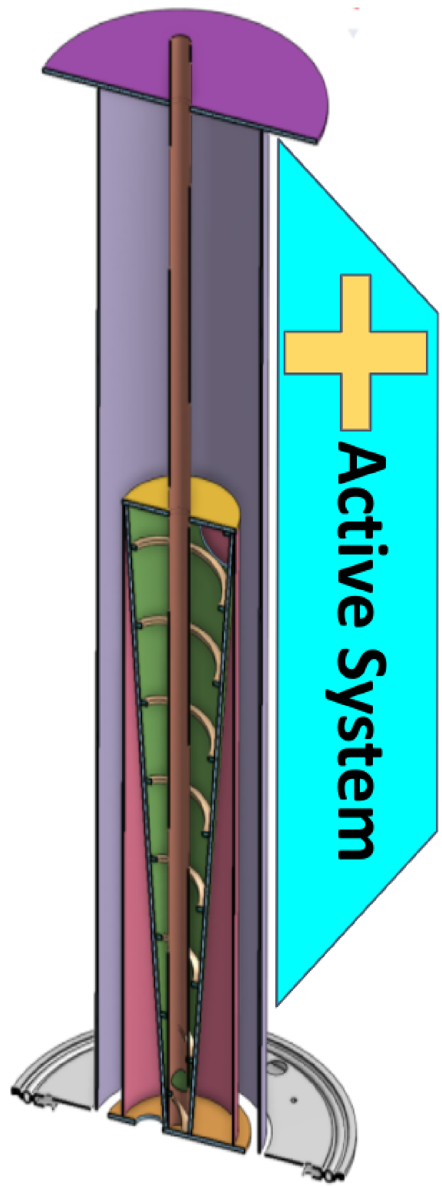
Innovative Climate Change Emissions Reduction: Flettner Rotor Active System for Improved Seakeeping



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I. Abstract:

Our global cargo ship fleet emits 4% of climate change emissions and particulate pollutants, leading to roughly 7.6 million childhood asthma cases, and 150,000 premature deaths annually. Integrating active seakeeping control into a novel centrifugal vortex scrubber designed into a Flettner rotor creates a hybrid wind and fossil fuel powered vessel that cleans exhaust while generating auxiliary wind propulsion and expanding the vessel's operating envelope with seakeeping capabilities. 3D CAD modeling, computational fluid dynamics analysis, and prototyping were used for design iterations and testing. Active seakeeping performance of Flettner Vortex Scrubber (FVS) rotor performance was evaluated in a wave pool simulating open water conditions, with the Active FVS mounted on scale mass and buoyancy model of a neopanamax cargo ship. Matched pairs t-Tests were used to statistically compare the angle of roll measured during the Forced Vibration Ocean Wave Simulation, with data points from waves with and without the Active FVS engaged. The 3D model, computational fluid dynamics results, and prototype test data show that the Active FVS can also serve as an effective seakeeping system, with maximum rolling angle reduced by 65.6%, and recovery time from an 18 degree displacement reduced by 45%. In addition to reducing climate change and improving health, this attractive investment pays for itself in less than a year through fuel savings and increased cargo space. A Flettner Vortex Scrubber would allow a neopanamax ship to transport an additional 53 TEU containers, which are worth $185,000 on a trip from Shanghai to New York. The novel Active FVS expands a vessel's operating envelope by improving crew comfort and effectiveness, and reducing risk of Parametric Rolling Movement (PRM). If conservative estimates of Flettner rotor performance scale to the global cargo shipping fleet, it could mean a climate change impact equivalent to taking five million cars off the road.

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IV. Abbreviations and Acronyms:

CFD: Computational Fluid Dynamics
IEC: International Electrotechnical Commission
FVS: Flettner Vortex Scrubber
PRM: Parametric Rolling Movement
PWM: Pulse Width Modulation
TTL: Transistor-Transistor Logic
ML: Machine Learning
AI: Artificial Intelligence

1. Introduction:

This is an exciting time for cargo ship naval architecture as technologies as new as AI and as old as wind power converge to reduce our transportation climate change footprint.

Despite electrification of vehicles, optimistic attempts to “leave it in the ground,” and a fossil fuel shift to plastic, petroleum fuels will be part of our lives for decades, and with it the heavy fuel oil byproducts of gasoline, diesel, and jet fuel. This dirty residual fuel is difficult to further refine and thus finds a use powering our cargo ship fleet, which are coming under increasing scrutiny as they contribute 4% to global climate change contributions (Walker et. al., 2019).

Our desire to use raw materials from around the globe or take advantage of relative efficiencies in production shows no sign of slowing, therefore our global cargo fleet consisting of over 100,000 vessels larger than 100 gross tonnes will persist and grow (Julià, 2020).

Engineering solutions abound, however many are costly, add complexity, and may even have unintended side effects such as reduced cargo capacity, increased maintenance, and water pollution. Environmental improvements often mean less cargo space, increased capital and operating costs.

Ships began using oil as an energy source around 1900, however use of exhaust scrubbers on ships was very limited until recently, due to light regulation. In 1973 the regulation of pollution in international waters was first discussed at the first marine pollution convention, or MARPOL. Sulfur emissions restrictions did not go into effect until 2012 with a 3.5% sulfur cap. In 2020 the Organisation for Economic Co-operation and Development (OECD) reported that this cap was reduced to 0.5% by the International Maritime Organization (IMO), prompting ships to either consume less residual fuels, or install scrubbers. Because of this, and as noted by Comer, 2020, and Sethi, 2020, it seems like scrubber technology is designed around land-based applications like power generating stations that have been more regulated, and not marine applications. Heavy fuel oil is a residual product of petroleum refining for gasoline and diesel (Lack et. al., 2009). Specifications are typically per the ISO 8217 Bunker Fuel Standard. Marine fuel oil engines are a mature, low cost, and reliable technology (Lack et. al., 2009). Marine exhaust scrubbers and cargo ship wind power are very important technologies to advance. Large ships contribute to 4% of global climate change emissions (Walker et. al., 2019). Anyone who has seen cargo ships entering or leaving harbors can clearly see the amount of particulate matter emissions from heavy fuel oil combustion, but there are additional pollutants that are not visible. According to Gallucci, 2018, from the Yale School of the Environment, we are just learning that the combustion products of heavy fuel oil are especially noxious pollutants which can travel hundreds of miles leading to roughly 7.6 million childhood asthma cases and 150,000 premature deaths annually.

Comer, 2020, and Sethi, 2020 observed that land-based exhaust gas scrubbers are a well-established method of cleaning emissions from oil and coal fired power generating stations. Comer, 2020; Sethi, 2020, as well as the United States Environmental Protection Agency, 2011, found that typical scrubber designs rely on fans and alkaline water mist to remove particulate matter and sulfur oxides from combustion products, especially from residual fuels such as heavy fuel oil. Open loop scrubbers require increased energy costs to run pumps, and discharge scrubber water overboard (Comer, 2020; Sethi, 2020). Closed loop scrubbers require treated water to be stored on board until discharged for treatment on land (Comer, 2020; Sethi, 2020). Capital cost of scrubbers ranges from $500K to $5M, not including loss of capacity for drydock and retrofit, loss of cargo space, increased maintenance, or associated decrease in engine efficiency (Comer, 2020; Sethi, 2020).

Flettner rotors use the Magnus effect to harness wind power without setting and trimming sails. In 1925 Herzog, observed that Flettner rotors generate approximately an order of magnitude more lift than sails of the same area as. The rotor ship *Baden Baden (ex Buckau)* used Flettner rotors and crossed the Atlantic in 1925, however the challenges of maintaining balanced rotating steel cylinders and vessel stability was shelved until recent improvements to composite materials improved stability, and climate change concerns renewed interest in wind power for large ships (De Marco, 2016; Norsepower, 2020; Flettner, 1926; Mason, 2020)

Figure 1: A rotor ship, E-Ship 1. *Image adapted from https://www.auerbach-schifffahrt.de/index_eng.php, by Schmidt-Ohm & Partner. (2020)*

More significant ship design changes also have downsides: sail trim is challenging on modern-size ships, nuclear propulsion is expensive to build, operate, and decommission, and presents insurance and national security challenges, electrification relies on Li-ion batteries already in short supply for automotive production (Norsepower, 2021).

The solution previously developed is the novel Flettner Vortex Scrubber (FVS) is a Flettner rotor with integrated vortex scrubber to clean engine exhaust and generate propulsion power with a minimum of cargo volume loss (Michaluk, 2021). A novel centrifugal vortex scrubber integrated into a Flettner rotor creates a hybrid wind and fossil fuel powered vessel that cleans exhaust while generating propulsive power that more than compensates for the engine power loss through the scrubber, and the initial capital investment. Multiple Flettner Vortex Scrubbers would be fit to a large vessel such as a neopanamax.

Seakeeping is the ability of a vessel to limit motion due to waves and weather, resulting in increased crew comfort, safety, and performance. Improving seakeeping broadens the operating envelope of the vessel, adding significant value by allowing vessel goals to be achieved in a wider range of weather conditions.

Ships such as research vessels and cruise ships where crew and passenger comfort is a priority are often fitted with active seakeeping measures such as hydraulically controlled hydrofoils, gyroscopes, or powerful pumps transferring water between port and starboard tanks as the ship rolls. Stabilization systems using underwater foils or underwater Flettner rotors are a completely different application than Flettner rotors employed for wind propulsion which are otherwise known as rotor sails. Stabilization systems using rotors and the Magnus effect do not serve any propulsion or efficiency purpose, are below the waterline, and require dedicated seakeeping hardware. On a ship, these active systems consume valuable cargo space and energy, and require costly hardware or hull appendages. This makes them cost prohibitive, especially to developing economies.

Parametric Rolling Movement (PRM) is a result of harmonic interaction between ocean waves and the ship hull, it can lead to extreme undesirable ship motion, loss of cargo, and even damage to the vessel. PRM causes loss of about 1000 shipping containers per year, an economic loss to the carrier, and a safety risk to other mariners as these containers become hidden hazards floating just beneath the surface. PRM is of special concern for container vessels and car carriers which have modern flared fore and aft deck hull forms that deviate from historical designs that stability calculations are based on.

Enhancing this Flettner Vortex Scrubber with active seakeeping control increases a vessel’s operating envelope with enhanced crew comfort, efficiency, and the ability to limit harmful PRM. The novel Active Seakeeping FVS would make this climate change mitigation technology an even more attractive investment for ship owners and operators, by allowing the same rotor and scrubber hardware to also act as an active seakeeping system.

Active Flettner Vortex Scrubber (FVS) vs Currently Marketed Technologies

	System Type	Weight	Cargo Volume	Hull Resistance
Hydrofoil / rotor	Active	Medium ✗	No Change ✓	Yes ✗
Gyroscope	Active	Heavy ✗	Reduced ✗	No ✓
Active antiroll tanks	Active	Heavy ✗	Reduced ✗	No ✓
Passive antiroll tanks	Passive	Heavy ✗	Reduced ✗	No ✓
Bilge keels	Passive	Medium ✗	No Change ✓	Yes ✗
Active FVS	Active	Same ✓	No Change ✓	Propels ship ✓

Figure 2: Active FVS compared with currently marketed technologies

An objective was to build upon past Flettner Vortex Scrubber research and development to integrate an active system of seakeeping, thus making the design even more marketable and a better investment for ship owners, who are primarily obligated with maximizing profit and efficiency, as opposed to environmental and health concerns. The Active Flettner Vortex Scrubber aligns the profit motive of ship owners and operators with the health motive of the general population.

2. Design Criteria and Constraints

Criteria:

1) Reduce harmful cargo ship emissions by adding active seakeeping to the Flettner Vortex Scrubber value proposition, making this climate change emissions-reducing technology more attractive to ship owners, operators, and crew
2) Reduce risk of Parametric Rolling Movement (PRM)
3) Develop streamlined scale prototype demonstrating proof-of-concept
4) Auxiliary wind propulsion power maintaining cargo capacity
5) A scale cargo ship test mule demonstrating minimal change to metacentric height thus maintaining stability within United States Coast Guard (USCG), International Maritime Organization (IMO), Safety of Life at Sea (SOLAS) and underwriters' hull stability limits
6) The test mule should support accelerometers, sensors, software, controls, motor, and mechanical linkage to drive the Flettner Vortex Scrubber
7) An attractive business case for ship owners and operators

Design Constraints:

1) Low speed and high torque motor for rapid angular acceleration
2) Rotational speed control for deceleration
3) Wave pool must fit in 17'x19' area

4) Wave period and amplitude scaled to open ocean cargo ship prototype scale
5) Cargo ship test mule mass distribution, buoyancy, and hull shape must all approximate current ship class design such as a neopanamax
6) Cargo ship test mule hull must be watertight to avoid motor damage
7) Software must prioritize stepper driver pulse signal

<u>Research Questions:</u>

1) Can the Flettner Vortex Scrubber be controlled in such a way that improves seakeeping by minimizing the maximum angle of roll and maximum acceleration caused by open ocean wave conditions?
2) What is the relationship between seakeeping performance, such as maximum angle of roll and maximum angular acceleration, and fuel consumption?
3) What is the relationship between seakeeping performance, such as maximum angle of roll and maximum angular acceleration, and vessel value for various mission purposes?
4) Can the Flettner Vortex Scrubber technology be applied in ships based in developing economies?

<u>2. Materials and Methods:</u>

2.1 Risk and Safety: Power tools were properly used in a well-maintained workspace, while wearing appropriate clothing. Personal protective equipment was appropriately used: safety glasses, N95 masks, hearing protection, carving gloves, utility gloves to protect from sharp edges, nitrile gloves. All wiring within 6 feet of water is low voltage. 110 VAC appliances and enclosures are UL / ETL certified. Electrical connections to the power supply were inspected by an electrician prior to use and testing to ensure safety in excess of National Electric code. 110 VAC appliances used during testing were powered through a Ground Fault Current Interrupt (GFCI) as well as a safety switch that disconnects both line and neutral. All electrical devices were properly grounded. Low voltage marine wire was used.

2.2 3D Modeling: 3D modeling with Onshape software was used to for design work as well as to provided a basis for Computational Fluid Dynamics (CFD) analysis.

2.3 CFD: Computational Fluid Dynamics was used to optimize the 3D modeling. ANSYS was utilized as the software. CFD required adapting the 3D model for computational fluid dynamics by defeaturing and creating a domain boundary. Next a mesh for finite element analysis was developed. The k–omega two equation turbulence model as was an appropriate balance of resolution and complexity. This model is used to approximate Reynolds-averaged Navier–Stokes equations for viscous fluid flow. Validating the model and running various input conditions determined the righting moment generated by the Flettner rotor under various weather and sea state conditions.

2.4 Prototype Test Assembly:

Principles of naval architecture were used to design a cargo ship test mule with a mass distribution, buoyancy, metacentric height, and hull shape approximating a neopanamax container ship for testing of the Active FVS. This test mule was designed to have minimal change to metacentric height thus maintaining stability within United States Coast Guard (USCG), International Maritime Organization (IMO), Safety of Life at Sea (SOLAS) and underwriters' hull stability limits. A motor and drive system that could quickly accelerate and decelerate the rotation of the Flettner Vortex Scrubber in response to wave action was designed. This included a low speed, high torque 4.2 Amp NEMA 23 stepper motor located low in the test mule to approximate engine location, paired with an offboard stepper driver to provide sufficient current. The stepper driver has inputs to enable the motor, select the direction of rotation, and a pulse input to step the motor. A timing belt and polyurethane friction wheel drive system was developed with a 1:1 gear ratio calculated to provide rotor speeds between 0 and 300 RMP at maximum motor torque. Control of the stepper driver was achieved with an ATMEL ATMEGA2560 microcontroller on an Arduino Mega 2560. A six-axis motion tracking sensor was selected to measure the test mule's angle of roll from wave action, which was transmitted to the ATMEGA2560 via the I2C interface using an open source library developed by Fetick & Tockn in 2021. An algorithm developed and tuned for the microcontroller calculates Flettner rotor reaction speed, and communicates the appropriate drive frequency to a Pulse Width Modulation (PWM) generator over a TTL serial connection. The PWM generator was a low cost and straightforward solution to output to the stepper driver pulse input, which controls the motor through marine grade 20 AWG cable. The motor and motion tracking sensor were installed onboard the test mule, all other low voltage electronics were remote and enclosed. The waterproof, floating test mule was constructed from a #2 lumber keel and frame to support the FVS and drive system, secured with 3" x #9 construction screws and Loctite PL375 adhesive for an appropriately rigid structure. Topsides and a removable deck of 3/16" hardboard were secured with 1 ¼" x 8ga coarse thread drywall screws. A waterproof sealant was applied to the hull and bilge to prevent ingress of water.

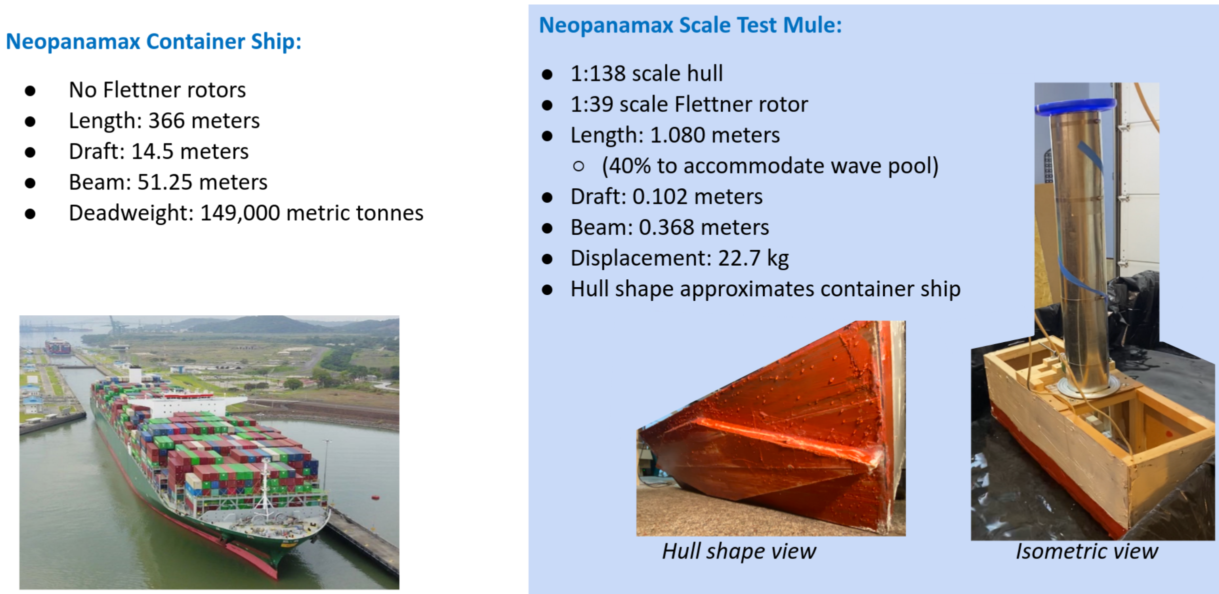

Figure 3: Neopanamax container ship, and neopanamax scale container ship test mule (American Journal of Transportation, 2021)

2.5 Wave Pool Design and Assembly:

A 309 gallon wave pool 3.05 meters long by 1.37 meters wide was designed to simulate frequency and amplitude of open ocean waves in various conditions, scaled to the cargo ship test mule. This resulted in waves with a 2.2 second period and 12.7 cm height, the equivalent of a container ship in 17.6 meter waves typical of the Beaufort Force 12 seas in a category 1 hurricane. The pool was constructed from #2 lumber, 7/16” plywood, and PVC membrane. At the one end a vertically reciprocating 130 x 30.5 cm panel displaced water to create waves. At the other end a damping pool and lift pump minimized reflected waves.

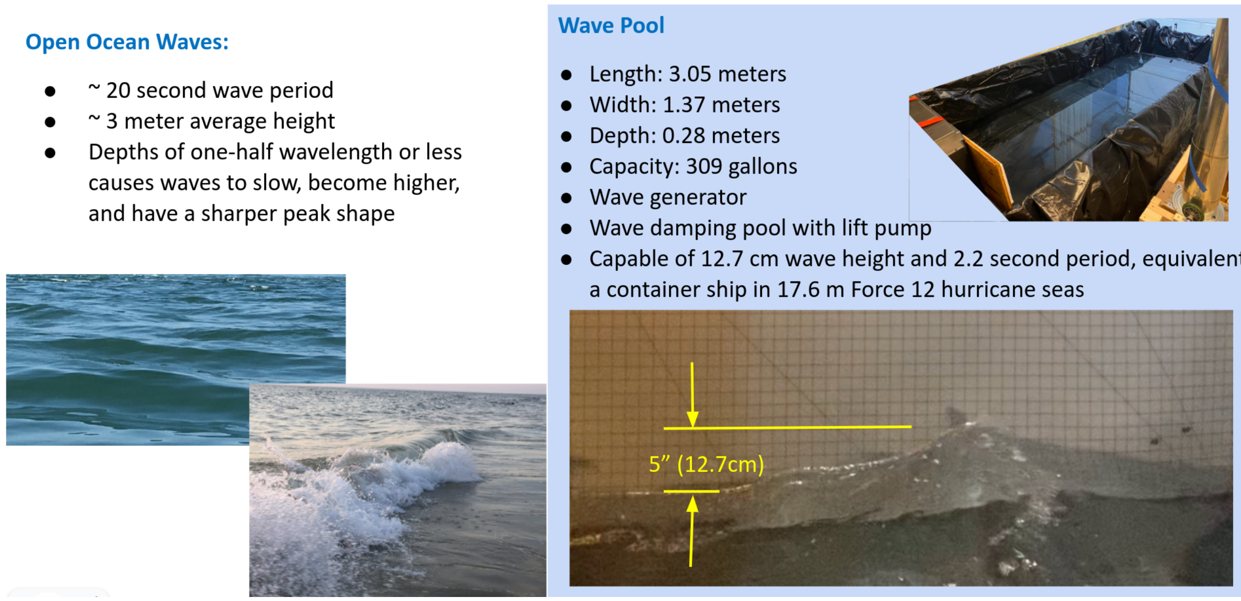

Figure 4: Wave pool design

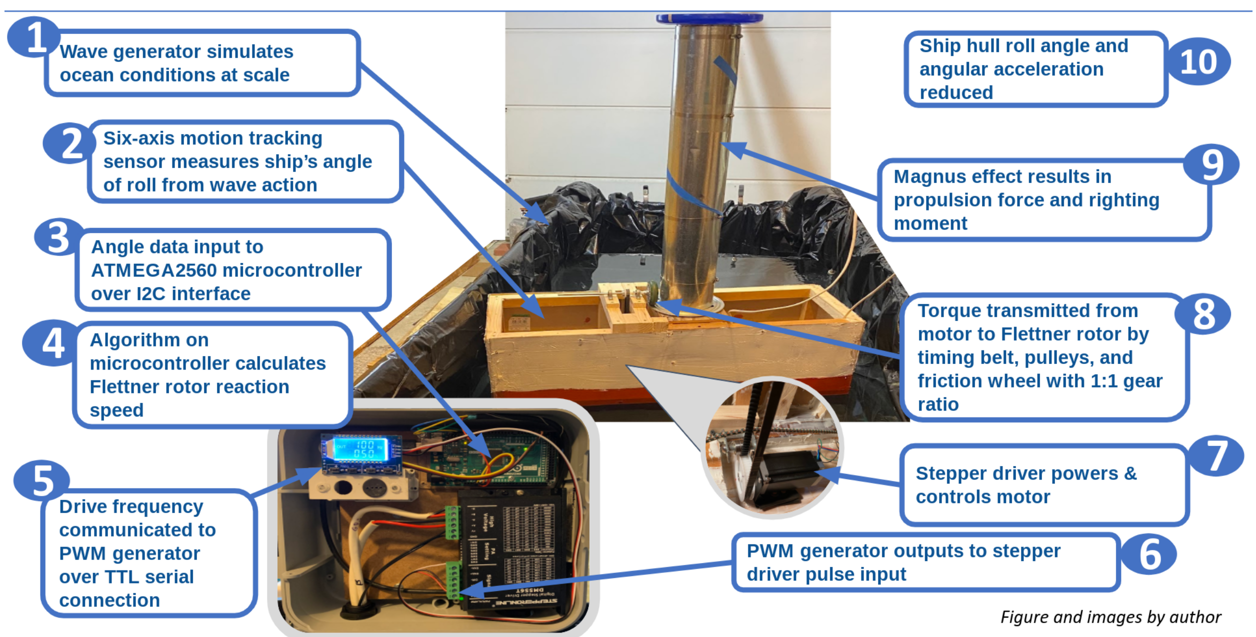

Figure 5: Cargo ship test mule with FVS in wave pool.

2.6 Free Vibration Test:

The free vibration test modeled a single ocean wave as a free vibration with an initial displacement. Damping was either only due to air and water resistance, or with the Active Flettner Vortex Scrubber (FVS) engaged. The wind tunnel was adjusted to 10 knots and wind speed was verified with an anemometer. Wind was positioned directly off the stern of the cargo ship test mule while it floated in the wave pool with the surface undisturbed. Independent variables:

1) Active FVS engaged / disengaged
2) Initial displacement
3) Wind speed
4) Wind angle

Dependent variable:

1) Maximum roll angle
2) Maximum roll acceleration

Positive control: the Flettner rotor set at maximum Revolutions Per Minute (RPM) and exposed to maximum wind speed

Negative controls: zero Flettner rotor RPM and maximum wind, maximum Flettner rotor RPM and zero wind speed.

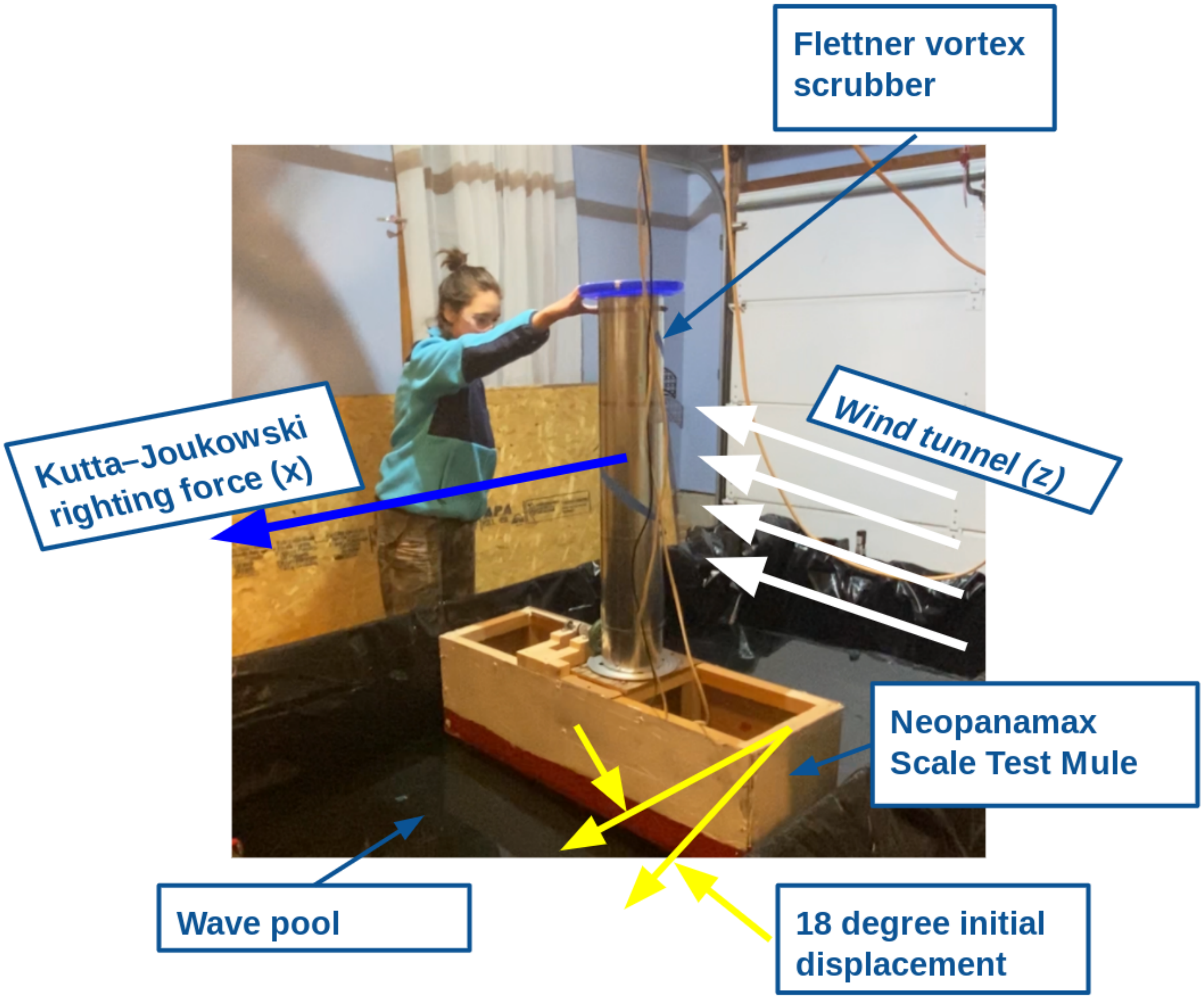

Figure 6: The author positions the cargo ship test mule for Free Vibration Test

2.7 Forced Vibration Ocean Wave Simulation:

The Forced Vibration Ocean Wave Simulation modeled ocean waves as a periodic forced vibration. Damping was either only due to air and water resistance, or with the Active Flettner Vortex Scrubber (FVS) engaged. The wind tunnel was adjusted to 10 knots and wind speed was verified with an anemometer. Wind was positioned directly off the stern of the cargo ship test mule while it floated in the wave pool with the surface undisturbed. Periodic waves were positioned directly off of the port beam of the cargo ship test mule.

<u>Independent variables:</u>

1) Active FVS engaged / disengaged
2) Wave period and amplitude
3) Wind speed
4) Wind angle

Dependent variables:

1) Maximum roll angle
2) Maximum roll acceleration

Positive control: the Flettner rotor set at maximum Revolutions Per Minute (RPM) and exposed to maximum wind speed

Negative controls: zero Flettner rotor RPM and maximum wind, maximum Flettner rotor RPM and zero wind speed

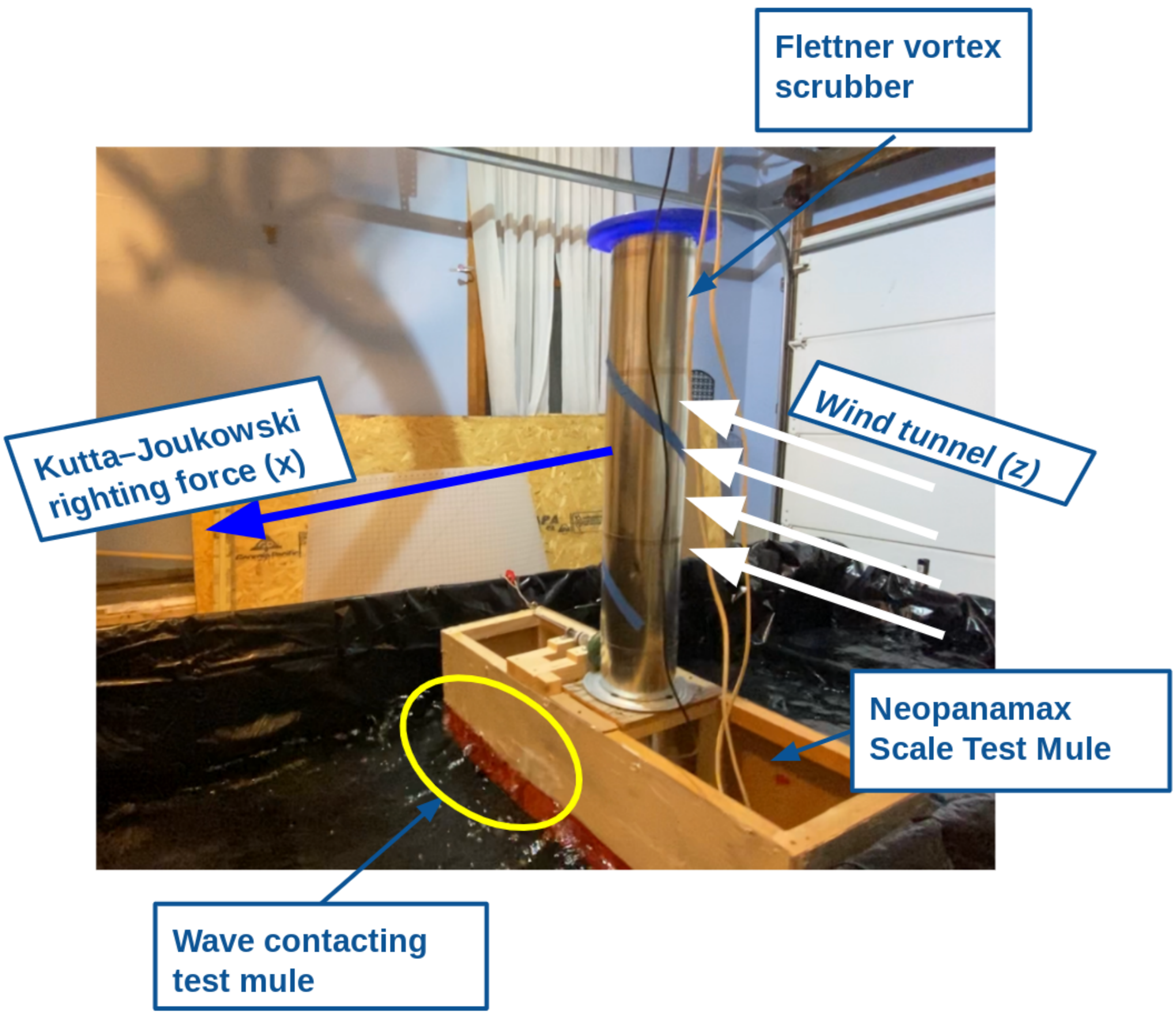

Figure 7: Forced Vibration Ocean Wave Simulation

3. Results:

It was confirmed through Computational Fluid Dynamics (CFD) optimizations and iterations that a functional Flettner rotor and exhaust scrubber system can be integrated and used as a component of an active system for seakeeping. CFD analysis with various input conditions was used to iteratively optimize scrubber geometry for prototype design, with the goal of maximizing velocity, centrifugal force, and particulate matter retained, and minimizing pressure drop (Michaluk, 2021). Additional CFD analysis of the Flettner Vortex scrubber was performed to gain insight about areas of turbulence and the impact on pressure drop across the scrubber.

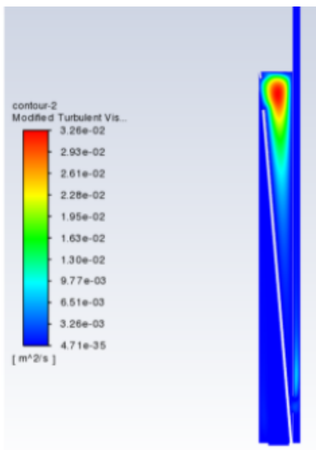

Figure 8: Area of turbulence at scrubber vortex entrance

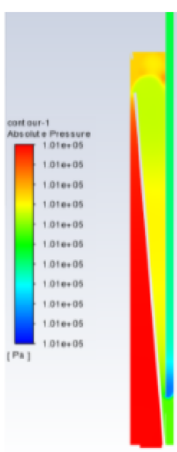

Figure 9: Pressure drop across scrubber

Computational Fluid Dynamics runs in ANSYS Fluent showed areas of laminar flow in parallel layers, as well as complex and chaotic turbulent flows. Mass flow imbalance residuals on the order of 10^{-8} indicate a well-converged model. A three-dimensional CFD model was meshed with approximately 300,000 cells, including finer mesh in the area of the rotor. Boundary conditions were input velocity set at 5.14 m/s (10 knots) at the entrance, zero pressure at the exit, and symmetry on all four sides. The boundary condition of the rotor was a wall with a no-slip surface velocity of zero. For the following figures rotor speed was set to 31.4 radians per second (300 RPM). Air was modeled as incompressible due to velocities well below subsonic. The k–epsilon two equation turbulence model used to approximate Reynolds-averaged Navier–Stokes equations for viscous fluid flow converged around 4000 iterations. This CFD analysis showed that the Flettner Vortex Scrubber could generate a righting moment that can be harnessed for seakeeping purposes.

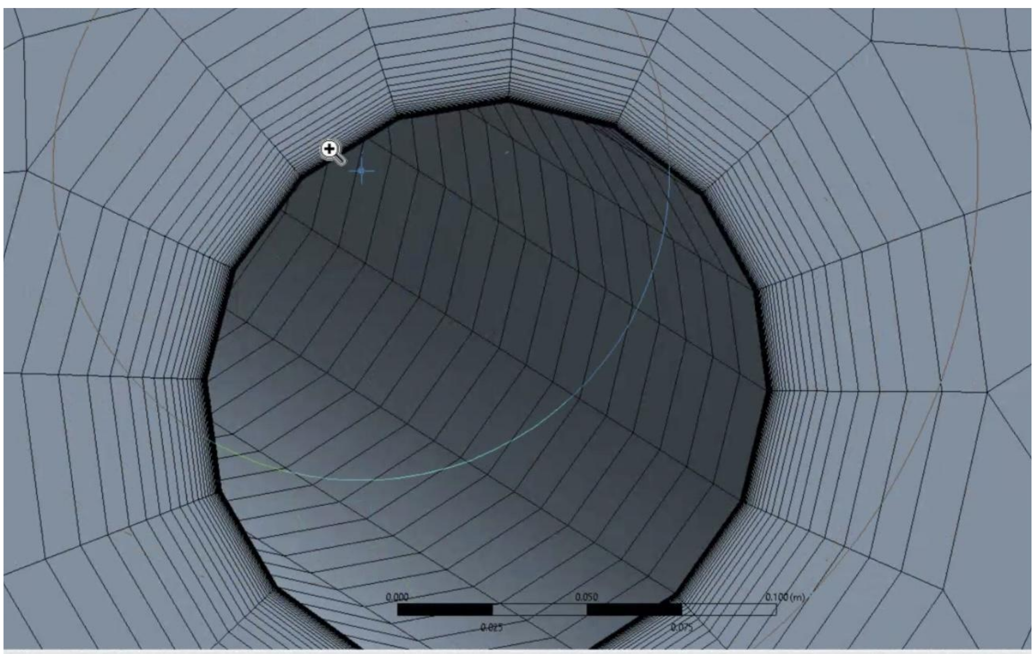

Figure 10: Close up of finer mesh around rotor

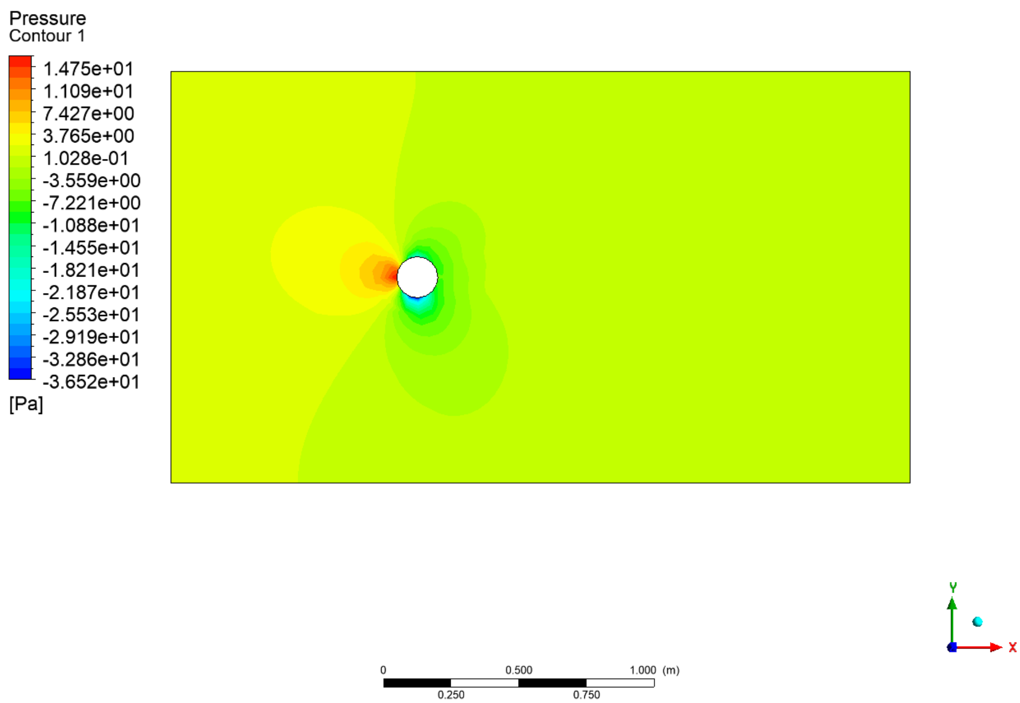

Figure 11: Pressure contour around spinning Flettner Vortex Scrubber

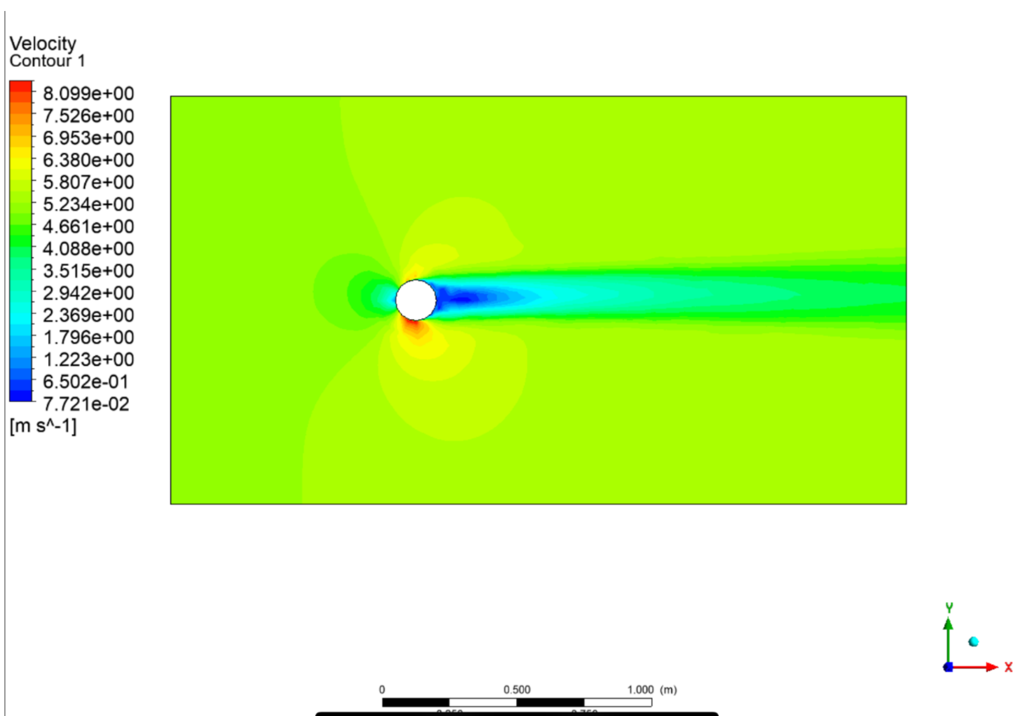

Figure 12: Velocity contour around spinning Flettner Vortex Scrubber

The Free Vibration Test showed that damping from the Active Flettner Vortex Scrubber reduced time to recover from a 18 degree displacement by 45%.

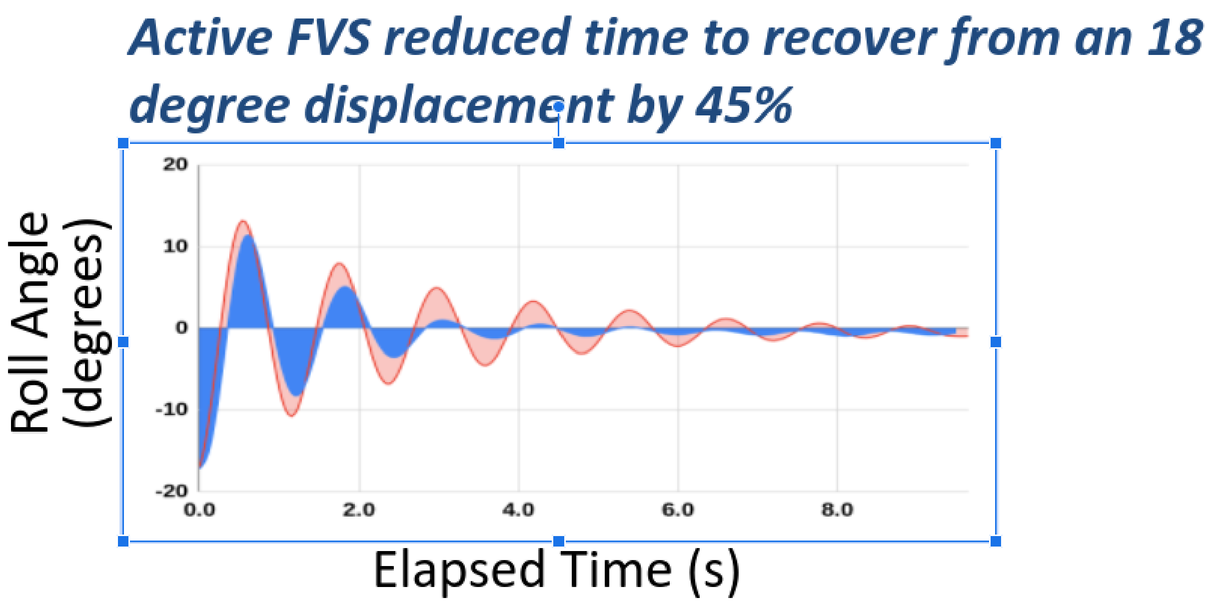

Figure 13: Results of Free Vibration Test

The Forced Vibration Ocean Wave simulation showed that the Active Flettner Vortex Scrubber reduced maximum rolling angle by 65.6%

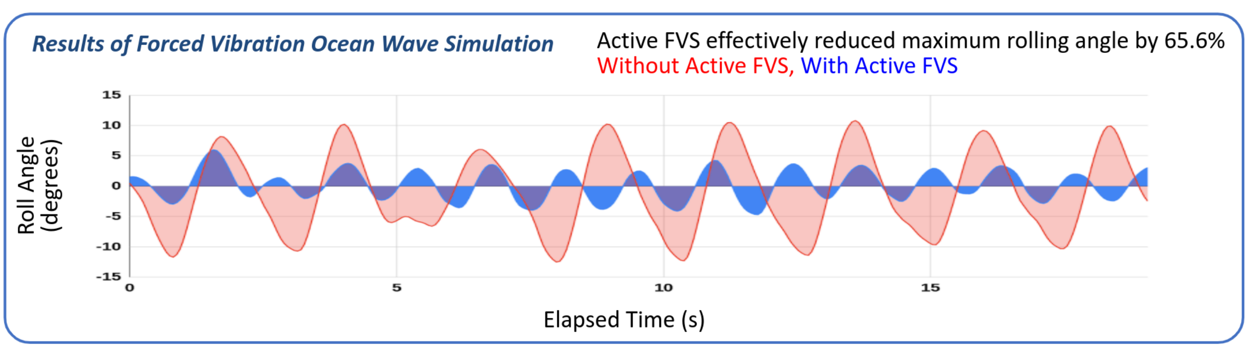

Figure 14: Results of Forced Vibration Test

<u>4. Discussion</u>

Repeated samples were taken. Matched pairs t-Tests were used to compare the angle of roll measured during the Forced Vibration Ocean Wave Simulation, with data points from waves with and without the Active FVS engaged. The null hypothesis was $\mu 1 = \mu 2$ that the Active FVS did not provide damping and therefore seakeeping. The alternate hypothesis was that $\mu 1 < \mu 2$ that the Active FVS did provide damping and therefore seakeeping. For all waves $p <$ alpha (0.05), the null is rejected and alternate accepted. The addition of controls for active seakeeping to a Flettner is a novel concept according to the research here, and adds value to the Flettner Vortex Scrubber.

5. Conclusions:

This work is broadly applicable. The 3D model, computational fluid dynamics results, and prototype test data show that the Flettner Vortex Scrubber can also serve as an effective seakeeping system. The performance tests in the wave pool were informative. The Free Vibration Test showed that damping from the Active Flettner Vortex Scrubber reduced time to recover from an 18 degree displacement by 45%. The Forced Vibration Ocean Wave simulation showed that the Active Flettner Vortex Scrubber reduced maximum rolling angle by 65.6%. This seakeeping performance expands the vessel's operating envelope by improving crew comfort and effectiveness, as well as reduces the risk of parametric rolling movement which can be damaging to both ship and cargo. Enhancing the value of the Flettner Vortex Scrubber with active seakeeping makes this technology more attractive for deployment, in particular for developing economies. Flettner Vortex Scrubber functioned effectively both as an auxiliary propulsion source, and an exhaust scrubber. In addition to reducing climate change and improving health, this attractive investment pays for itself in less than a year through fuel savings and increased cargo space (Michaluk, 2021). A flettner vortex scrubber would allow a neopanamax ship to transport an additional 53 TEU containers, which are worth $185,000 on a trip from Shanghai to New York (Michaluk, 2021).

Previously it was shown that a conservative estimate for Flettner rotor auxiliary power performance is the Timberwolf (ex Maersk Pelican) tanker's 8.2% reduction in fuel use (Global Maritime Energy Efficiency Partnerships, GloMEEP, 2021; Norsepower, 2021; Offshore Energy, 2019). If this result were to scale to the global cargo shipping fleet, it would mean a climate change impact equivalent to taking five million cars off the road. Combining Flettner rotors with an exhaust scrubber will make the investment more attractive for ship owners and operators and can increase the rate of adoption of this climate change mitigation technology.

The Flettner vortex scrubber collects particulate matter as a solid, which may be upcycleable as a feedstock for industrial processes such as carbon black

6. Limitations and Next Steps:

Further development is being funded by federal, corporate, and nonprofit grants. Next steps include design and construction of a seaworthy prototype for open water testing. This will require performing fatigue analysis and accelerated lifetime testing. MIL STD 810 G will be a good reference for salt fog and mechanical vibrations of shipboard equipment. Further exploration of Machine Learning algorithms that maximize six-axis sea state detection, as well as investigating global shipping lane weather routing to incorporate weather forecast inputs into the algorithms are planned. I am currently in the process of applying for a patent.

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3D Design and modeling performed in PTC Onshape CAD software
Computational Fluid Dynamics analysis performed in Ansys Fluent
Statistical tests performed in Excel Analysis ToolPak