Problems and Solutions

Seakeeping Value Proposition: Ships, such as research vessels, where passenger comfort is a priority, increase their operating envelope with active seakeeping measures such as hydraulically controlled hydrofoils, gyroscopes, or powerful pumps that transfer water between large port and starboard tanks as the ship rolls. These systems consume valuable cargo space and energy, and require costly hardware. This makes them cost prohibitive, especially to developing economies.

Solution: Enhancing the Flettner Vortex Scrubber (FVS) with active seakeeping control would make this climate change mitigation technology an even more attractive investment for cargo ship owners and operators, by allowing the same rotor and scrubber hardware to also act as an active seakeeping system.

Emission Problem: Our 100,000 cargo ships transport 90% of goods and contribute **4% to global emissions**, cause **7.6 million childhood asthma** cases, and cause **150,000 premature deaths** annually.[14][18] The International Maritime Organization (IMO) lowered sulphur emissions restrictions to 0.5% in 2020, forcing ships to install scrubbers or use expensive non-residual fuels.[10][14] Electric propulsion requires batteries, which are expensive and in short supply.

Scrubber Problem: Current land-based gas scrubbers used in power plants are complex and expensive.[17] Open loop scrubbers discharge waste water overboard trading air pollution for water pollution. Closed loop scrubbers require storage of waste that must be processed later.[2][15] Adding onboard hardware results in less cargo space, leading to demand for more ships and more trips.

Solution: (My previous work) 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.

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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 1: A rotor ship, E-Ship 1

adapted from https://www.auerbach-schifffahrt.de/index_eng.php, by Schmidt-Ohm & Partner. (2020)

Flettner rotors use the Magnus effect to harness wind power without setting and trimming sails. Flettner rotors generate approximately an order of magnitude more lift than sails of the same area.[7][8]
The Flettner rotor ship *Baden Baden* (ex *Buckau*) crossed the Atlantic in 1925, however the challenges of maintaining balanced rotating steel cylinders was shelved until composite materials improved stability, and climate change concerns renewed interest in wind power for large ships.[3][4][6][12]

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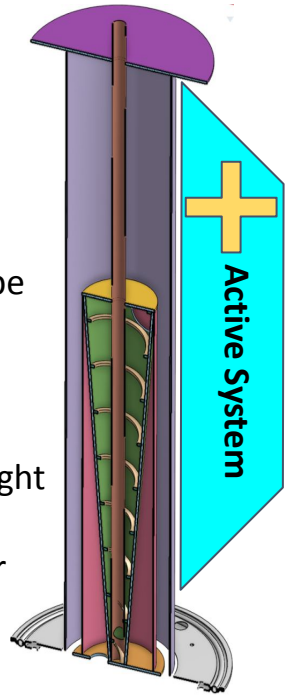
Design Criteria and Constraints

Design Goals and Criteria:

- 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
- Reduce risk of parametric roll
- Develop streamlined scale prototype demonstrating proof-of-concept
- Auxiliary wind propulsion power maintaining cargo capacity
- Minimal change to metacentric height thus maintaining stability within USCG, IMO, SOLAS and underwriter limits
- An attractive business case for ship owners and operators



Design Constraints:

- Low speed and high torque motor for rapid angular acceleration.
- Rotational speed control for deceleration
- Wave pool must fit in 17’x19’ area
- Wave period and amplitude scaled to open ocean cargo ship prototype scale
- Prototype mass distribution, buoyancy, and hull shape must approximate cargo ship
- Prototype ship hull must be watertight to avoid motor damage
- Software must prioritize stepper driver pulse signal

Research Questions:

- 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?
- What is the relationship between seakeeping performance, such as maximum angle of roll and maximum angular acceleration, and fuel consumption?
- What is the relationship between seakeeping performance, such as maximum angle of roll and maximum angular acceleration, and vessel value for various mission purposes?
- Can the Flettner Vortex Scrubber technology be applied in ships based in developing economies?

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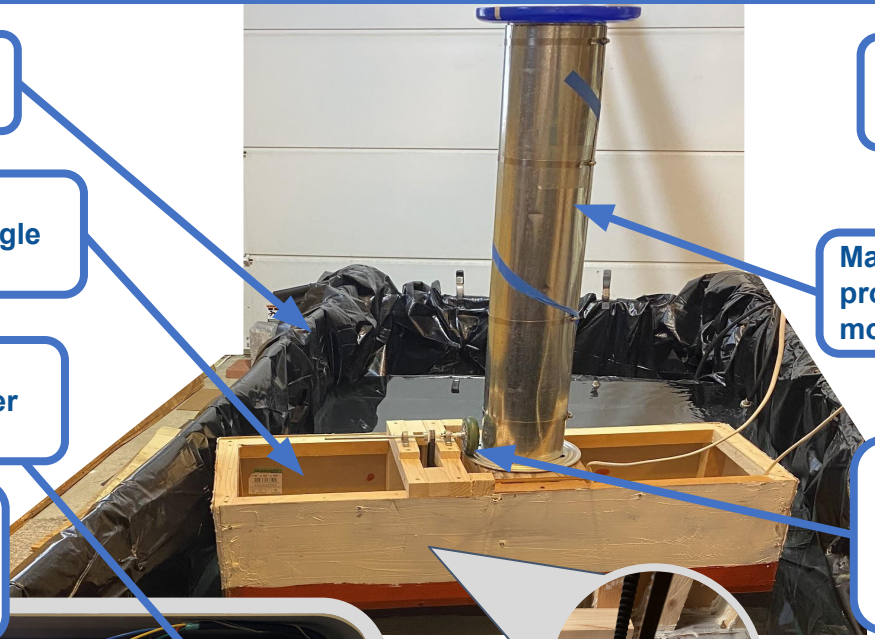
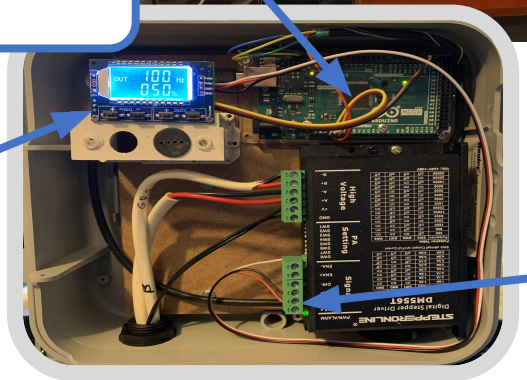
Methods: Prototype in Wave Pool Test Tank

1. Wave generator simulates ocean conditions at scale
2. Six-axis motion tracking sensor measures ship's angle of roll from wave action
3. Angle data input to ATMEGA2560 microcontroller over I2C interface
4. Algorithm on microcontroller calculates Flettner rotor reaction speed
5. Drive frequency communicated to PWM generator over TTL serial connection
6. PWM generator outputs to stepper driver pulse input
7. Stepper driver powers & controls motor
8. Torque transmitted from motor to Flettner rotor by timing belt, pulleys, and friction wheel with 1:1 gear ratio
9. Magnus effect results in propulsion force and righting moment
10. Ship hull roll angle and angular acceleration reduced





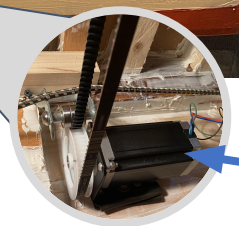


Figure and images by author

Methods: Naval Architecture
Building physical container ship model for wave testing

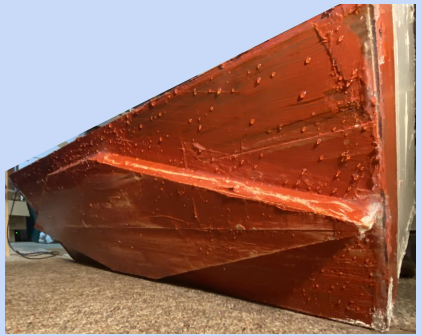
Neopanamax Container Ship:

- No Flettner rotors
- Length: 366 meters
- Draft: 14.5 meters
- Beam: 51.25 meters
- Deadweight: 149,000 metric tonnes

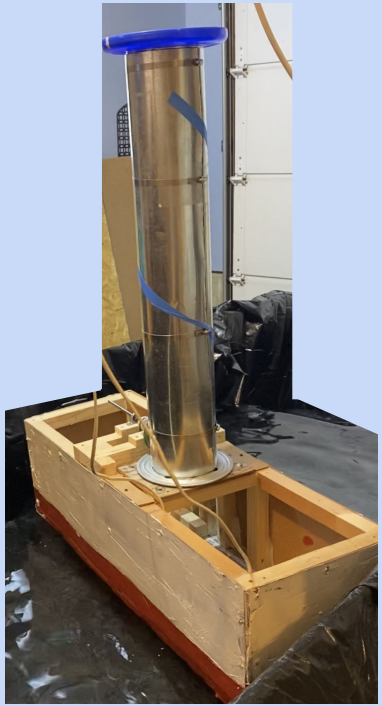
Neopanamax cargo ship by: https://ajot.com/news/panama-canal-extends-max-length-and-increases-draft-for-neopanamax-locks
Figures and image by author

Neopanamax Scale Test Mule:

- 1:138 scale hull
- 1:39 scale Flettner rotor
- Length: 1.080 meters
  - (40% to accommodate wave pool)
- Draft: 0.102 meters
- Beam: 0.368 meters
- Displacement: 22.7 kg
- Hull shape approximates container ship



Hull shape view



Isometric view

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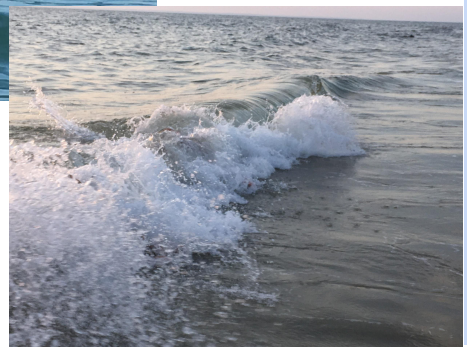
Methods: Naval Architecture
Building wave pool to test FVS active system

Open Ocean Waves:

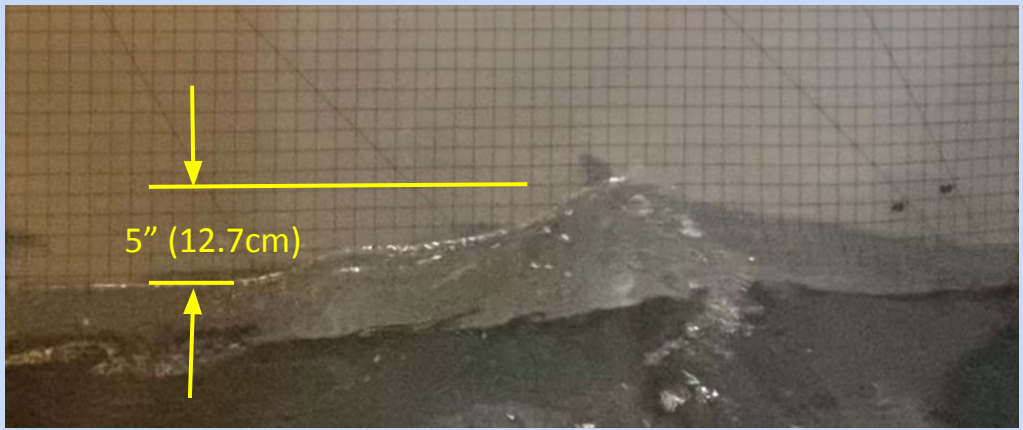
- ~ 20 second wave period
- ~ 3 meter average height
- Depths of one-half wavelength or less causes waves to slow, become higher, and have a sharper peak shape



Figures and images by author

Wave Pool

- Length: 3.05 meters
- Width: 1.37 meters
- Depth: 0.28 meters
- Capacity: 309 gallons
- Wave generator
- Wave damping pool with lift pump
- Capable of 12.7 cm wave height and 2.2 second period, equivalent
  a container ship in 17.6 meter Force 12 hurricane seas



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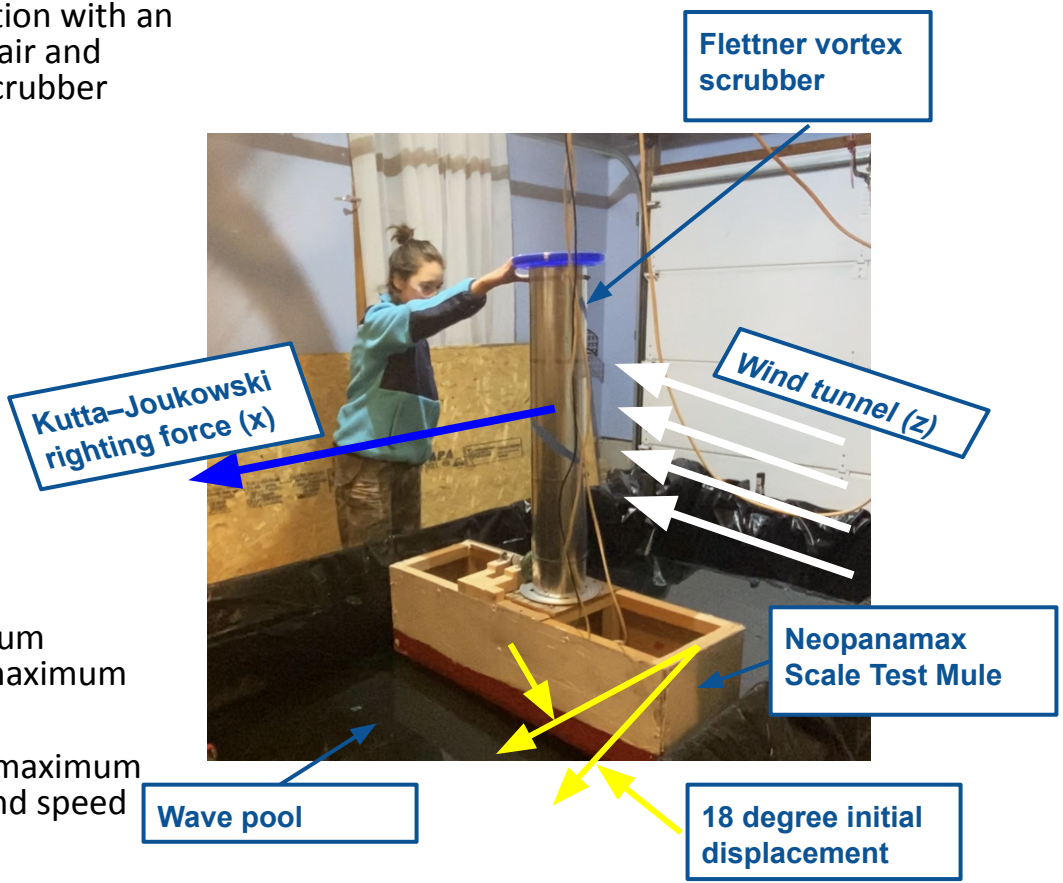
Methods: Free Vibration Test

This 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.

- **Independent variables:**
  - Active FVS engaged / disengaged
  - Initial displacement
  - Wind speed
  - Wind angle
- **Dependent variables:**
  - Maximum roll angle
  - 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



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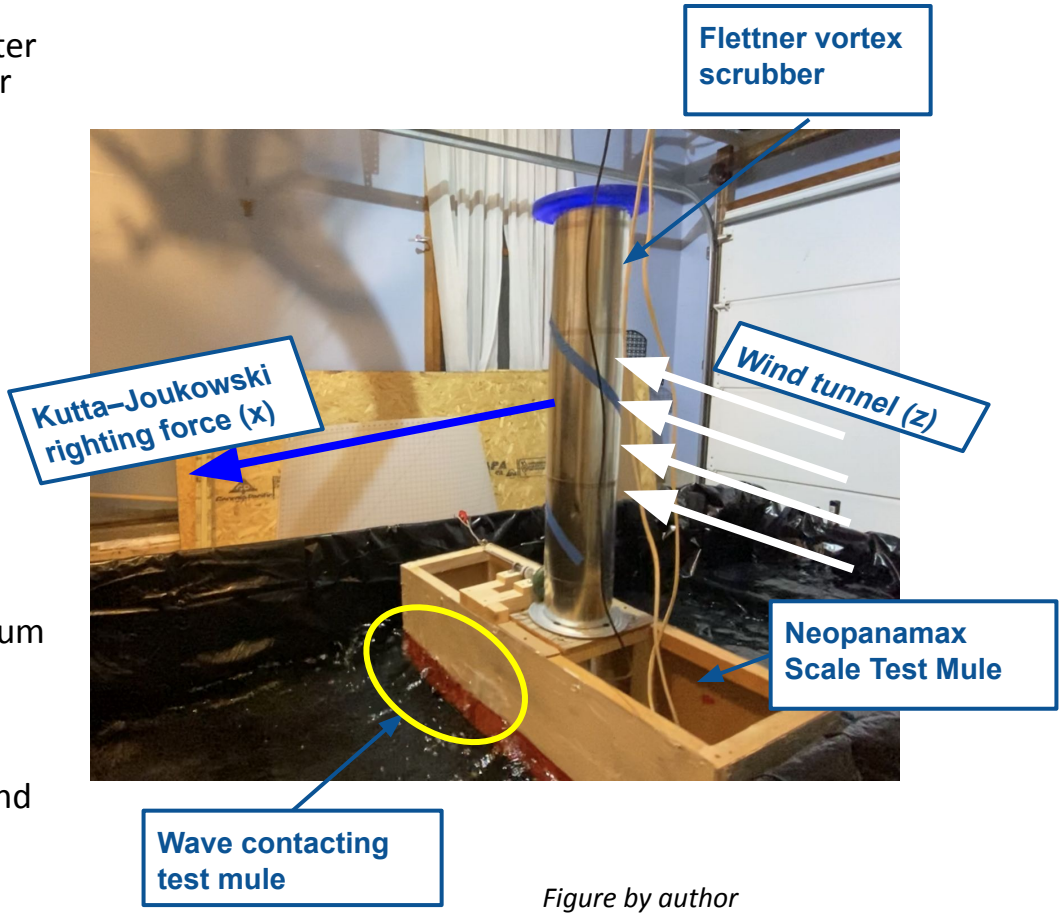
Methods: Forced Vibration Ocean Wave Simulation

This test 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.

- **Independent variables:**
  - Active FVS engaged / disengaged
  - Wave period and amplitude
  - Wind speed
  - Wind angle
- **Dependent variables:**
  - Maximum roll angle
  - 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



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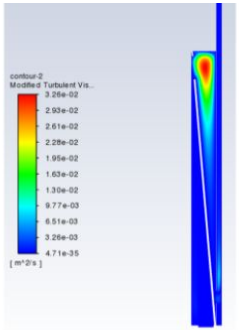
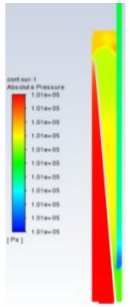
Results

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.

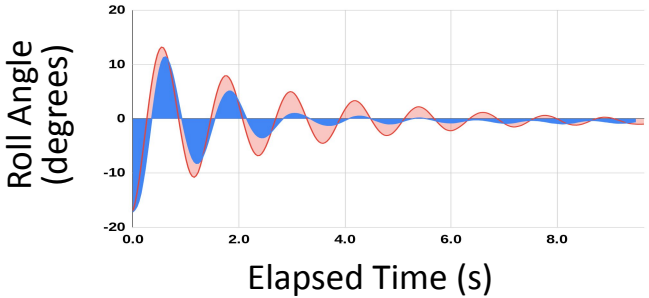


Areas of turbulence at scrubber vortex entrance



Pressure drop across the scrubber

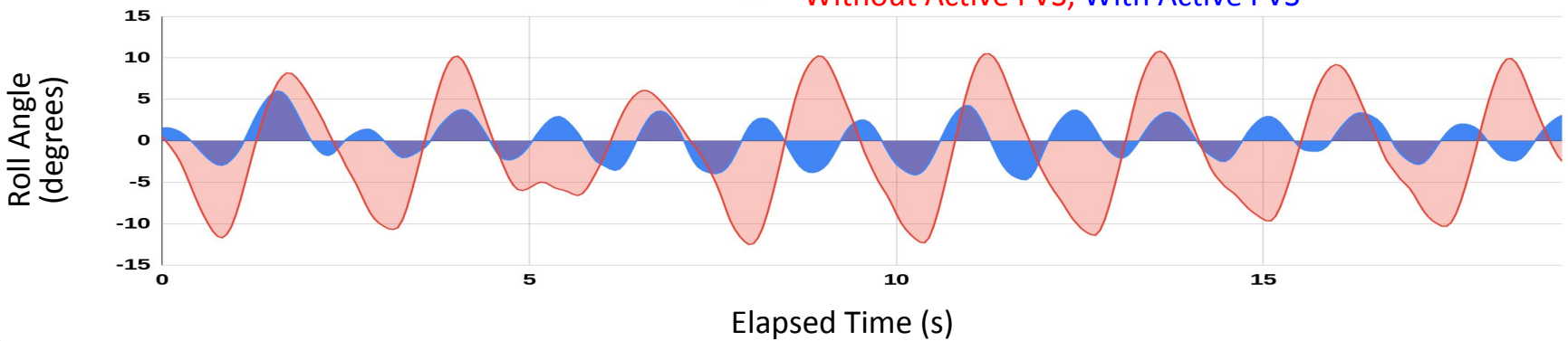
Active FVS reduced time to recover from an 18 degree displacement by 45%



Results of Forced Vibration Ocean Wave Simulation

Active FVS effectively reduced maximum rolling angle by 65.6%

Without Active FVS, With Active FVS



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Analysis & Discussion

Statistical Analysis

- 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.

Discussion

- CFD analysis showed that the Flettner Vortex Scrubber could generate a righting moment that can be harnessed for seakeeping purposes
- According to a review of current literature, the addition of Flettner rotor controls for active seakeeping is a novel concept, and adds value to the Flettner Vortex Scrubber

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Conclusions

New 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.
- Reduces maximum rolling angle by 65.6%
- Active Flettner Vortex Scrubber Damping reduces time to recover from a 18 degree displacement by 45%
- Expands vessel operating envelope by improving crew comfort and effectiveness
- Reduces risk of parametric rolling
- Reduces fuel consumption making particularly viable for developing economies
- The 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. 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.

Previous Conclusions

- A conservative estimate for Flettner rotor auxiliary power performance is the Timberwolf *(ex Maersk Pelican)* tanker's 8.2% reduction in fuel use.[5][13][16] 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

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Next Steps

Further development funded by federal, corporate, and nonprofit grants. Next steps include:

1) A seaworthy prototype
2) Open water testing
3) Further exploration of Machine Learning algorithms that maximize six-axis sea state detection
4) Incorporation of weather forecast inputs into the algorithms
5) Performing fatigue analysis and accelerated lifetime testing, and investigating global shipping lane weather routing. MIL STD 810 G will be a good reference for salt fog and mechanical vibrations of shipboard equipment
6) I am currently in the process of applying for a patent