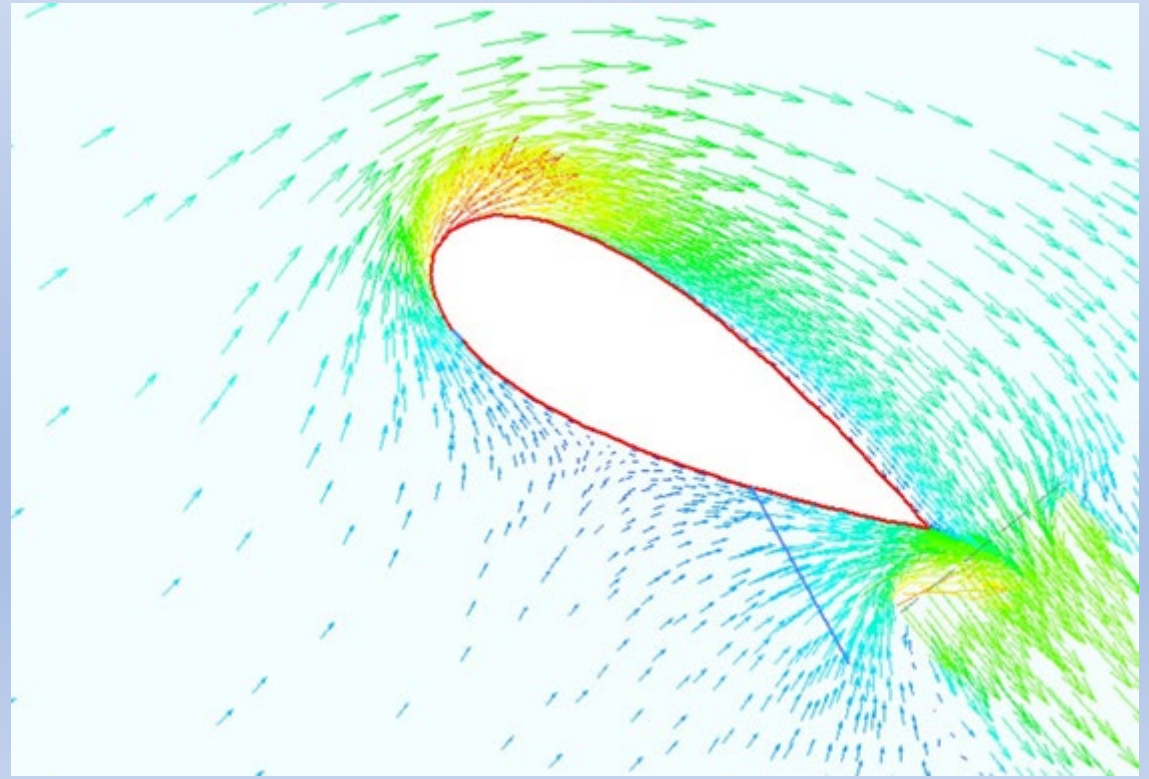
2) By increasing the flow velocity over the wing since: Lift increases with the square of the air velocity

3) Propeller creates a thrust with a lift component



RESULTS OF 2-DIMENSIONAL COMPUTATIONAL FLUID DYNAMICS (Preliminary Results)

20,000 cells allowed quick prediction of general trends (seconds)



But cannot account for wingtip vortices (3-dimensional phenomenon)

Propeller simulated as linear actuator disc (no rotation)

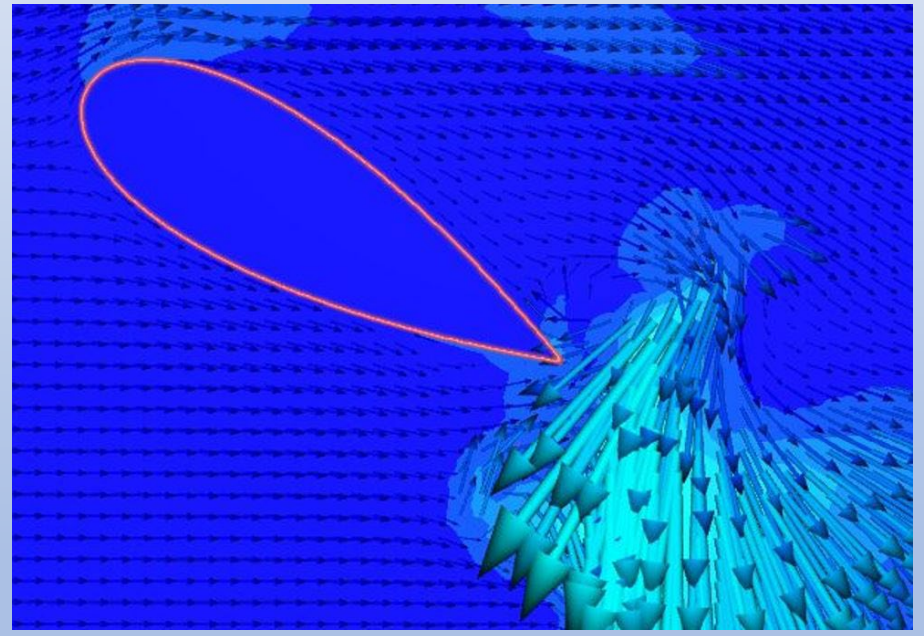
Preliminary findings from 2-dimensional CFD (Jan – May)

- Propeller thrust increases lift and reduces downwind drift
- Huge lift coefficients possible, given enough power
- Using a flap with Propeller Sail increases lift but drag penalty may be too large
- Mounting propeller on trailing edge of wing appears to be better
- Tilting the propeller slightly down appears to increase lift markedly with relatively small increase in drag.

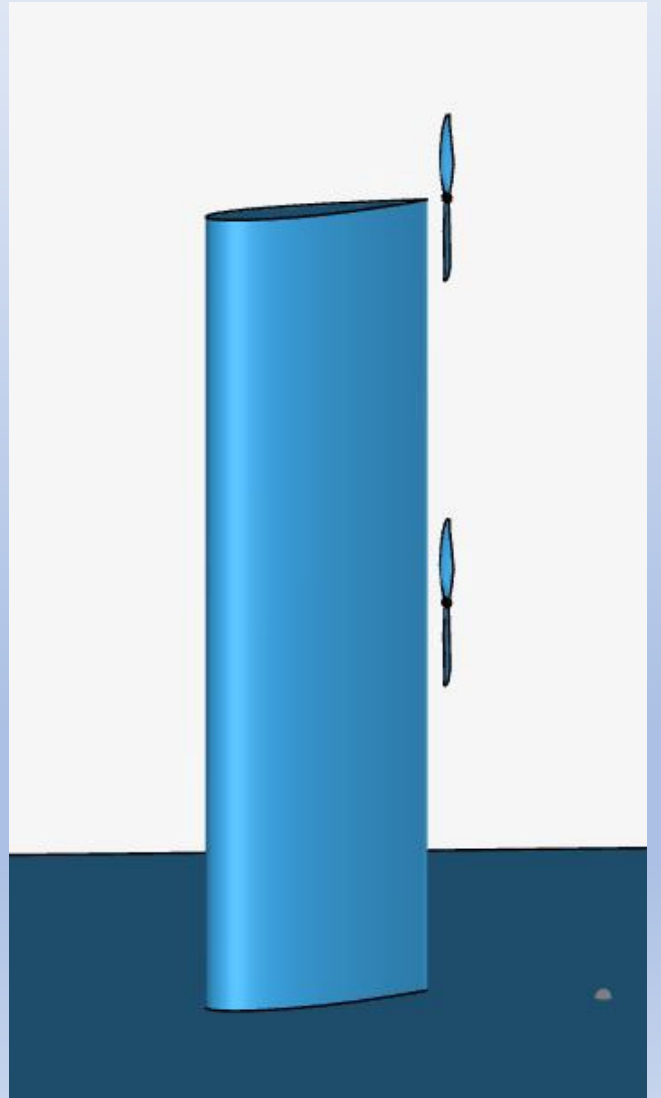
RESULTS OF VERY LIMITED 3-DIMENSIONAL COMPUTATIONAL FLUID DYNAMICS with SimScale (June-present)

Tested only 30 degree angle of attack, NACA 0030 airfoil, 20 degree propeller downward tilt

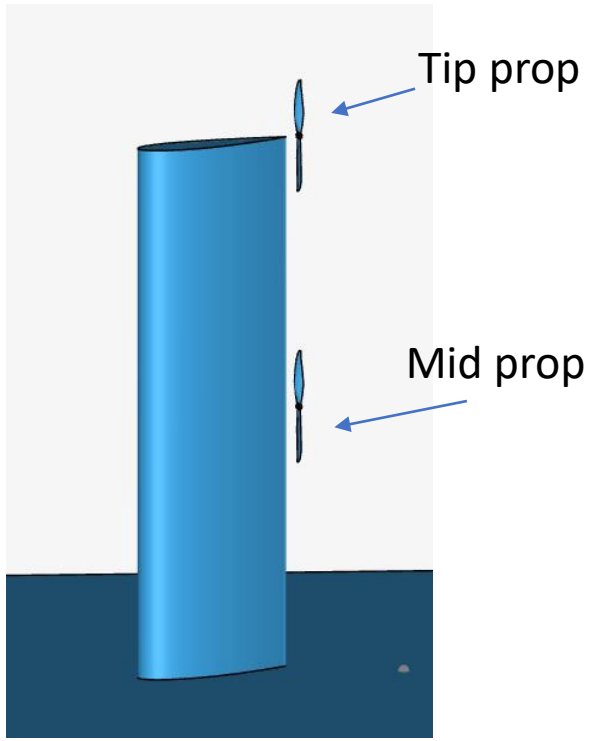
13.1 million cells

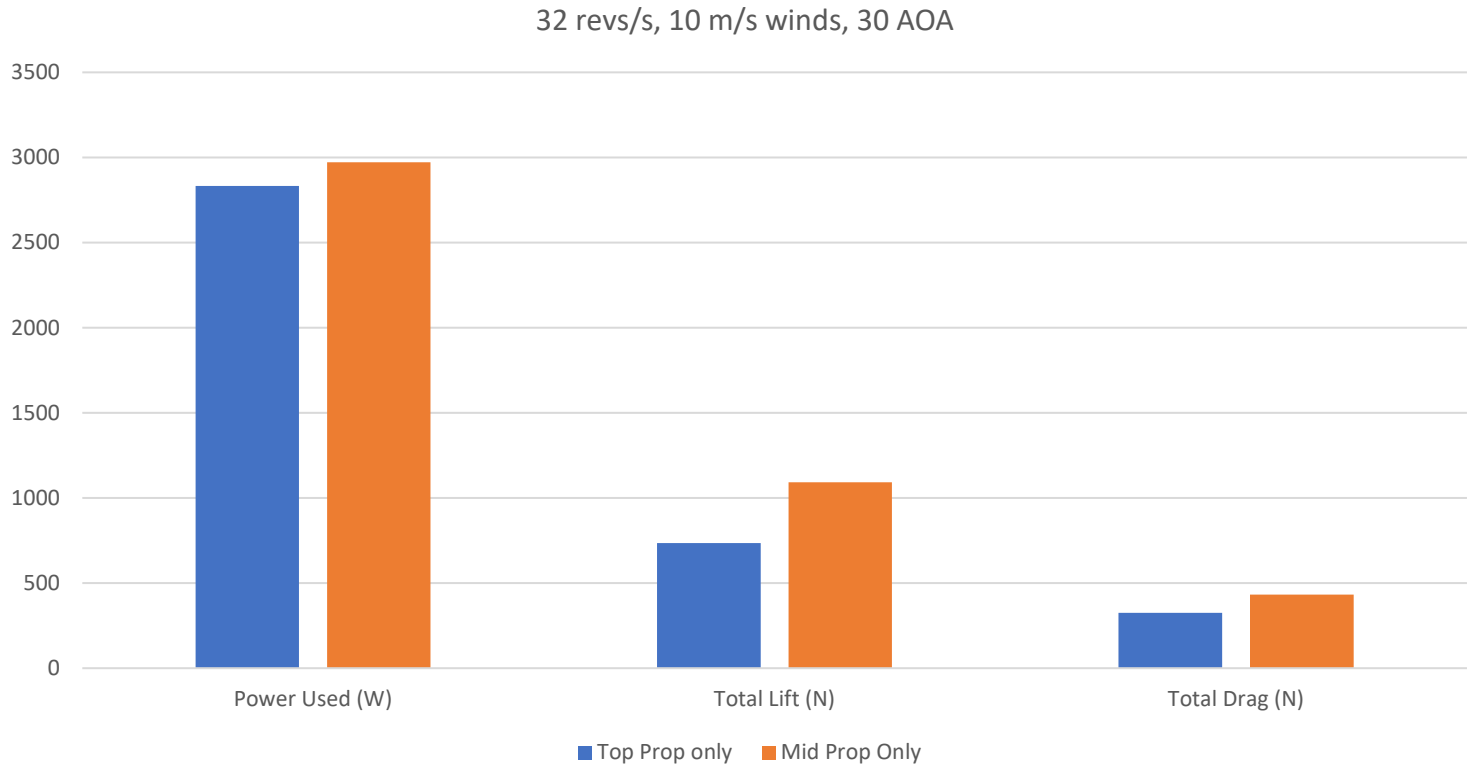


Rotating propeller accounted for in 3D



If using one propeller only: is it better to mount the propeller at the wingtip or mid-wing?

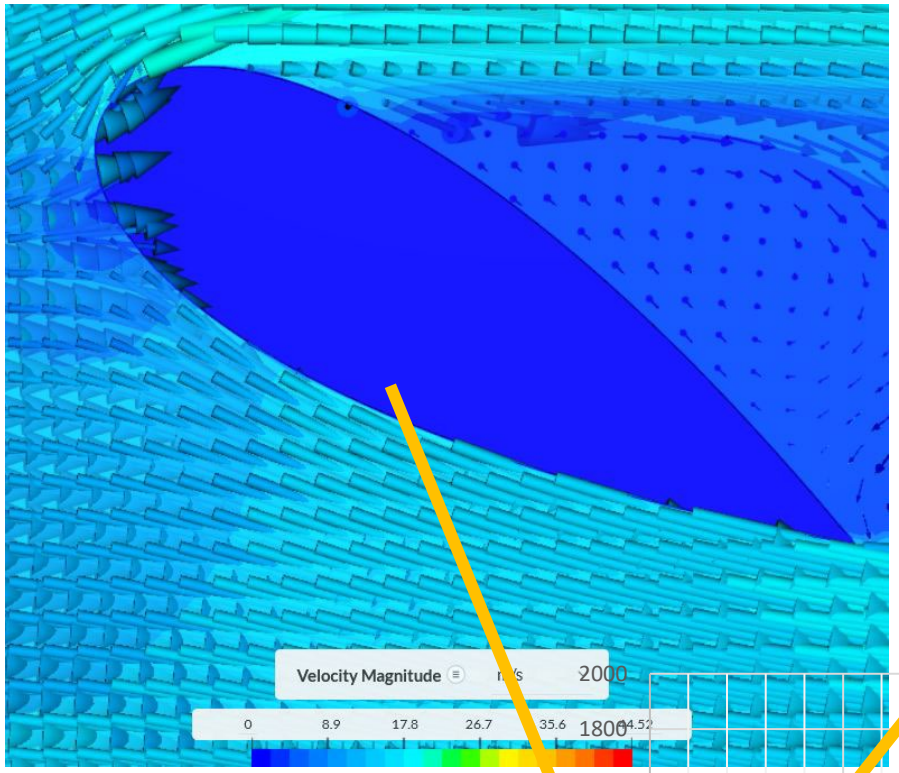


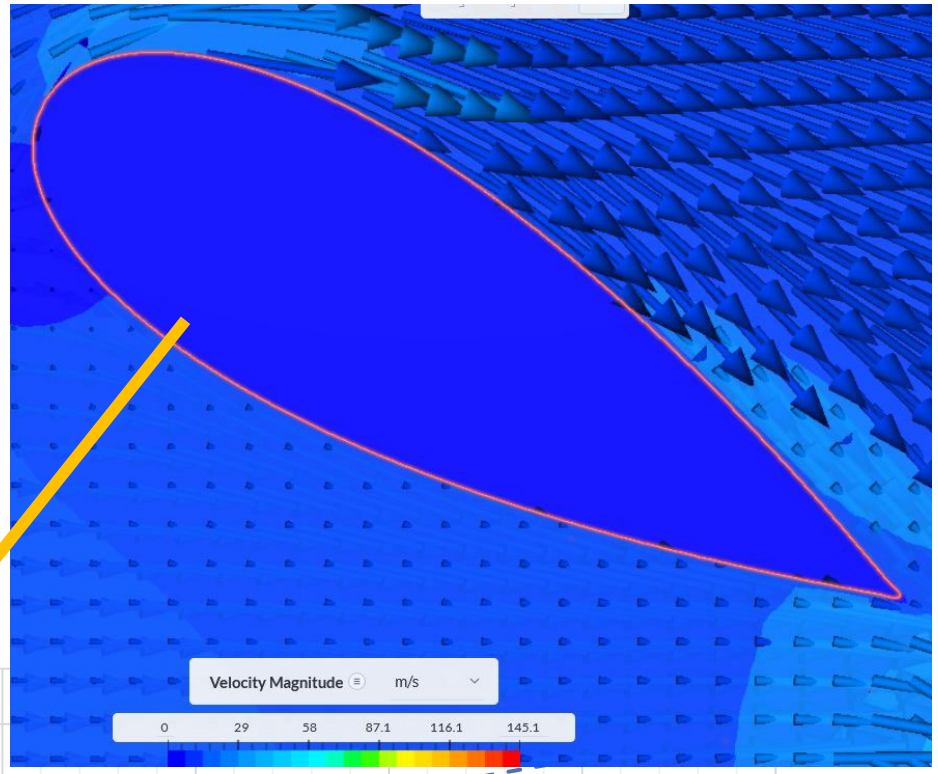


L/D ratio: Tip Mounted 2.25, Mid Mounted: 2.52

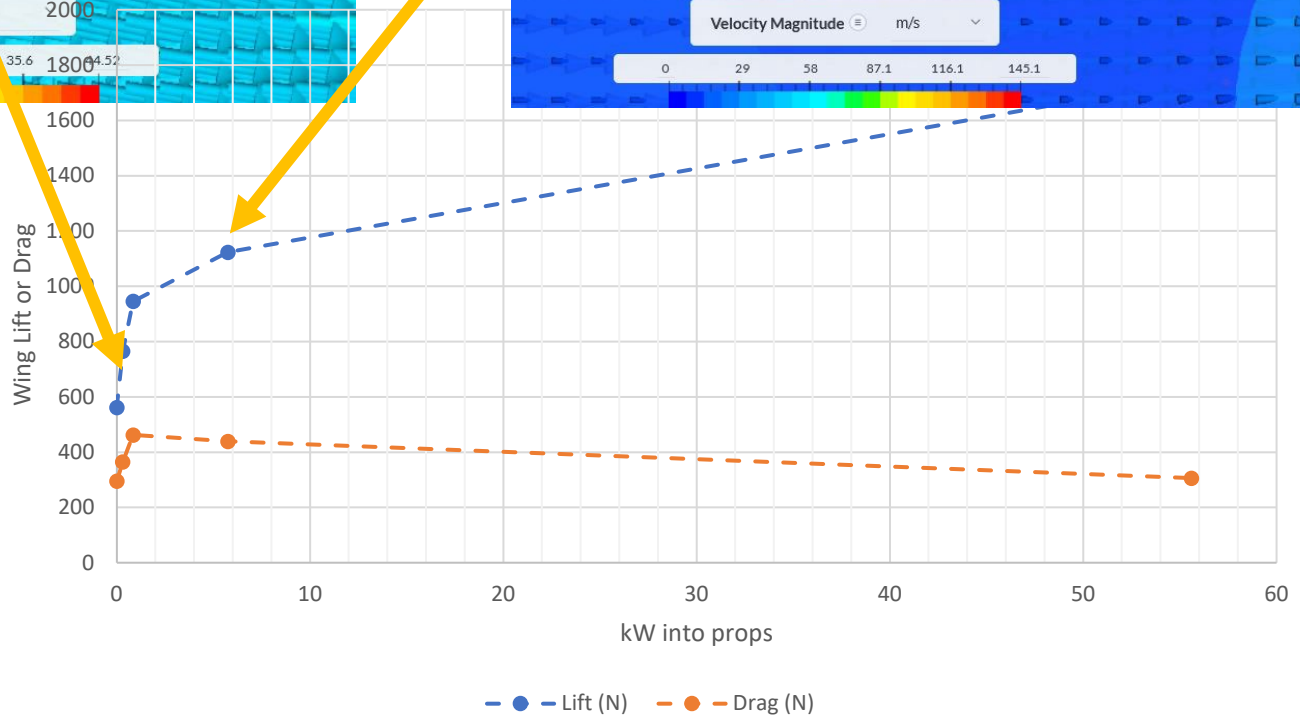
It appears that no advantage to wingtip mounting, as tested.

<u>RESULTS, TWO PROPELLERS TOGETHER</u>: 30 degree wing angle of attack, wind speed = 4 m/s . Two propellers on the wing .



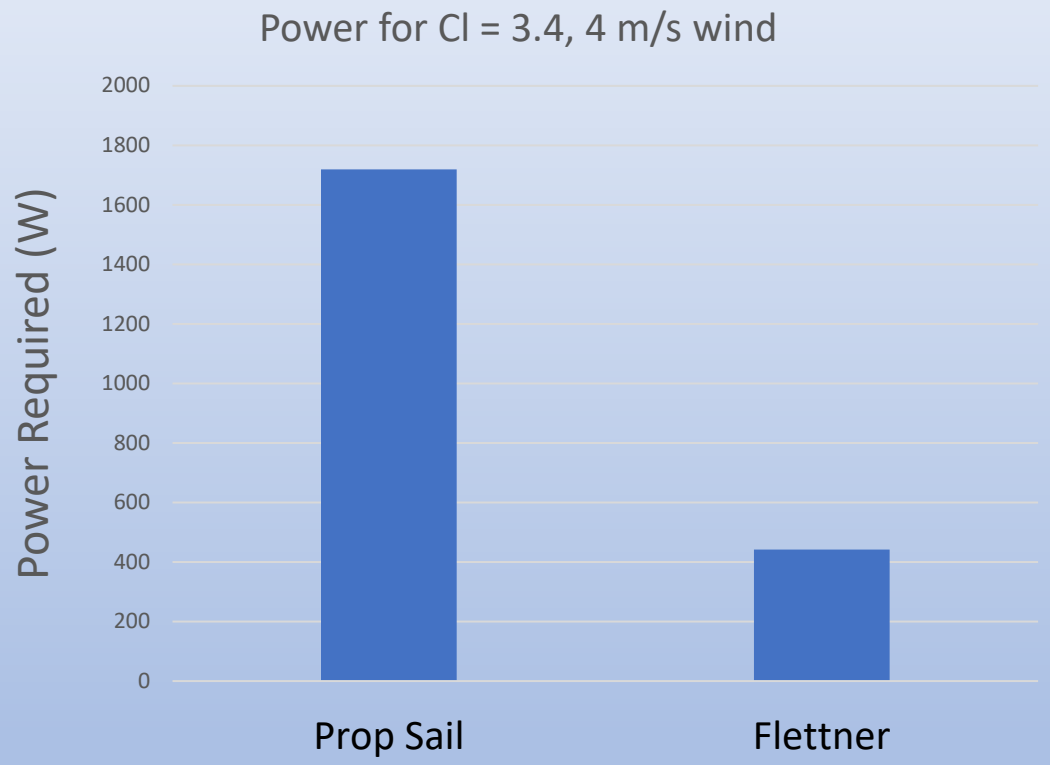


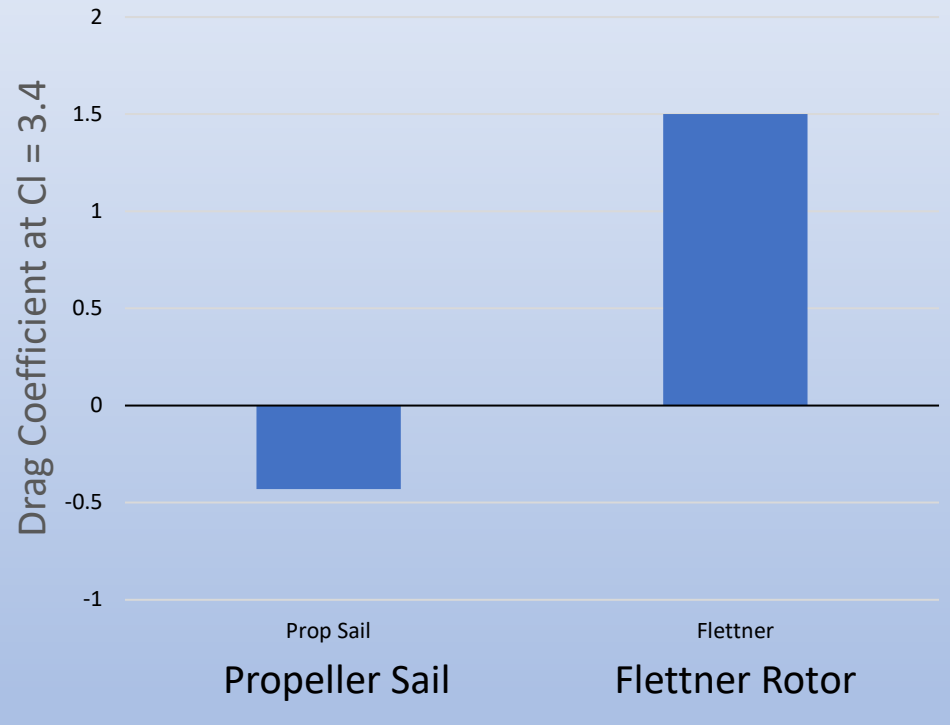
Low propeller power settings



Higher propeller power setting

Comparison with Flettner Rotors at Cl = 3.4, 4 m/s winds





RADIO CONTROL MODEL TESTING

Tested at Oyster Bay Center Island Beach and in Eisenhower Park lake.

Purpose of tests was modest since rig had never been tested by anyone.

TEST RESULTS

- Ship model can stably move in any direction into the wind
- Rudder control was effective
- Ship model sailed quite well with and without the propeller activated.
- In pure sailing, activation of motor increased sailing speed
- No de-stabilizing list

VIDEOS

- Downwind run with low power on https://youtu.be/ofmo3aFl0nc
- Moving directly into wind at low power, followed by downwind turn: https://youtu.be/D13Rzl8eIHI
- List when high power is applied while sailing downwind: https://youtube.com/shorts/bO34Hl8lSBo
- Two laps in light winds using two levels of power: https://youtu.be/MuRGIxDHTfU

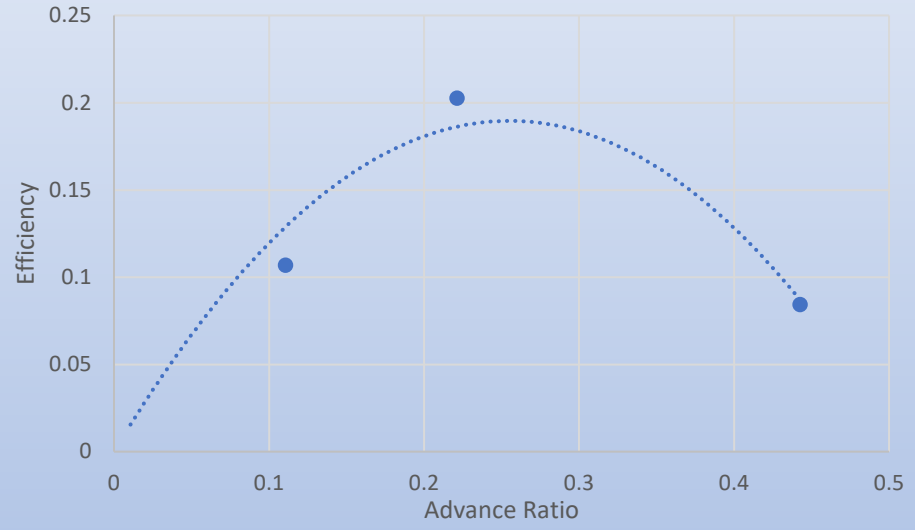
THERE IS STILL A LOT TO LEARN ABOUT THIS IDEA (great thesis topic):

- Limited testing done. Can we get the power down?
- As tested, there appeared to be no advantage to mounting one propeller at tip. Does this mean the contra-vortex concept won't work?
- Can we mitigate or even eliminate downwind drift with the propellers? Can the propellers be used to limit ship rolling?
- Try smaller propellers, other airfoil shapes, tilt angle of propellers
- Use instead of bow and stern thrusters?
- Eliminate ship's engine entirely?

Thank you for attending.

Calculating Propeller efficiency

Simscale gives torque and force on propellers in three dimensions, allowing calculation of thrust, power and torque coefficients, as well as efficiency of the propeller.



The efficiency is very low. The propeller was a “stock” 3D model downloaded from an open-source site (GrabCAD), with no information about its design or even intended platform.

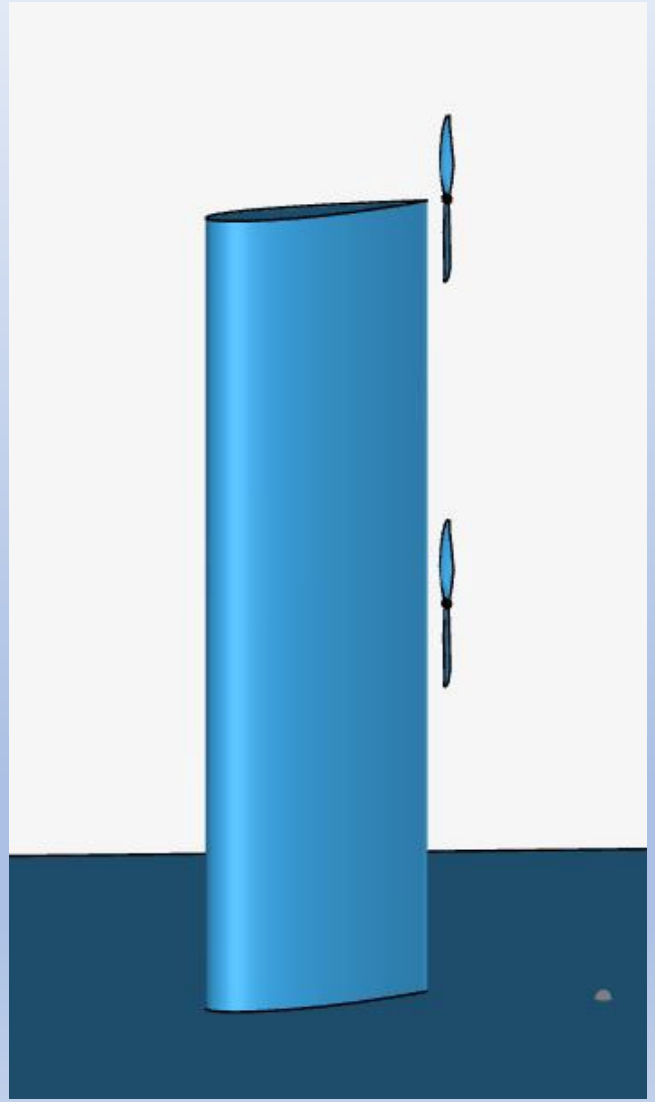
Shape of plot is correct, but propeller efficiencies of about 0.8 or more are possible.

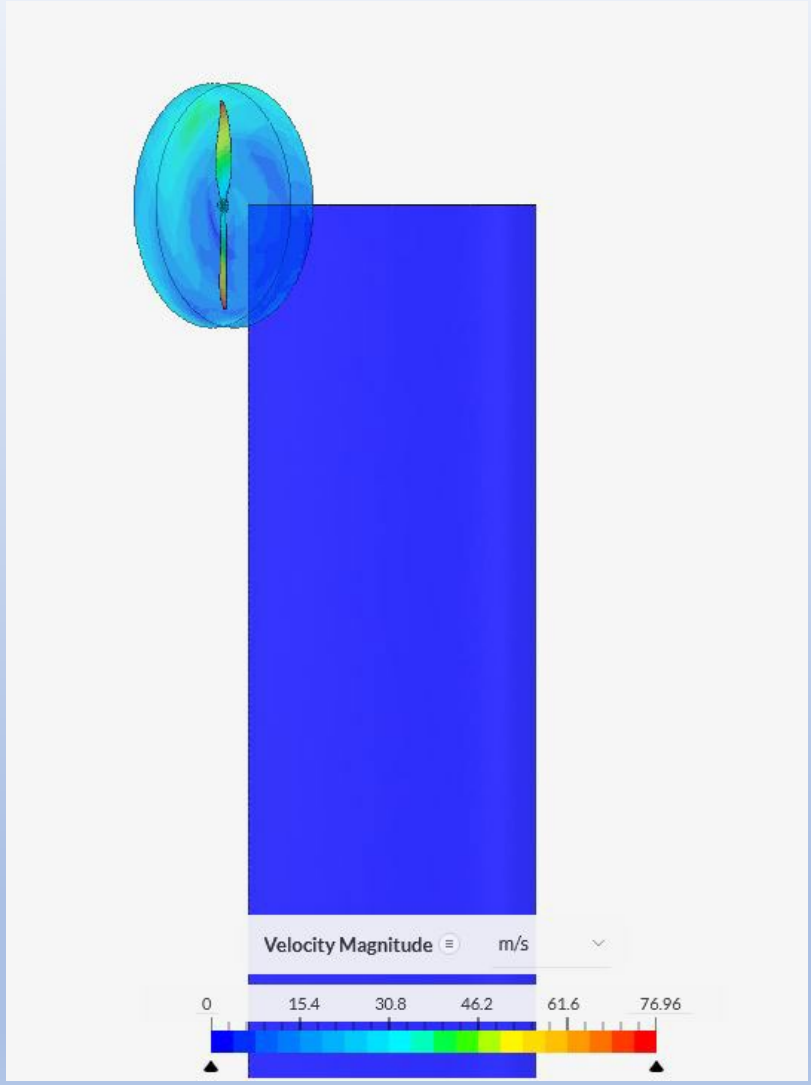
Sailing vessels much larger than the Preussen will be the ideal for near-future ships

Very limited testing conducted

Tested only one angle of attack, with NACA 0030 airfoil, at a variety of wind speeds

Tested only two propellers on the wing, as shown





MRF (Moving Reference Frame) region visible around prop. The prop is assumed to stand still, rotating flow imposed over propeller at user-specified rpm’s.

From a study done in 2021: it pays to use large sailing vessels with wind as primary power source (45,000 CDWT Dynarig bulk carrier)

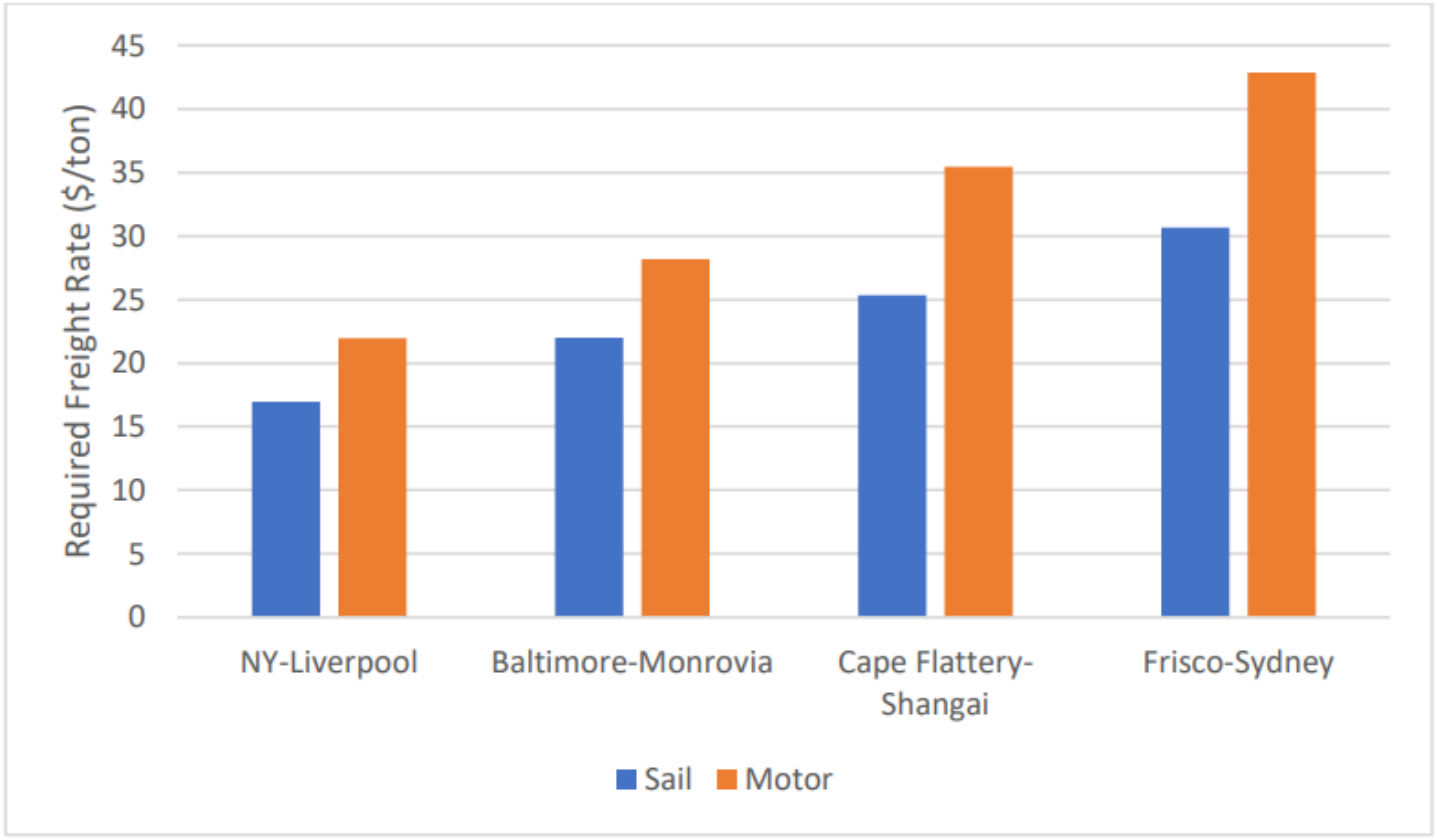
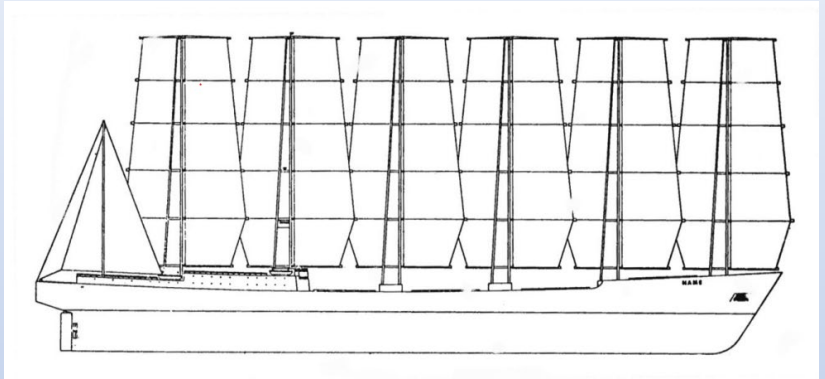


Figure 4c. 45 kDWT vessel Required Freight Rate (RFR)

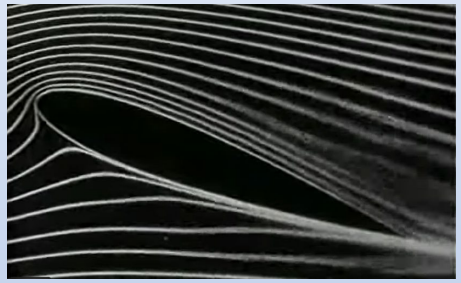


Source: Perez, S; Guan, C; Mesaros, A; Talay, A, Economic Viability of bulk cargo merchant sailing vessels, Journal of Merchant Ship Wind Energy, 17 August 2021.

Getting more lift with High-lift devices (powered)

- **Boundary Layer Suction**: Lift Coefficients 5 and greater. Normal sail about 1.

Suction off



Suction on

Images from National Science Foundation, Boundary Layer Control film
https://www.youtube.com/watch?v=w1Q6-NJPpkk

Econowind Suction Wing

Suction wing base

Images from tradewindnews.com (left) and https://northsearegion.eu/wasp/photo-gallery/ (right)

- **Flettner rotors**: spinning cylinder in wind causes pressure differential and lift. Lift coefficients 5 and greater

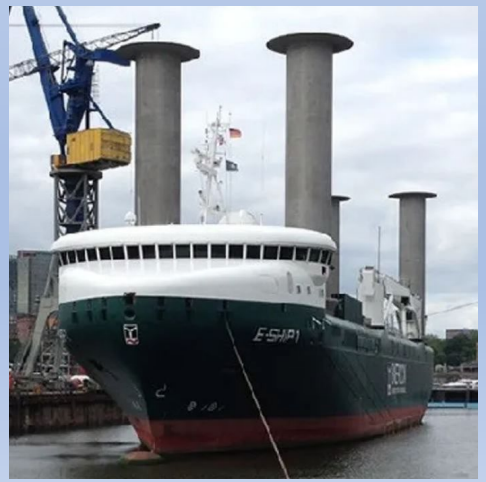


Image from interestingengineering.com