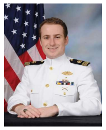
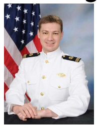
Approved for Public Release

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

UNITED STATES
MERCHANT MARINE
ACADEMY



MIDN 1/C Zachary Almadani
Marine Engineering Systems
Future U.S. Air Force Pilot



MIDN 1/C Joshua Garcia-Billings
Marine Engineering
Future U.S. Marine Corps Fixed-Wing Pilot

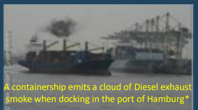
MIDN 1/C Hannah Newsom
Marine Engineering
Future 3rd A/E, Strategic Sealift Officer

Advised by: Dr. Lubomir Ribarov, United States Merchant Marine Academy
Team Name: USMMA Team B

WISE WARFIGHTER INNOVATION IN SCIENCE & ENGINEERING

Introduction

- 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
- Despite these stringent regulations, the propulsion and power generation plants for future ships must significantly reduce fuel consumption and emissions over the coming years

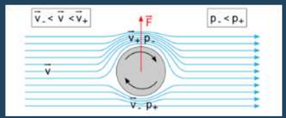


A containership emits a cloud of Diesel exhaust smoke when docking in the port of Hamburg*

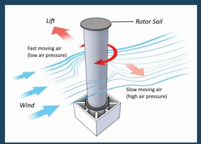
- The use of available wind power for merchant shipping has seen an increased interest due to rising fuel costs, ever-stringent environmental protection requirements (especially stringent in specific emission control areas, ECAs**), and resulting increased operational costs, etc.
- The purpose of this 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.

History and Background

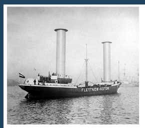
- The Magnus effect is a phenomenon in which a lifting force occurs upon a rotating body when subjected to fluid flow and when perpendicular to its rotational axis.



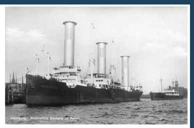
Magnus Effect
(Graphics adapted from Science Mag)



- 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)

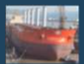
https://www.stg-online.org/onTEAM/shipefficiency/programm/06-STG_Ship_Efficiency_2013_100913_Paper.pdf
4th conference on Ship Efficiency, Hamburg, Germany, 23-24 September, 2013

- 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.

"Estraden" (2014)

"Maersk Pelican" (2018)

"Copenhagen" (2020)

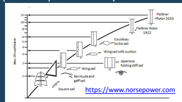


"Sea Zhoushan" (2021)

"Delphine" (2022)

- 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/



CFD Parameters and Considerations

- 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

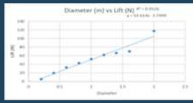
Easy CFD Constraints

- 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.

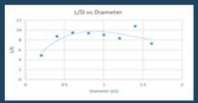
CFD Analysis

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)

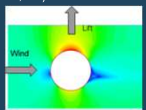


Lift vs Rotor diameter

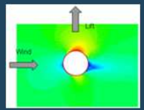


L/D vs Rotor diameter

- 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.



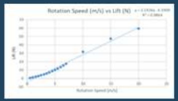
Lift for Rotor diameter D = 1.61 m



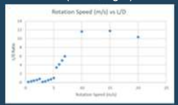
Lift for Rotor diameter D = 0.20 m

Varying Rotor Diameter

- 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)

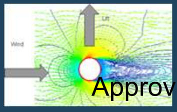


Lift vs. Rotational speed (dia. = 0.3 m, wind speed = 5 m/s)



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

- 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.

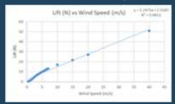


Lift for rotational speed = 1.5 m/s

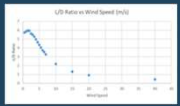
Lift for rotational speed = 20 m/s

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.

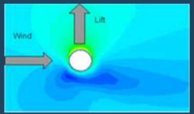


Lift vs. wind speed (dia. = 0.3 m, wind speed = 5 m/s)

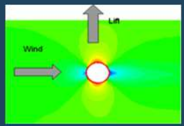


L/D vs. wind speed (dia. = 0.3 m, wind speed = 5 m/s)

- 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



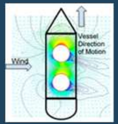
Lift for Wind speed = 40 m/s

Rotor Configurations

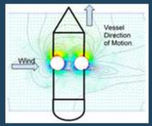
- A very important consideration we investigated with the EasyCFD analysis was the effect of the configuration and the number of rotors on Lift and Lift-to-Drag Ratio.
- We tested several different configurations to find the appropriate and efficient options for shipboard applications. Below are some of the designs investigated through EasyCFD.

Two Rotors

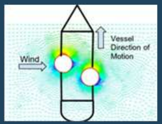
- The three primary configurations with two rotors (each with dia. = 0.6 m): "in-line" (below, left), "side-by-side" (below, center), and "in-wake" (below, right) are compared.
- Subsequently, the "in-wake" configuration was more specifically investigated as will be shown below.



Rotors in "in-line" configuration



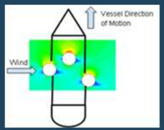
Rotors in "side-by-side" configuration



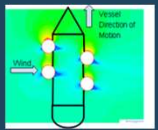
Rotors in "in-wake" configuration

Multiple 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

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.