2023 Sustainability in Ship Design & Operations Conference

Flettner Rotor-Powered Marine Vessel – Design Evaluation and Systems Optimization

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Webb Institute

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Outline

- Motivation
- History and Background
- Sailing Rig
- Calculations
- Comparison to a Motor Ship
- Cargo Considerations
- Conclusions
- Future Work
- Acknowledgements

Motivation

- The global shipping industry faces significant challenges towards reduction of its environmental impact. At the current rate, it is expected that carbon dioxide (CO_2) emissions are projected to increase 50–250% by 2050
- Modern advances in conventional marine power (i.e., 2-stroke/4-stroke diesel engines) and propulsion systems and energy management improvements, have already significantly contributed to reducing both CO_2 and nitrogen oxides (NO_x) emissions from marine diesel engines

A containership emits a cloud of Diesel exhaust smoke when docking in the port of Hamburg*

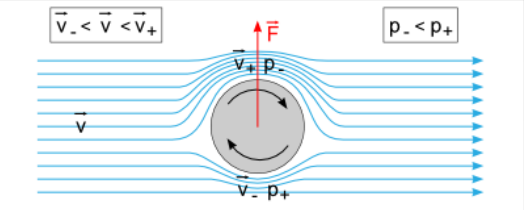
- Despite these stringent regulations, the propulsion and power generation plants for future ships must significantly reduce fuel consumption and emissions over the coming years
- The use of available wind power for merchant shipping has seen an increased interest due to rising fuel costs, ever-stringent environmental protection requirements (especially stringent in specific emission control areas, ECAs**), and resulting increased operational costs, etc.
- The purpose of this paper is to address a reduction of pollution from hydrocarbon (HC) emissions present in the exhaust of heat engine-powered merchant ships, specifically, during operations of such ships both near, and in port.
- The present research is focusing on the feasibility of the Flettner rotor –powered marine vessels, which could be used to reduce HC fuel consumption and exhaust emissions towards green (or “more-green”) energy technologies to be implemented in ship propulsion systems.

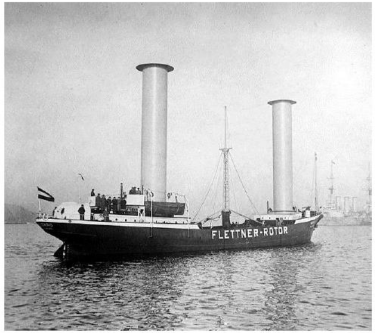
*“CO_2- Emissionen der Schifffahrt bisher stark unterschätzt”, (“CO_2 emisions from shipping have so far been greatly underestimated”) Greenpeace Redaktion, 13.02.2008 (based on article in The Guardian)

**ECAs – emission control areas can be designated for SOx, PM, or NOx (or all three types of emissions combined)

History and Background

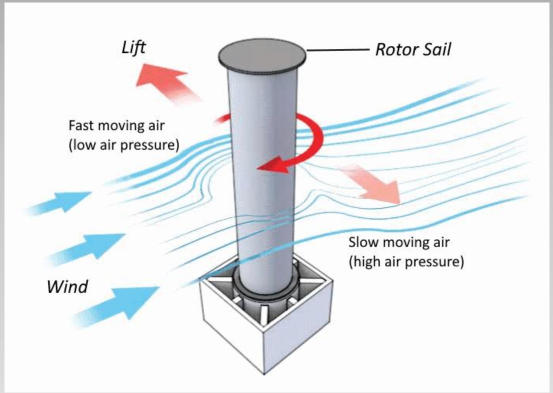
- The Magnus effect is a phenomenon in which a lifting force occurs upon a rotating body when subjected to fluid flow and when perpendicular to its rotational axis.
- First discovered in 1852 by German Professor Gustav Magnus, this effect has been demonstrated to have numerous applications in sports, ballistics, aviation, as well as ship propulsion and stabilization.
- The first maritime use of the Magnus effect was sighted by Captain La Croix around 1895 when a sampan was fitted with a single rotor operated by hand gears.
- First ship trials in 1924 with ship “Buckau” using two rotors designed by Anton Flettner.
- In 1927, a larger ship, “Barbara” uses three Flettner rotors





“Buckau” (1924)

“Barbara” (1927)



Magnus Effect
(Graphics adapted from Science Mag)

https://www.stg-online.org/onTEAM/shipefficiency/programm/06-STG_Ship_Efficiency_2013_100913_Paper.pdf
4th conference on Ship Efficiency, Hamburg, Germany, 23-24 September, 2013

History and Background

- There is a resurgence in Flettner rotor propulsion technology mostly due to recent fuel price increases and more stringent environmental considerations
- In 2008, Enercon launched a hybrid rotor ship E-Ship 1 with operational fuel savings of up to 25%.
- A growing number of existing vessels are being retrofitted with Flettner rotors as well as some new ship builds.
- While other wind-assisted propulsion systems (WASPs) are being explored (e.g., wing-sails, turbo-sails, etc.,) Flettner rotor technology appears to be leading the way with numerous options for growth, including tilt-rotor applications for maneuvering below bridges.

“E-Ship 1” (2008)

https://www.stg-online.org/onTEAM/shipefficiency/programm/06-STG_Ship_Efficiency_2013_100913_Paper.pdf
4th conference on Ship Efficiency, Hamburg, Germany, 23-24 September, 2013

“Estraden” (2014)

“Maersk Pelican” (2018)

“Copenhagen” (2020)

“Sea Zhoushan” (2021)

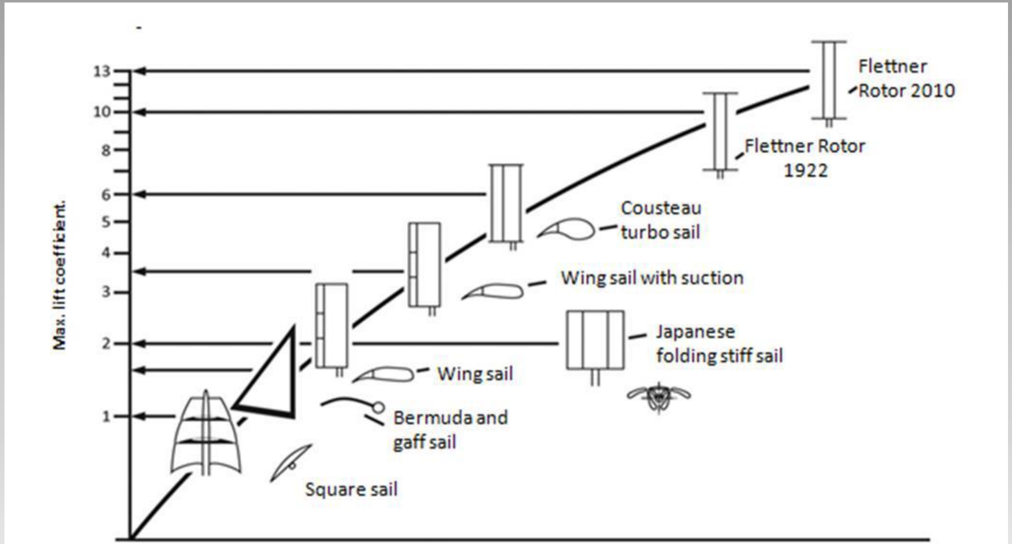
“Delphine” (2022)

https://www.norsepower.com

History and Background

- While other wind-assisted propulsion systems (WASPs) are being explored (e.g., conventional sails (square/Bermuda), folding-sails, wing-sails (suction), turbo-sails (Cousteau), etc.,) Flettner rotor technology appears to be leading the way with numerous options for growth, including tilt-rotor applications for maneuvering below bridges (below, left).
- In relation to surface area, Flettner rotors appear to generate at least 10x (or more) thrust compared to conventional sails as used on traditional sailing ships (below, right).

https://gcaptain.com/stena-bulk-unveils-energy-efficient-product-tanker-prototype/



https://www.norsepower.com

CFD Analysis and Optimization

- Used EasyCFD analysis tool for modeling and prediction
- The following parameters were considered in our investigation of finding the most efficient and appropriate design for the Flettner rotor-powered vessel:

Design Considerations

- Diameter of Rotor
- Rotation Speed and Direction
- Height (Length of Cylinder)
- L/D Ratio and H/D Ratio
- Flettner Rotor(s) Configuration(s)
- End Cap Considerations
- Surface Roughness and Properties
- Drag and Lift Components
- Material(s)

Environmental Considerations

- Wind Direction
- Wind Speed
- Sea Current
- Sea State
- Weather

Vessel Considerations

- Size of Vessel
- Flettner Rotor Attachment
- Rudder/Steering
- Vessel Stability

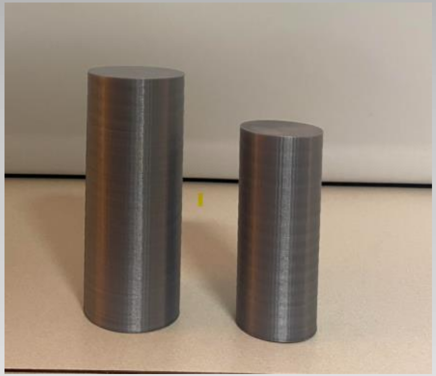
EasyCFD Constraints

- The primary software, EasyCFD, was useful and user friendly however, somewhat limited to basic calculations and computations.
- We did not have accessibility to alternative software at the time these simulations were conducted, so EasyCFD was utilized to find trends and general conclusions on design aspects.
- Due to the lack of 3D capabilities, we were unable to fully investigate the Height of the Rotor, H/D Ratio, Turbulence, End Cap Considerations, Surface Roughness, and Materials considerations.
- However, some of these considerations have been investigated through prior research; in turn, these parameters were based on this respective prior research (Flettner, 1926).
- For further/future investigations, more advanced software would be necessary to better optimize the Flettner Rotor analyses.
- Overall, any parameters not investigated will be supplemented with conclusions found through experimental work.
- Moreover, the parameters that cannot be demonstrated within the EasyCFD software will be tested with the 3D-printed prototypes to obtain quantitative data on the effects of varying these parameters.
- The 3D-printed prototype Flettner rotors will be tested on a scaled model of a Type C2 class cargo ship.

3D-Printed Flettner Rotors

- 3D-printed prototypes of the modeled Flettner rotors were manufactured at the 3D printing lab at USMMA
- These 3D-printed prototypes of the modeled Flettner rotors will be tested on a scaled model of a Type C2 cargo ship to obtain quantitative data on the effects of varying these parameters.
- Consequently, the parameters that were unable to be investigated with the 2D EasyCFD modelling can be further analyzed through experimentation.
- The two dimensions printed for the models were 10 cm length with 3.8 cm diameter and 12.7 cm length with 5.1 cm diameter. These were stacked to create rotors of 20 cm and 25.4 cm length. This configuration allowed for a height-to-diameter ratio of 5.26 and 4.98, respectively.

3D-printed rotors, singular,10/3.8 cm and stacked 20/3.8 cm and 25.4/5.1 cm



Singular printed rotors, 12.7/5.1 cm and 10/3.8 cm

USMMA Model Ship

- The ship model hull (below, left) at approx. scale of 1:100 was made of balsa wood along the lines of the Type C2 (Series 60 – Model 4212W) cargo ships.
- Hull restoration and strengthening of the USMMA model hull was completed to ensure water-tightness
- Steel plates weights were distributed inside the USMMA hull the allow the model to reach its correct design draft.
- Careful balancing of the weighted model at the correct draft was completed* in the experimental water tank at the USMMA Fluids Lab.
- A museum-quality ship model (below, middle), in similar scale to the USMMA model, of the C2-class currently on display at the American Merchant Marine Museum**
- A comparison between the basic dimensions of the Series 60 (Model 4212W) and the USMMA ship model hull are shown in Table 1 (below, right).

USMMA Ship Model Hull

AMMM Ship Model of C2 class cargo ship

Table 1. Basic characteristics of Series 60 hull (Model 4212W) and the USMMA ship model hull

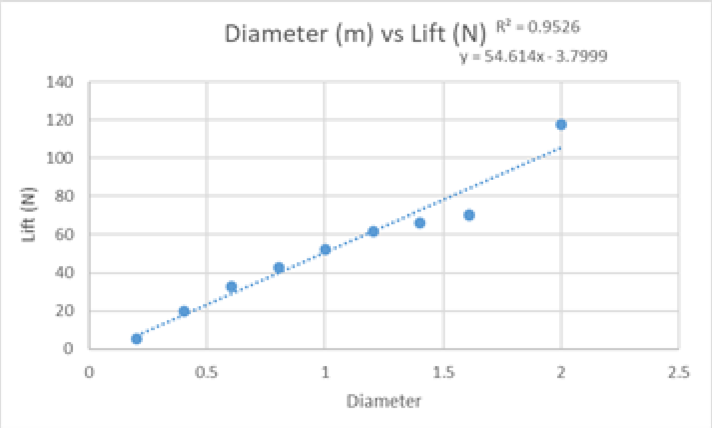
	Series 60 (Model 4212W)		Model (1:100)
Dimension	English	SI	SI
L_{BP}, ft / m	400.00	121.92	1.22
B, ft / m	53.33	17.42	0.17
H, ft / m	21.33	6.97	0.07
Δ, Tons	10456	10456	N/A
C_B	0.70	0.70	0.70
L_{WL}, ft / m	406.70	123.96	1.24
L/B (L = L_{BP})	7.50	7.00	7.00
B/H	2.50	2.50	2.50
W.S., ft^2 / m^2	31705.00	2945.49	29.45

*We are grateful to Dr. Sergio Perez for this effort. Further details can be found in these two prior publications (Perez, 2023a; Perez, 2023b).

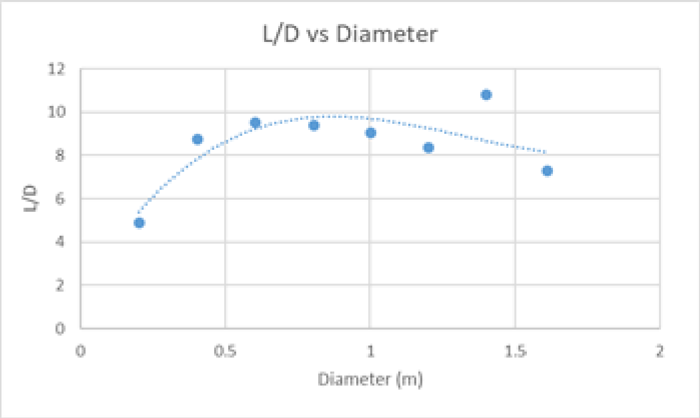
*American Merchant Marine Museum, Kings Point, NY, USA. https://www.usmma.edu/museum.

Varying Rotor Diameter

- To investigate the effects of varying the diameter, we held the rotation and wind speed constant at 5 m/s for both.
- As observed from the modeling results, an increase in rotor diameter causes an increase in lift (lower, left)
- Notably, the lift to drag ratio (L/D) peaks at approximately 0.6 m rotor diameter (lower, right)



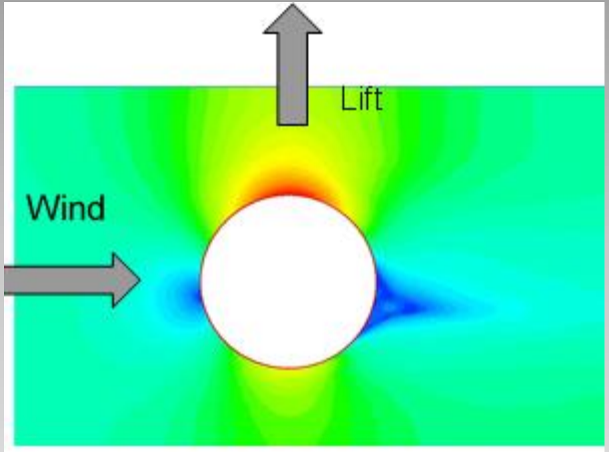
Lift vs Rotor diameter



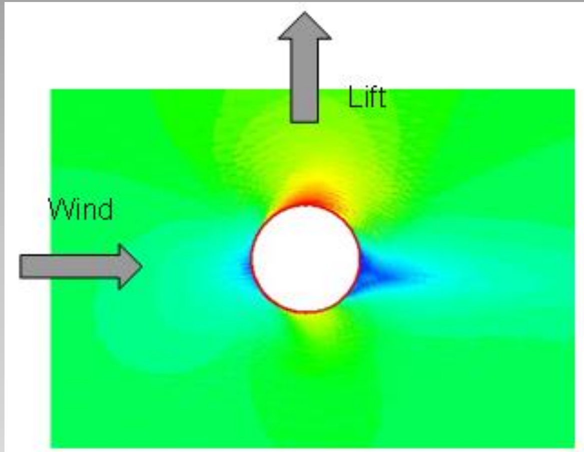
L/D vs Rotor diameter

Varying Rotor Diameter

- Examples of varying rotor diameter for the same constant wind speed and direction are shown for the largest rotor diameter (lower, left) and the smallest rotor diameter (lower, right), respectively.



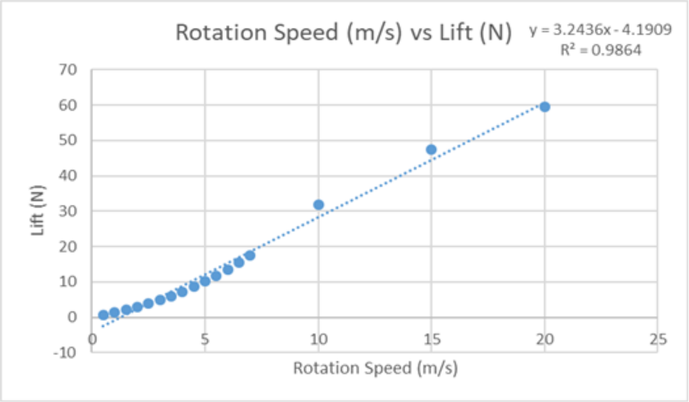
Lift for Rotor diameter D = 1.61 m



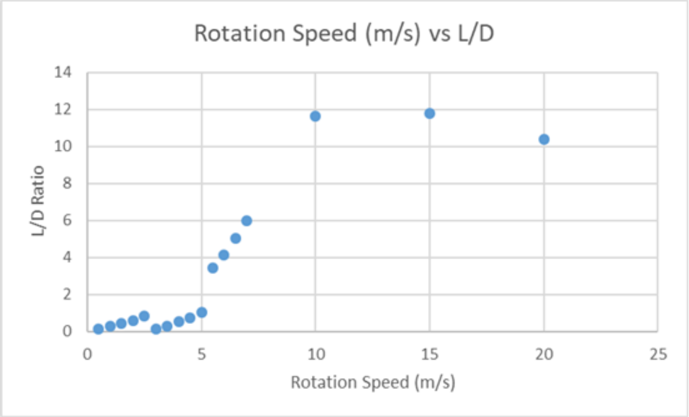
Lift for Rotor diameter D = 0.20 m

Varying Rotation Speed

- To investigate the effects of rotor rotational speed on the generated lift, the rotor's diameter was held constant at 0.3 m, and the wind speed was held constant at 5 m/s.
- As observed form the modeling results (and expected from theory), lift increased as the rotor's rotational speed increased in a relatively linear manner (1st degree polynomial curve fit $R^2 \approx 0.98$) as shown in lower, left.
- Additionally, the lift-to-drag ratio (L/D) peaked at rotational speed of 10-15 m/s (lower, right)



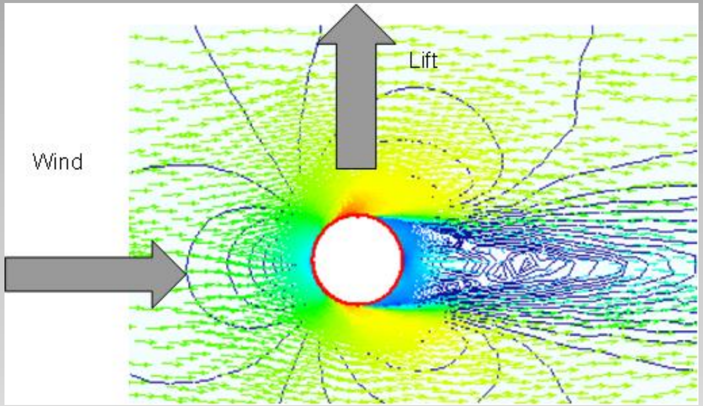
Lift vs. Rotational speed (dia. = 0.3 m, wind speed = 5 m/s)



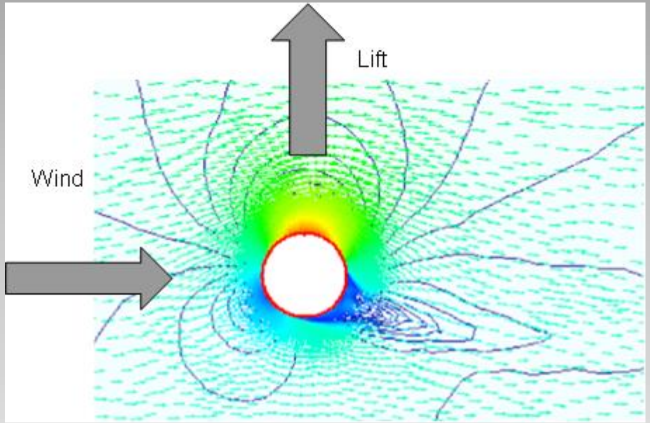
L/D Ratio vs. Rotational speed (dia. = 0.3 m, wind speed = 5 m/s)

Varying Rotation Speed

- Examples of varying rotor diameter for the same constant wind speed and direction are shown for rotational speed = 1.5 m/s (lower, left) and for rotational speed = 20 m/s (lower, right), respectively.



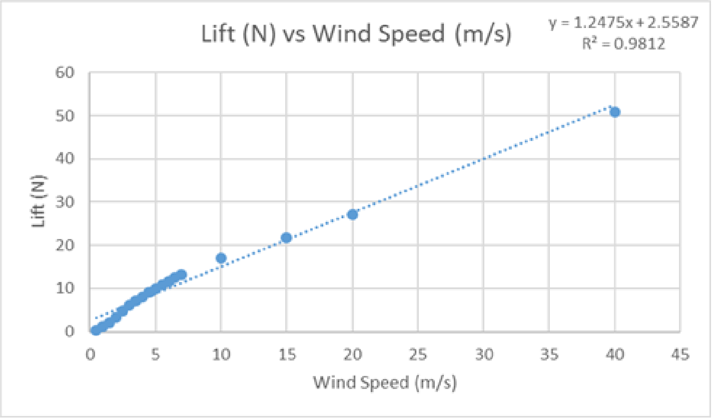
Lift for rotational speed = 1.5 m/s



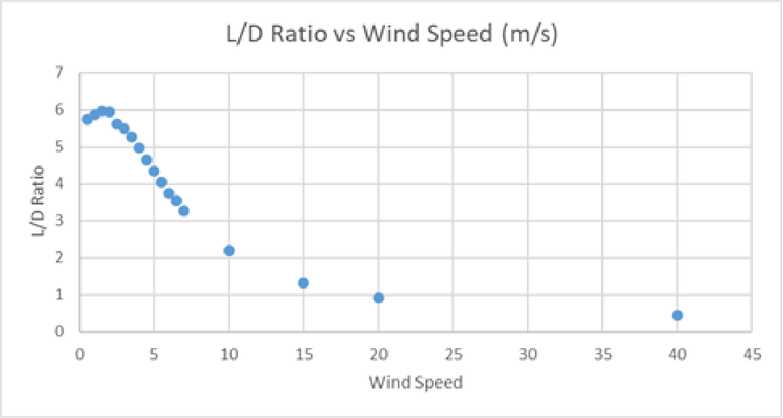
Lift for rotational speed = 20 m/s

Varying Wind Speed

- To test the effects of varying wind speed, we held the rotor diameter constant at 0.3 m and the rotational speed constant at 5 m/s.
- As observed form the modeling results, lift increased almost linearly (1st degree polynomial curve fit $R^2 \approx 0.98$) as the wind speed increased (lower, left).
- However, the lift to drag ratio peaked at approx. 1.5 m/s wind speed, then decreased as wind speed increased (lower, right).
- Hence, although lift is increasing rapidly with wind speed (lower, left), the associated drag is increasing at a higher rate, consistent with the findings shown in the lower right image.



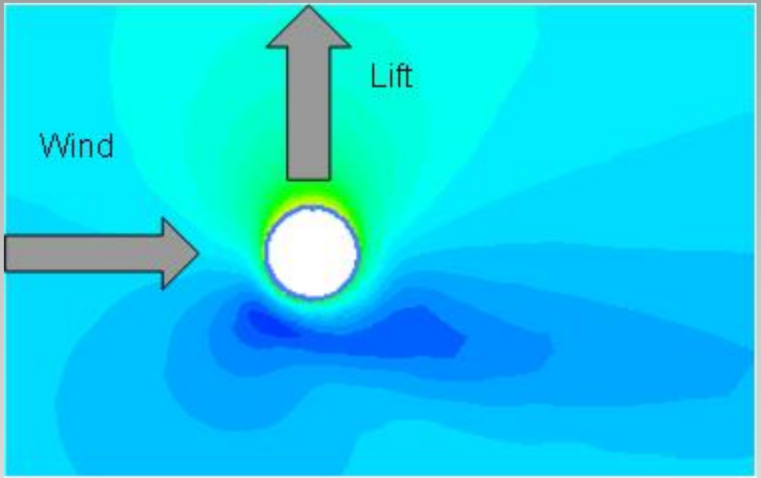
Lift vs. wind speed (dia. = 0.3 m, wind speed = 5 m/s)



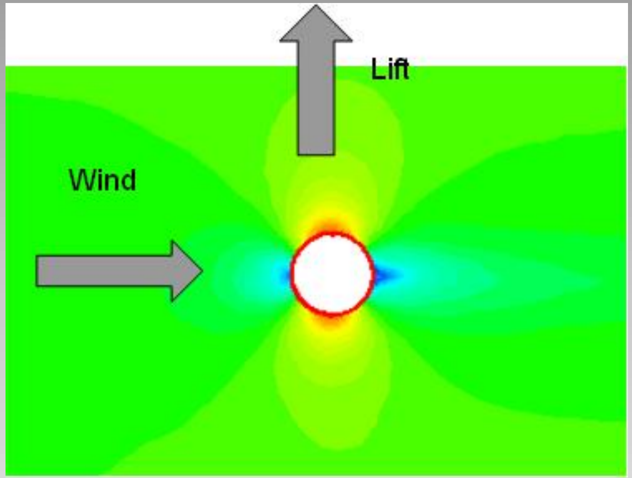
L/D vs. wind speed (dia. = 0.3 m, wind speed = 5 m/s)

Varying Wind Speed

- Examples of varying wind speed for 0.5 m/s and 30 m/s for the same constant rotational speed (5 m/s) and constant diameter (0.3 m) are shown (lower, left) and (lower, right), respectively.



Lift for Wind speed = 0.5 m/s



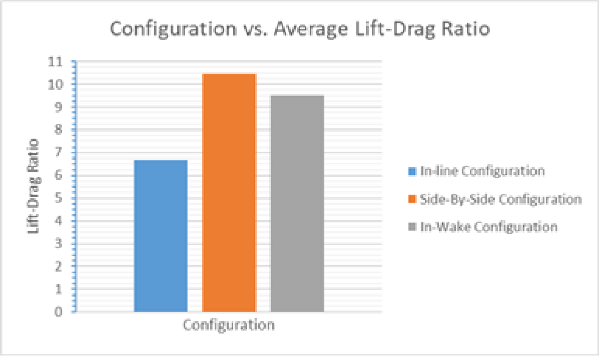
Lift for Wind speed = 40 m/s

Rotor Configurations

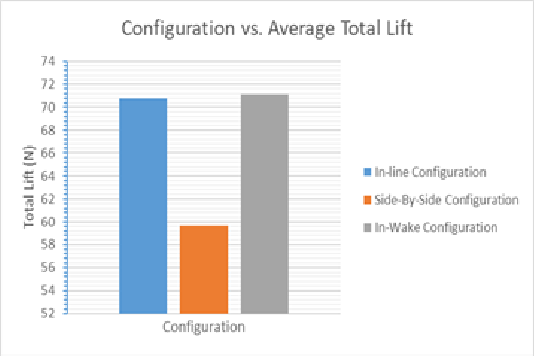
- A very important consideration we investigated with the EasyCFD analysis was the effect of the configuration and the number of rotors on Lift and Lift-to-Drag Ratio.
- We tested several different configurations to find the appropriate and efficient options for shipboard applications. Below are some of the designs investigated through EasyCFD.
- Notably, there are several variations to each design that we investigated in addition to the designs presented below.

Two Rotors

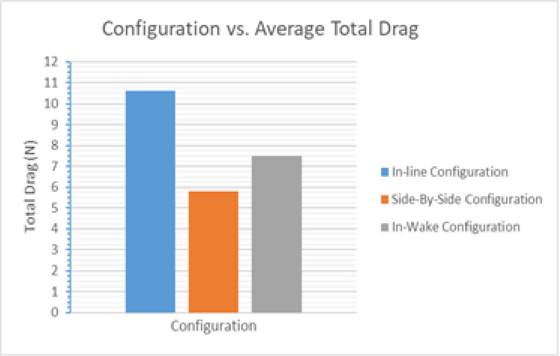
- The three primary rotors configurations that were investigated were an “in-line” configuration (blue bars), a “side-by-side” configuration (orange bars), and an “in-wake” configuration (grey bars) where one rotor is placed within the wake of the other rotor (each with dia. = 0.6 m).
- The plots below show the L/D ratio (lower, left), Total Lift (lower center), and Total Drag (lower, right) all vs the three different rotor configurations.
- As can be seen from the plots, the highest L/D was obtained with the “side-by-side” configuration, (lower, left) however, the highest total Lift was achieved with the “in-wake” configuration (lower, center)



L/D vs rotors configurations



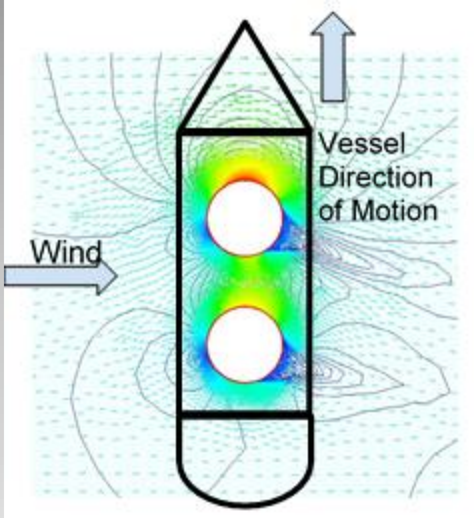
Total Lift vs rotors configurations



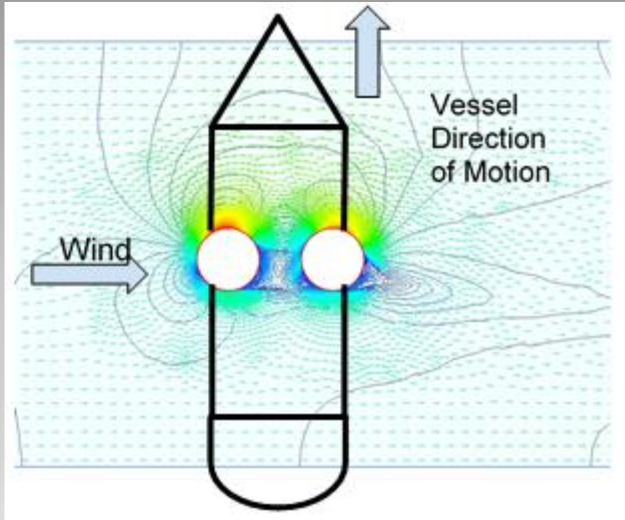
Total Drag vs rotors configurations

Two Rotors

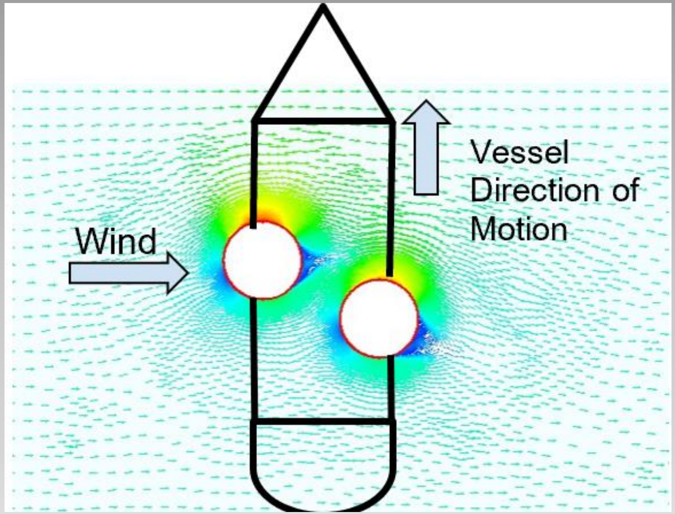
- The three primary configurations with two rotors (each with dia. = 0.6 m): “in-line” (below, left), “side-by-side” (below, center), and “in-wake” (below, right) are compared.
- Subsequently, the “in-wake” configuration was more specifically investigated as will be shown below.



Rotors in “in-line” configuration



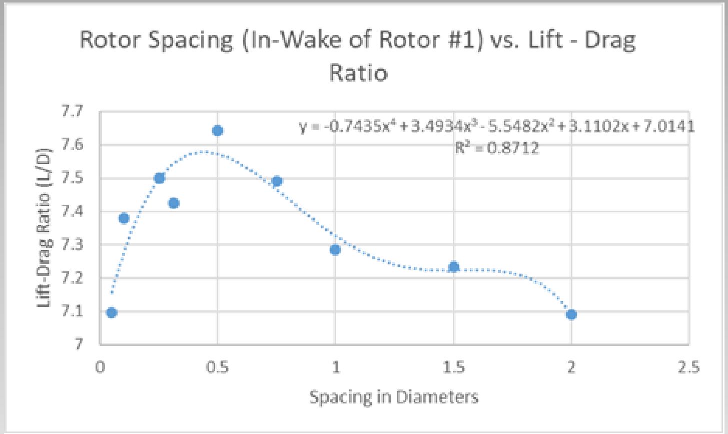
Rotors in “side-by-side” configuration



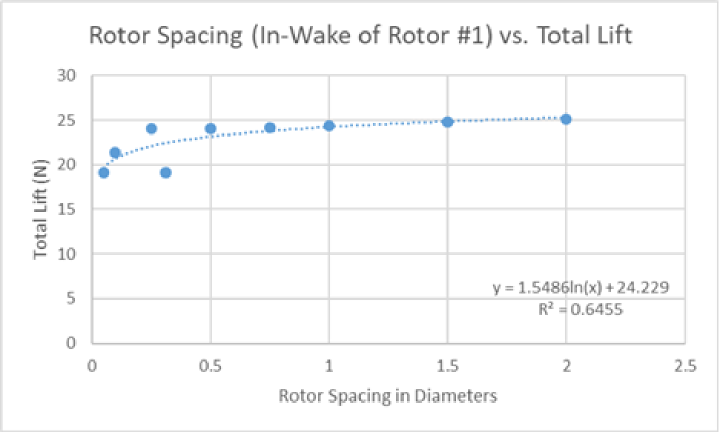
Rotors in “in-wake” configuration

Two Rotors – "in-wake" configuration

- After determining that the in-wake configuration was the most applicable configuration for shipboard application, more CFD simulations were conducted to produce the two graphs below investigating the effect of rotor spacing on the lift-to-drag ratio and the total lift/propulsion of the vessel.
- The highest L/D ratio (approx. 25) was reached at a spacing between rotors of 0.5 m (below, left).
- For these CFD simulations, the rotor diameters were reduced to 0.3 m, hence the total Lift was lower (below, right) compared to the Lift values shown in slide 18 (lower, center).



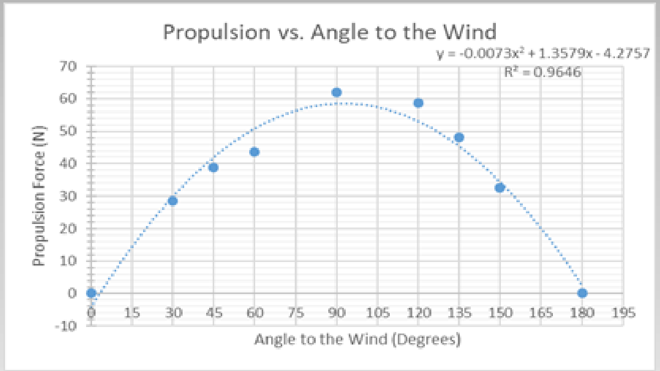
L/D vs rotors' spacing (rotor dia. = 0.3 m)



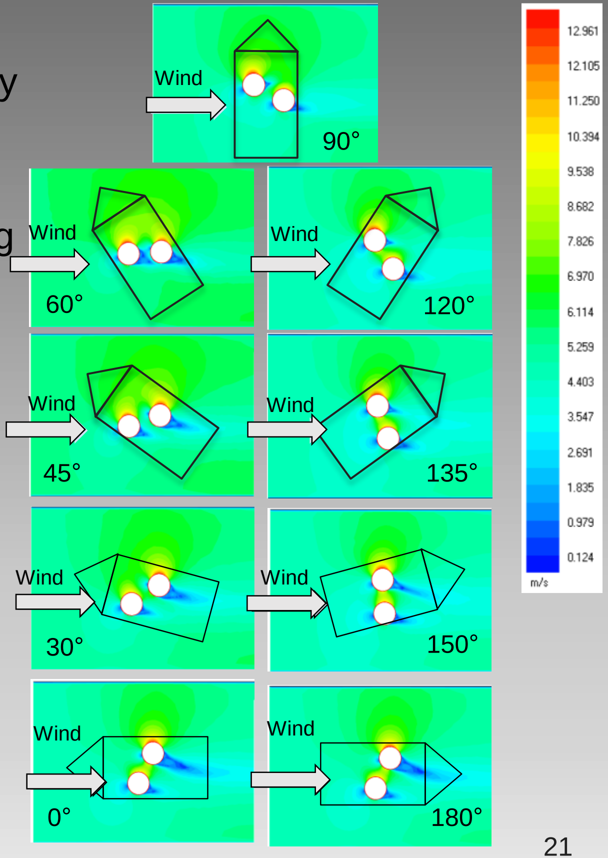
Total Lift vs rotors' spacing (rotor dia. = 0.3 m)

Two Rotors – Lift force based on Angle to the Wind

- To investigate the effects of wind direction relative to the vessel, the angle of the vessel to the wind was varied (0° - vessel is pointing directly into the wind; 180° - vessel pointing directly away from the wind)
- For these CFD simulations (below, right), the wind speed was 5 m/s, the rotational speed was 5 m/s clockwise for both rotors, and the spacing of the rotors was 1-m apart.
- The maximum propulsion (Lift) force was achieved with the vessel perpendicular to the wind (at 90°), as expected (below, left).

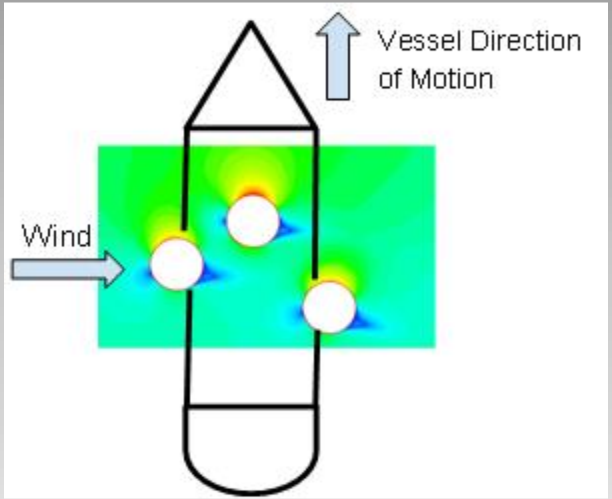


Propulsion (Lift) vs angle to the wind

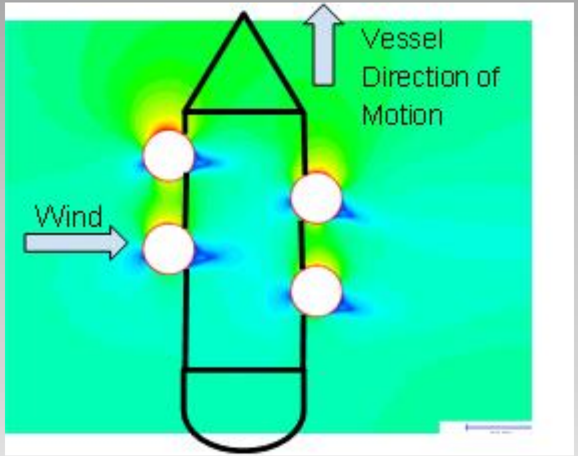


Configurations with Increased Number of Rotors

- The addition of more rotors in similar configurations to the “in-wake” configuration were investigated, specifically: a 3-rotor configuration and a 4-rotor configuration (all rotors with dia. = 0.3 m).
- As expected, the addition of Flettner rotors increased the total lift experienced.
- The total lift force increased with some effects to the lift-to-drag ratio.
- Thus, it was concluded that having two sets of a 2-rotor “in-wake” configuration can produce the highest total lift.



Three-rotor configuration



Four-rotor configuration

Comparisons with other WASP Technologies

- With limited time and resources, prior research works on other wind technologies were investigated to substitute further CFD Analysis for other wind propulsion designs.
- One report (Nelissen et al., 2013) presents these alternative Wind-Assisted Ship Propuslion (WASP) Technologies and a thorough comparison of the benefits and drawbacks of each piece of technology. Additionally, the polar graphs provided in this presentation were derived from the Nelissen Report.
- Within this source, Wingsails, Towing Kites, Flettner Rotors, and Wind Turbines are described.
- In general, the Average Relative Savings presented in this report indicate that Flettner rotors and Wingsails provide the most substantial savings predominantly for large vessels (large bulk carriers and large tankers compared to small vessels)(as shown in Table 2 below).
- These solutions work best for larger vessels primarily due to the availability and space for larger wind power devices, and the larger wind speeds experienced in large sea going vessel applications.

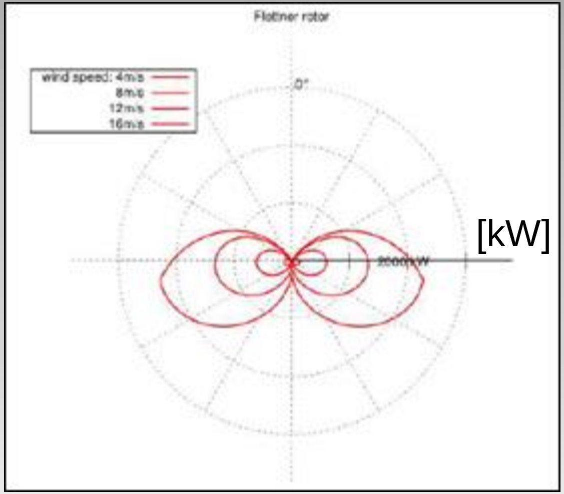
Table 2. Average Relative Saving Across Vessel Voyages

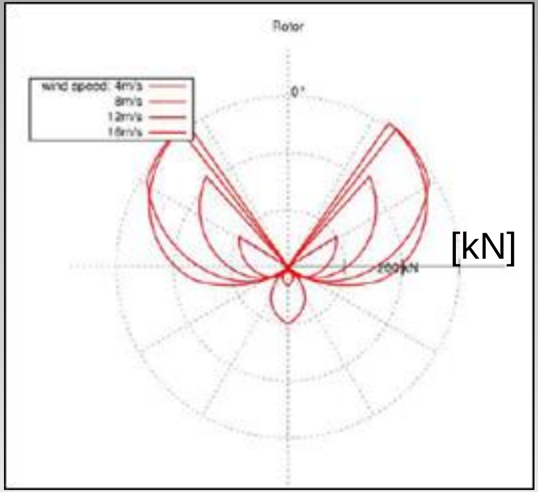
	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	17%	18%	5%	2%
Small bulk carrier (7,200 dwt)	5%	5%	9%	1%
Large tanker (90,000 dwt)	9%	9%	3%	1%
Small tanker (5,400 dwt)	5%	5%	9%	1%

Polar Coordinate Graphs

Flettner Rotor Thrust Force vs. Wind Direction

- Below are the polar coordinate graphs in kW and kN at various wind speeds for the Flettner Rotor Wind Propulsion Device.
- The Flettner Rotor has the best versatility at various wind speeds when compared to the other wind devices shown in the following slides.
- As demonstrated in the polar graphs below, the Flettner rotor is able to produce a thrust force/propulsion force at any wind angle except 0 degrees and 180 degrees, or parallel to the vessel’s motion.

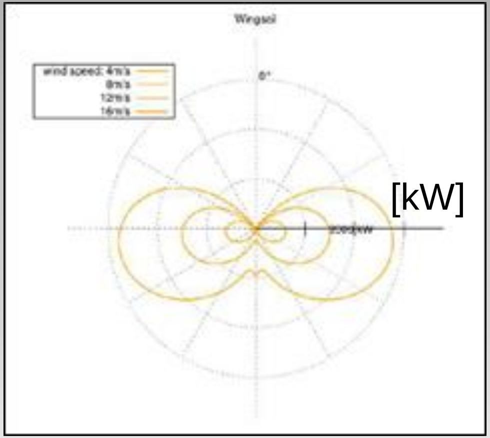


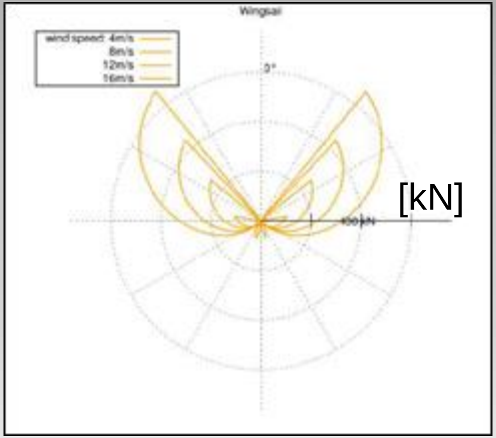


Polar Coordinate Graphs

Wing Sail Thrust Force vs. Wind Direction

- Below are the polar coordinate graphs in kW and kN at various wind speeds for the Wing Sail Wind Propulsion Device.
- Similar to Flettner rotors, wing sail technology has a similar thrust force vs. wind direction polar graph; however, the previously shown Flettner rotor plot shows a greater thrust force [kN] for a large area. Thus, the Flettner rotor produces thrust force at a larger variety of wind angles with a higher thrust force.
- Like the Flettner rotor, the wing sail polar graphs below show that wing sails are another viable option to produce a thrust force/propulsion force, specifically for larger vessels as discussed previously.

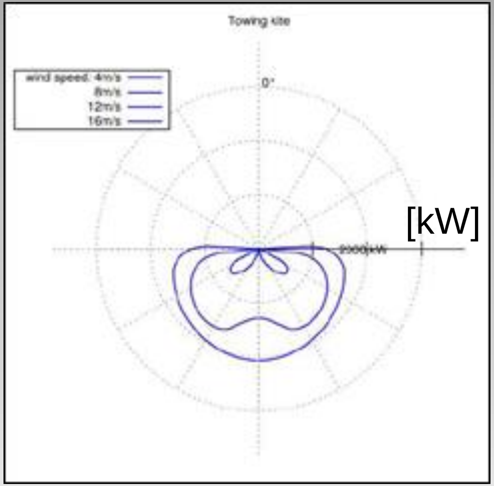


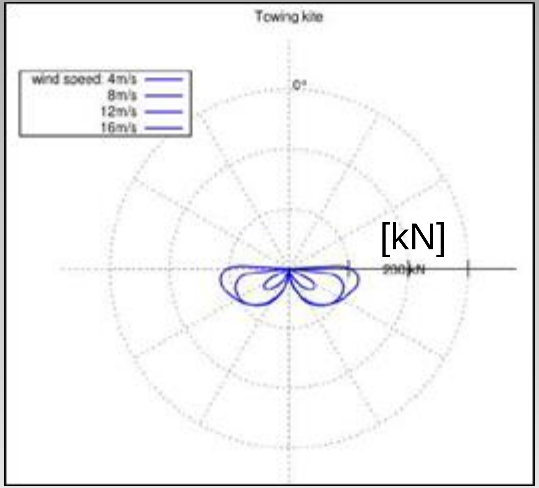


Polar Coordinate Graphs

Towing Kite Thrust Force vs. Wind Direction

- Below are the polar coordinate graphs in kW and kN at various wind speeds for the Towing Kite Wind Propulsion Device.
- Unlike wing sails or Flettner rotors, the Towing Kite polar graphs demonstrate the lack of versatility at different wind angles to the vessels motion. Specifically, the towing kite is primarily applicable when the wind is coming aft of the vessel.
- Moreover, the total savings for this propulsion device was significantly less for larger vessels because it was not scaled to a larger size within the Nelissen Report.
- The towing kite takes no space on the deck of the vessel, which is primary advantage to this device.

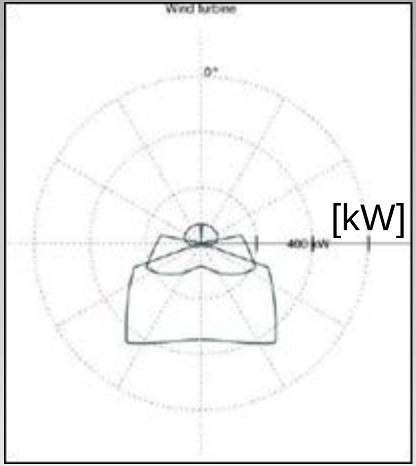


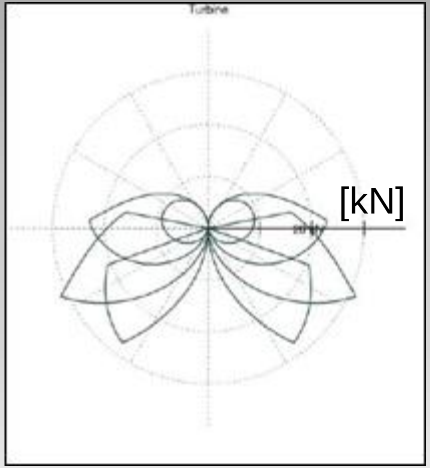


Polar Coordinate Graphs

Wind Turbine Thrust Force vs. Wind Direction

- Below are the polar coordinate graphs in kW and kN at various wind speeds for the Turbine Wind Propulsion Device.
- Similar to the towing kite, the wind turbine polar graphs demonstrate the lack of versatility at different wind angles to the vessels motion. Specifically, the wind turbine is primarily applicable when the wind is coming aft of the vessel.
- The wind turbine had the smallest savings within the Nelissen report primarily due to the low representation by suppliers, and the disadvantage of having less power generation when operating in variable wind conditions.





Conclusions

Results based on the completed CFD analysis suggest that there is:

- A directly proportional relationship by which an increase in Flettner rotor diameter results in an increase in lift. This relationship is optimized at 0.6 m in terms of the lift to drag ratio.
- A directly proportional relationship between Flettner rotor rotational speed, and resulting lift. This appears to be optimized with respect to the lift to drag ratio at approximately 10 to 15 meters per second.
- The 4-staggered Flettner rotor configuration is best observed option, due to the addition of thrust when adding Flettner rotors. However, having a configuration with one rotor forward and one rotor aft would assist with the vessels manueverabilty and ability to turn.

Further Investigations

- Conduct more thorough CFD Analyses utilizing a CFD software with 3-D capabilities.
- Complete more CFD calculations with additional Flettner rotor different sizes and configurations
- Compete towing tank testing with ship model hull to investigate the effects of the 3-D printed scaled-to-model Flettner rotors
- Investigate effects of “end caps” on Flettner rotor performance, as this is difficult to model with the CFD software.
- Investigate various locations of Flettner rotors on ship decks relative to ships CG

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References

Ammar, N. R. “Harnessing Wind Energy on Merchant Ships: Case Study Flettner Rotors Onboard Bulk Carriers.” Environmental Science and Pollution Research, 28:25 (2021): 32695-32707. https://doi.org/10.1007/s11356-021-12791-3.

De Marco, A., S. Mancini, C. Pensa, G. Calise, and F. De Luca. “Flettner Rotor Concept for Marine Applications: A systematic study.” International Journal of Rotating Machinery, (2016): 1-12. doi.org/10.1155/2016/3458750.

Flettner, A. “Mein Weg zum Rotor.” MIT 114 ABB. Verlag Koehler & Amelang, Leipzig 1926. 123 S. ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift Für Angewandte Mathematik Und Mechanik, 6:6 (1926): 505-505. doi.org/10.1002/zamm.19260060625

Lu, R. and J.W. Ringsberg. “Ship Energy Performance Study of Three Wind-Assisted Ship Propulsion Technologies Including a Parametric Study of the Flettner Rotor Technology.” Ships and Offshore Structures, 15:3 (2019): 249-258. doi.org/10.1080/17445302.2019.1612544

Nelissen, D., M. Traut, J. Köhler, M. Wengang, F. Jasper, and A. Saliha. (2016). “Study on the Analysis of Market Potentials and Market Barriers for Wind Propulsion Technologies for Ships.” CE Delft, Nov., 2016, Publication Code: 16.7G92.114.

Perez, S. (2023a). “Preliminary Analysis of a New High Lift Device for Sailing Cargo Ships using Distributed Wing-Mounted Propellers.” Journal of Merchant Ship Wind Energy, Feb., 2023, www.jmwe.org.

Perez, S. (2023b). “A Second Look at the Propeller Sail High Lift Device for Sailing Cargo Ships, using Distributed, Wing-Mounted Propellers.” *2023 Sustainability in Ship Design and Operations (SISDO 2023) Conference*, Webb Institute of Naval Architecture/United States Merchant Marine Academy, Nov. 6-7, 2023, New York.

Sawyer, L.A. and W.H. Mitchell. From America to United States in Four Parts: The History of the Long-Range Merchant Shipbuilding Programme of the United States Maritime Commission, (Part Two), World Ship Society, London, 1981.

Seifert, J. “A Review of the Magnus Effect in Aeronautics.” Progress in Aerospace Sciences, 55 (2012): 17-45. doi.org/10.1016/j.paerosci.2012.07.001

Schuler, M. “Wind Propulsion Vessel E-Ship 1 – Interesting Ship of the Week.” *gCaptain magazine*, Nov. 14, 2008.

Smith, T.W.P., et al., Third IMO Greenhouse Gas Study 2014 – Executive Summary and Final Report, London, UK, 2015.

Thom, A. (1970). “Effect of Discs on the Air Forces on a Rotating Cylinder.” AERADE Home. https://reports.aerade.cranfield.ac.uk/handle/1826.2/1421

Tillig, F and J.W. Ringsberg. “Design, Operation and Analysis of Wind-Assisted Cargo Ships.” Ocean Engineering, 211, (2020):107603.

Todd, F.H. (1963). Series 60 Methodical Experiments with Models of Single-Screw Merchant Ships. Dept. of the Navy Research and Development Report 1712.

Wagner, C. D. Die Segelmaschine. Kabel Verlag. Hamburg, 1991.