Hybrid Glider Progress and Future Directions

6th Biannual NRC-IOT Workshop on Underwater Vehicle Technology

Halifax, NS

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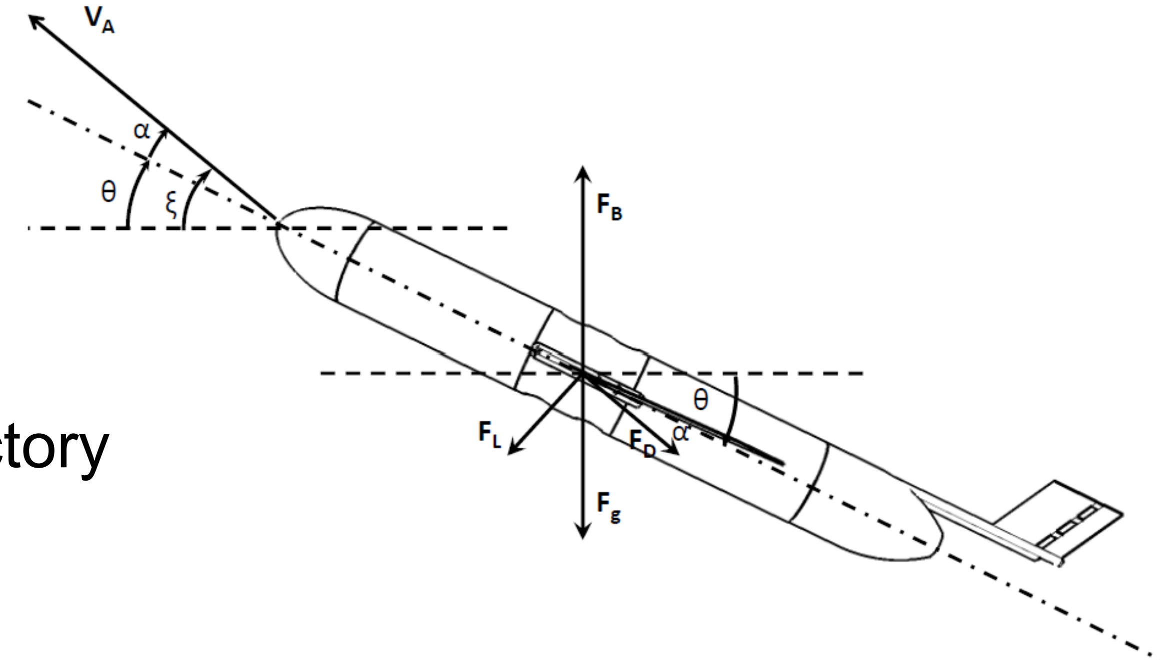
Gliders

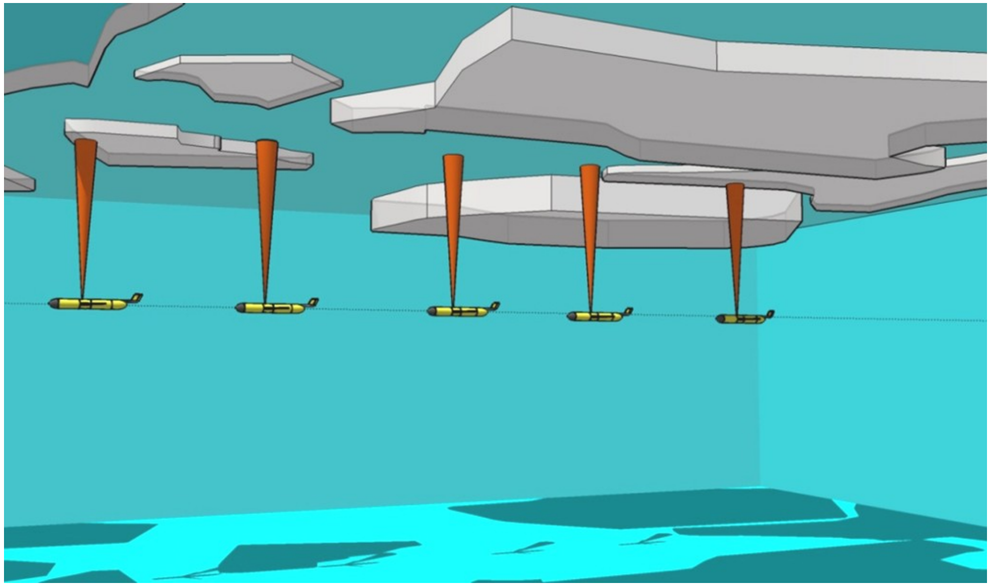
- **Specialized AUV**
  - Ballast
  - Wings
  - Sawtooth trajectory



Schematic defining relevant angles and forces

Motivation

- **Why are you putting another propulsion device onto a Glider?**
  - Horizontal flight
  - Higher speeds
  - Underwater docking


Hybrid Glider flying potential ice profiling mission. [RB]

Test System

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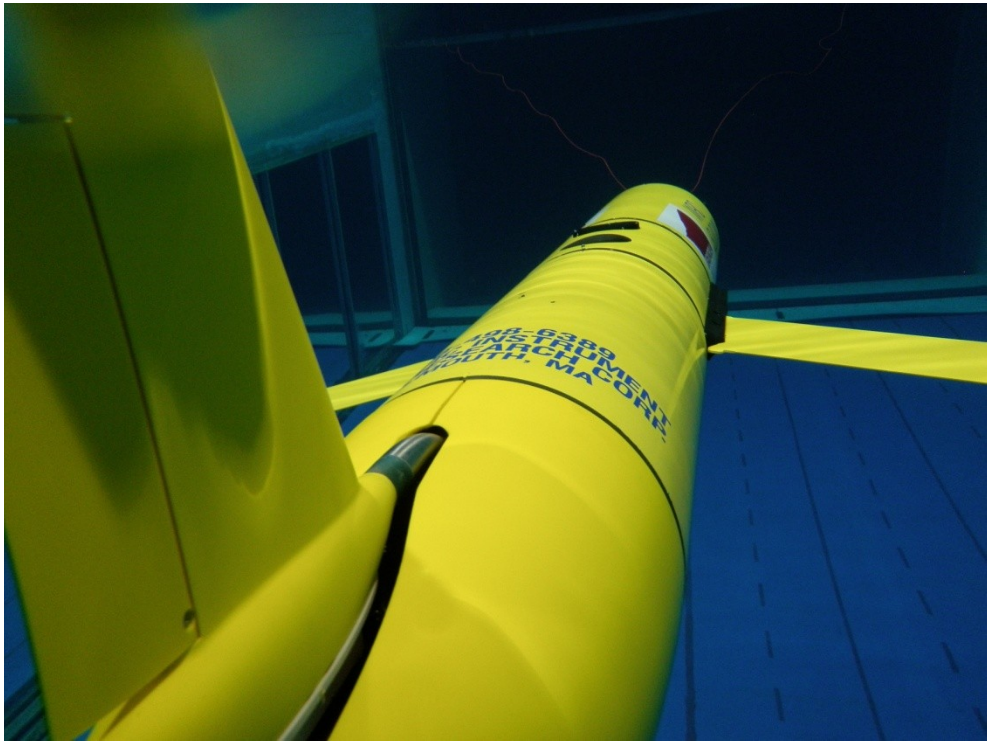
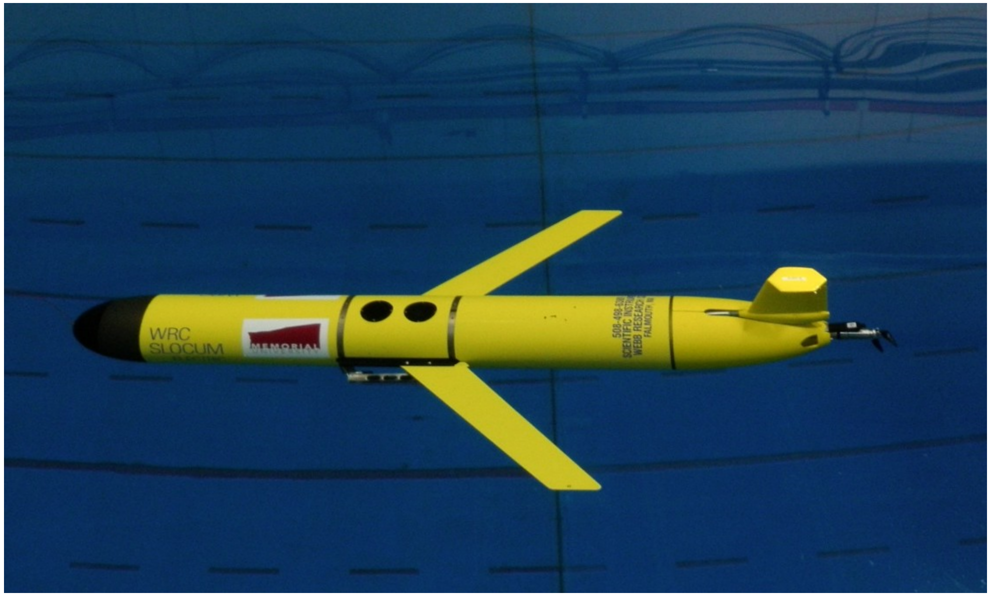
- **Slocum 200m electric glider**
  - ASL ice profiling sonar
  - Prototype auxiliary propulsion



Glider 49 in Marine Institute Flume Tank

Integration

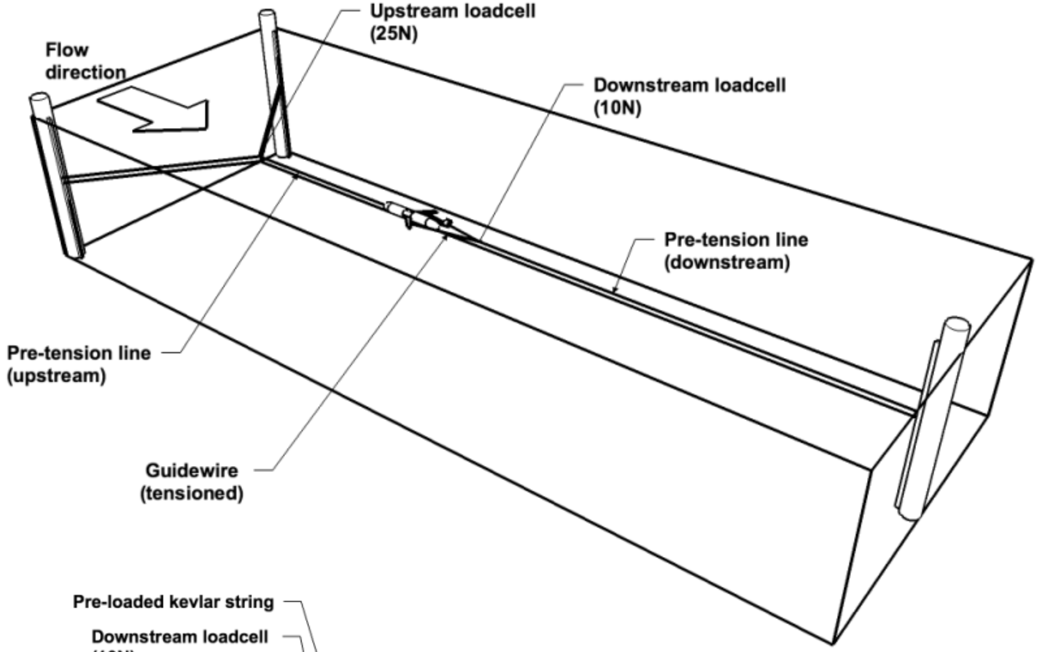
- **Mechanical**
  - Propulsion device replaces 500g emergency drop weight
- **Electrical**
  - Plugs into standard impulse connector
  - Controlled through science computer



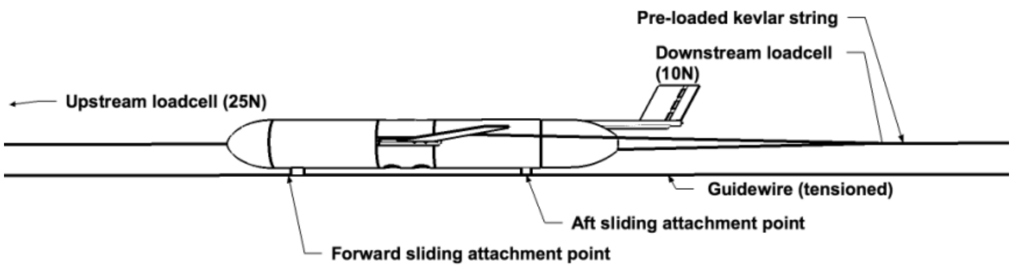
Hybrid Glider in Marine Institute Flume Tank with propulsion module installed

Full Scale Flume Tank Tests

- **Drag and Self Propulsion**
  - Zero angle of attack



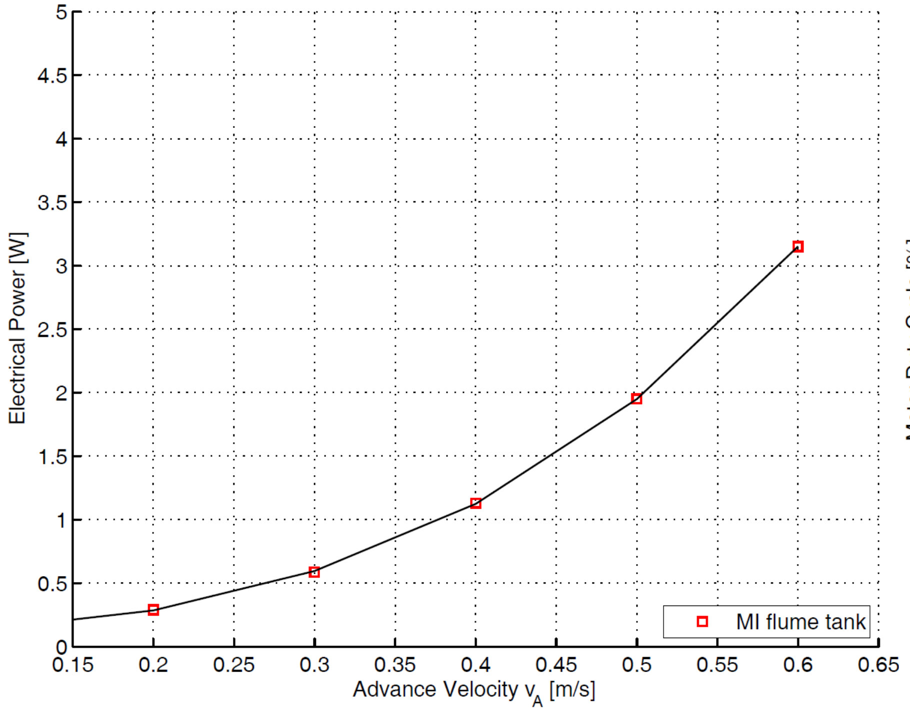
Test layout



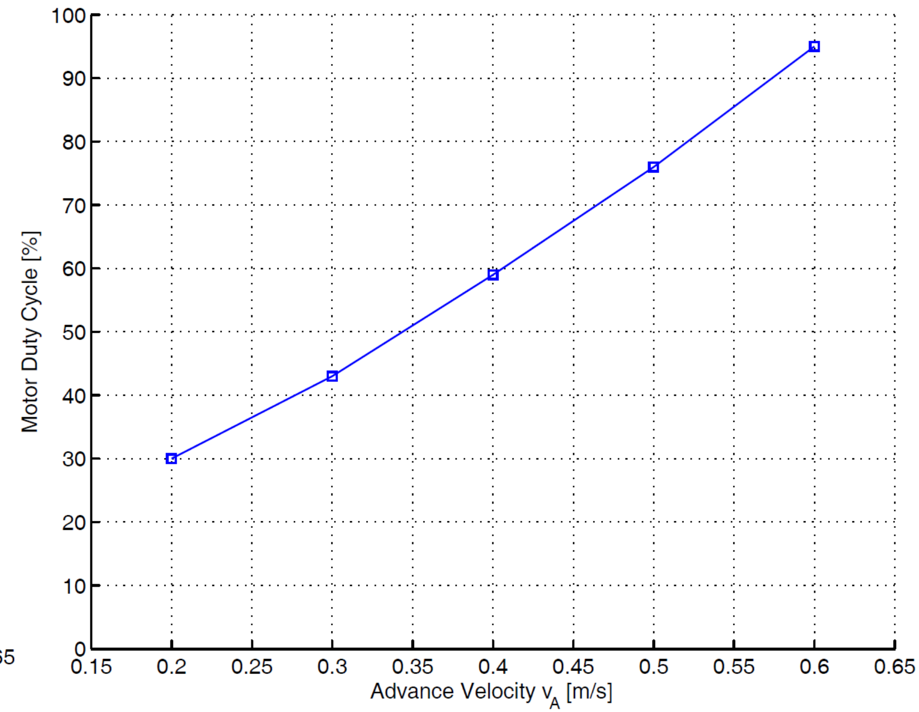
Close up of Test layout

Full Scale Flume Tank Tests

- **Results**



Electrical Power for Self Propulsion

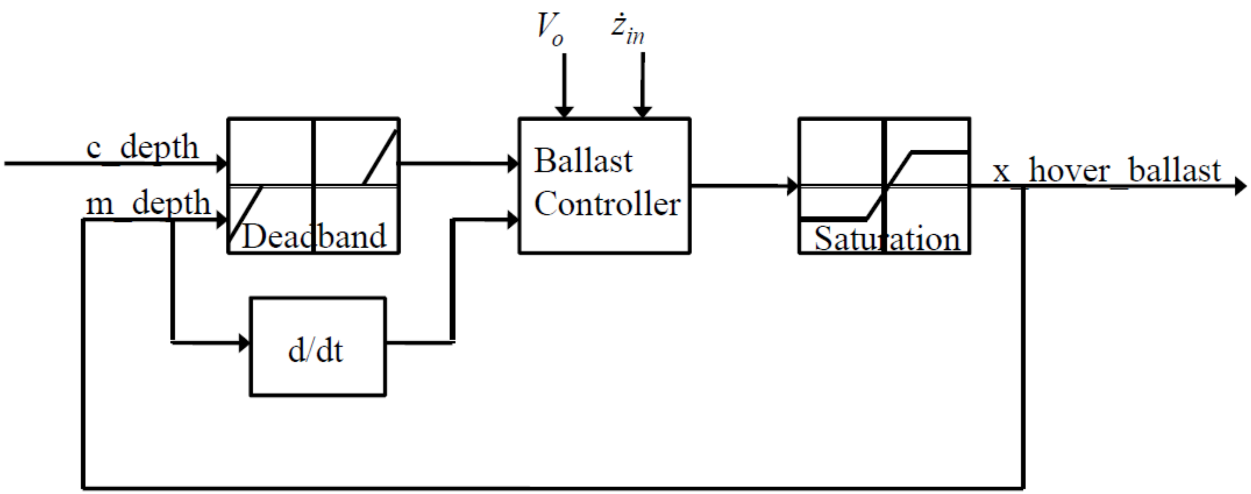


Motor Duty Cycle for Self Propulsion

Horizontal Flight

- **Strategy**
  - Existing drift-at-depth behaviour
    - Depth – Ballast system
    - Pitch – Mass shifting
  - Auxiliary propulsion system for horizontal movement

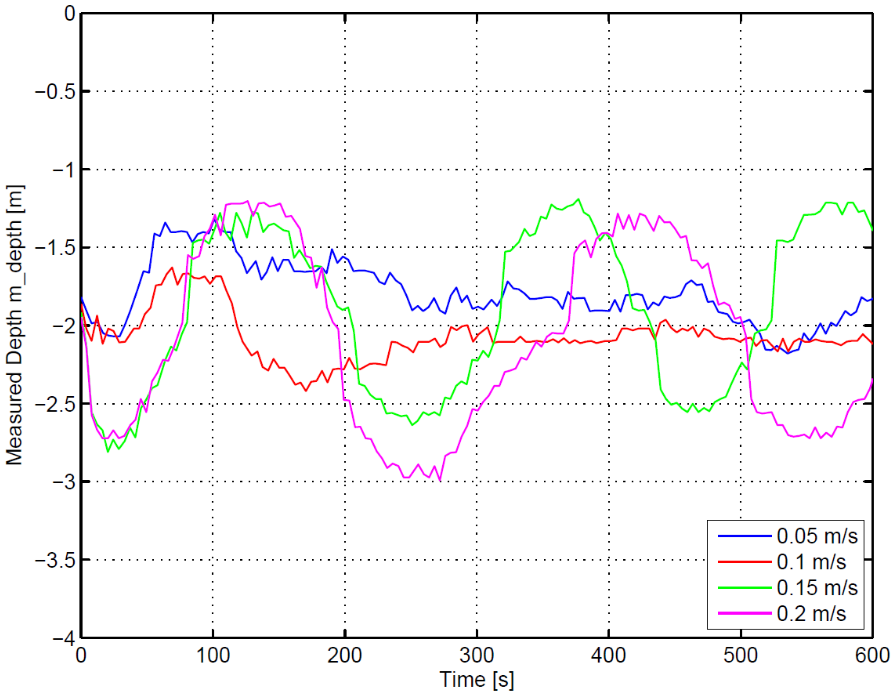
Depth Controller Tuning



- **To Tune**
  - $\dot{z}_{in}$, V_o
- **Tests in Deep Water Test Tank**

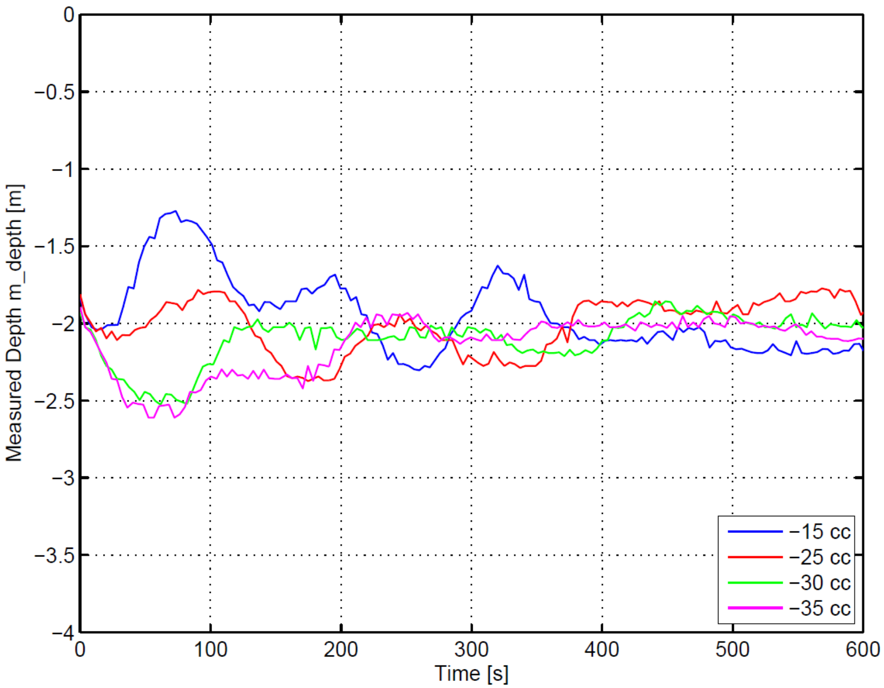
Depth Controller Tuning

- **$\dot{z}_{in}$ tuning**
  - $\dot{z}_{in}$ = 0.1 m/s



Hovering Depth Rate Tuning

- **V_o tuning**
  - V_o = -30 cc



Initial Ballast Volume Tuning

Ocean Engineering Basin

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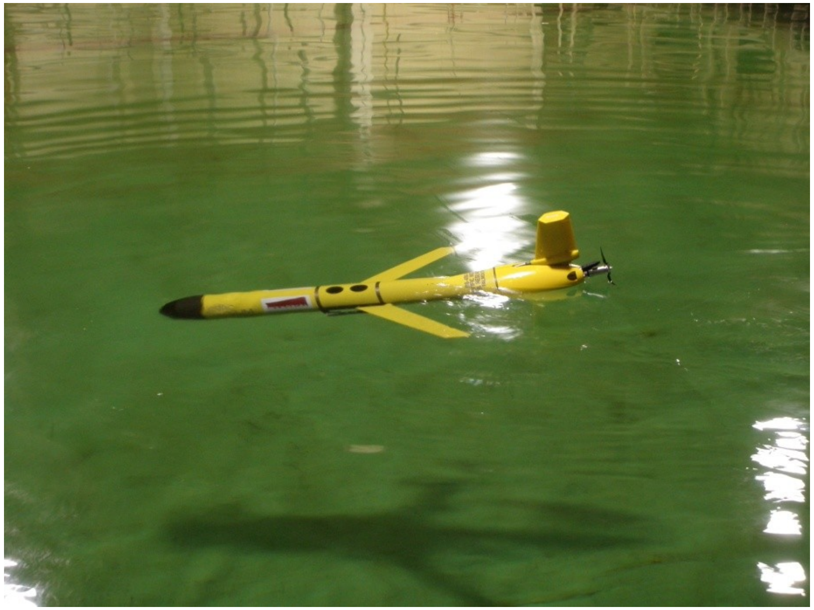
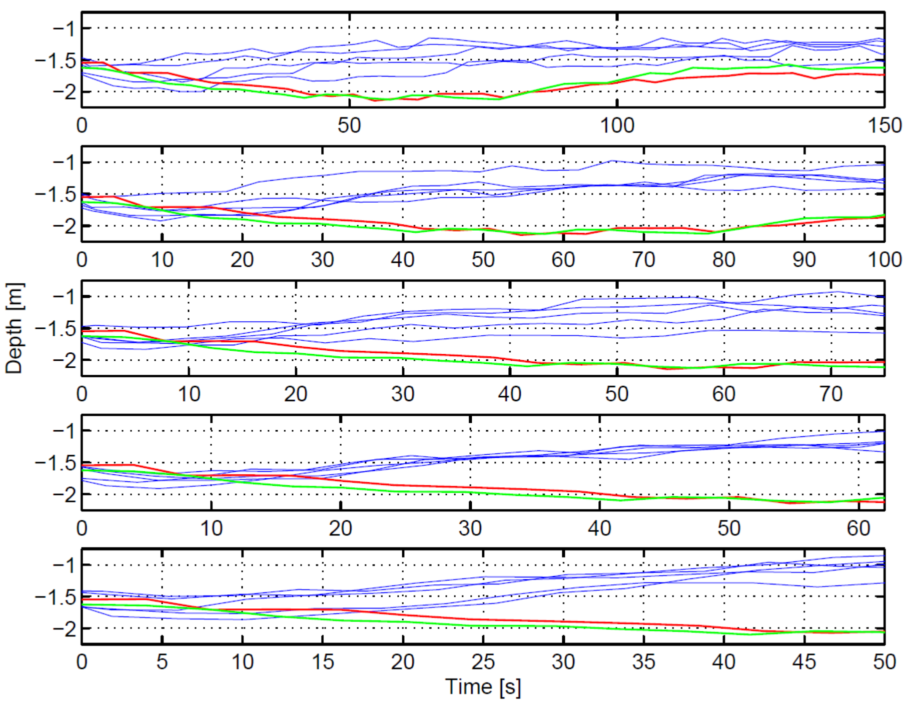
- **Open Water tests**
  - Depth, pitch controlled
  - Heading fixed
  - 30m at different speeds



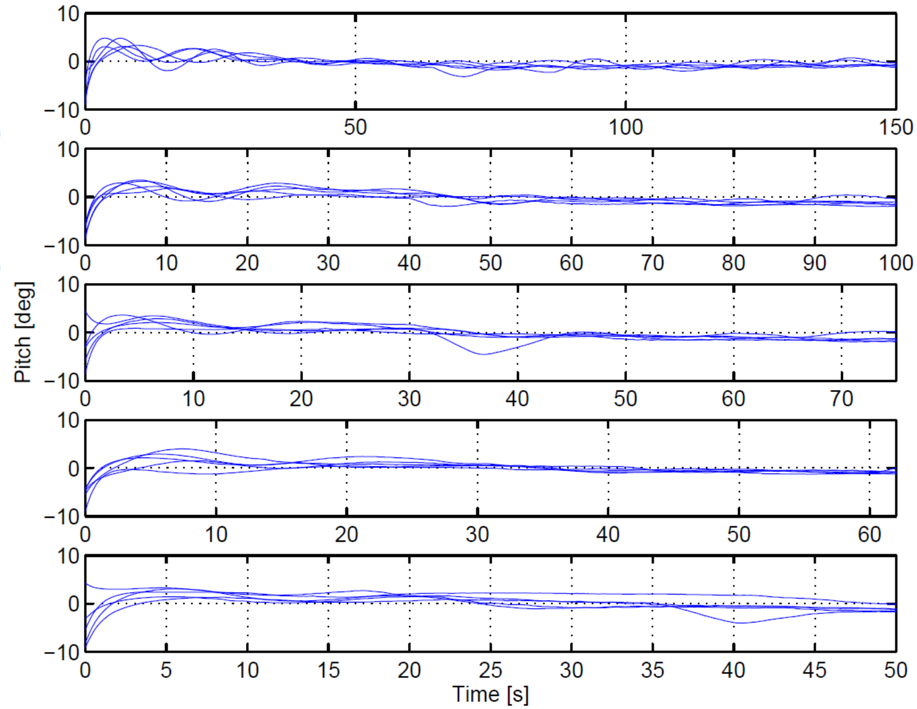
Glider 49 in the OEB

Ocean Engineering Basin

- **Results**



Depth



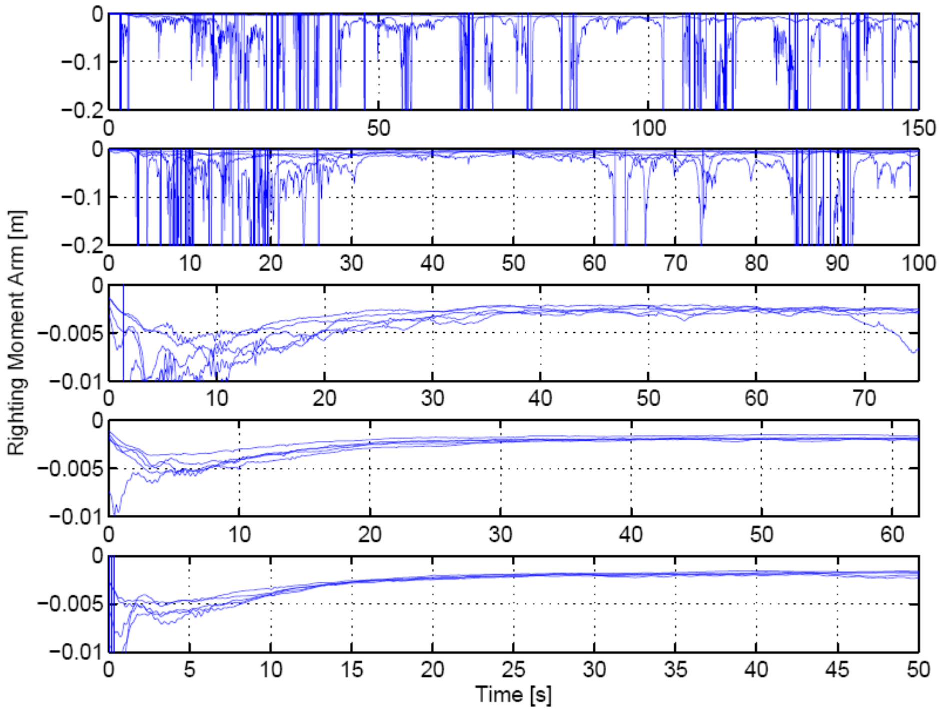
Pitch

Top to Bottom 0.3 – 0.6 m/s

Ocean Engineering Basin

- **Righting moment**
  - Roll/torque measurements

$$H = \frac{\tau_m}{F_g \sin(\phi)}$$



Long Range Navigation

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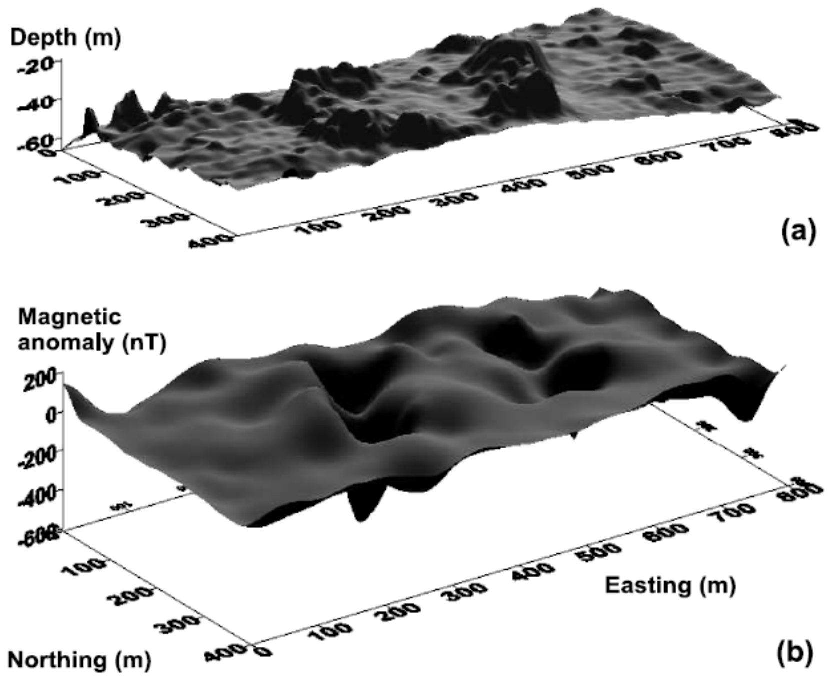
- **Problems with Inertial Systems**
  - Continuous power requirements
  - Drift over time
- **Augmentation**
  - Surface Fix
  - Acoustic solutions
  - Terrain Relative Navigation
  - Geomagnetic Relative Navigation

Geomagnetic Navigation

- **Local Magnetic Fields**
  - Additional Information for augmentation of map relative navigation



Bathymetry shown in top figure with magnetic variation shown in bottom figure[2]

2. Teixeira et al. "Geophysical Navigation of Autonomous Underwater Vehicles Using Geomagnetic Information," in Proc. 2nd IFAC Workshop, Navigation, Guidance and Control of Underwater Vehicles, Ireland, 2008.

Geomagnetic Navigation

- **Earth Magnetic Field**
  - Main field
  - Use field intensity and direction to locate vehicle

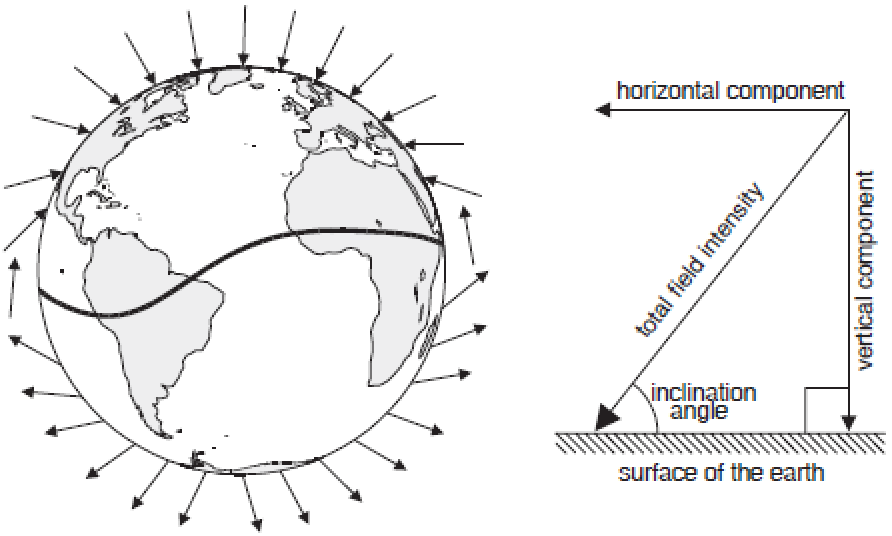
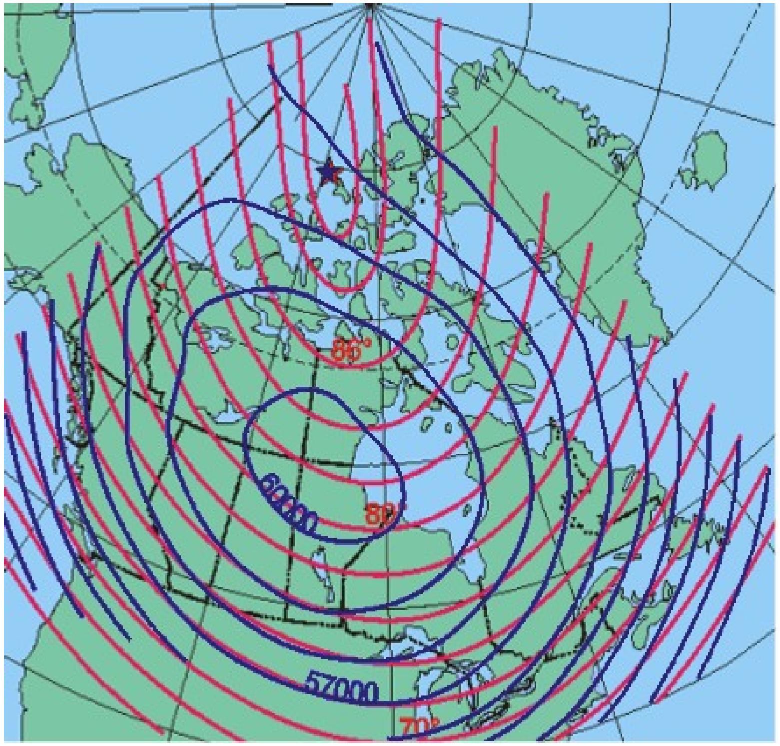


Diagram showing earth main field line directions and a breakdown of the main field into horizontal and vertical components[1]

1. Lohmann et al. "Long Distance Navigation in Sea Turtles," Ethology Ecology & Evolution, 11: 1-23, 1999.

Geomagnetic Navigation

- **Bicoordinate Map**
  - ❖ Intensity and inclination not parallel
  - ❖ Allows calculation of lat/lon
  - ❖ Roughly
    - 3.3nT/km
    - 0.0066°/km



Map showing the lines of equal intensity [nT] (blue) and inclination angle [deg](red). From Geological Survey of Canada Website.

Geomagnetic Navigation

- **Problems**
  - Field variations
    - Quiet daily field time variations
      - 20-100nT
    - Solar disturbance time variations
      - 250-1000nT
  - Sensing
  - Model predictive accuracy

Future Work

- Stability analysis
  - Ocean trials over longer distance
- Navigational Behaviors
  - Long range low power navigation without surface access
  - Combining depth and pitch controllers
  - Updating glider ded-reckoning algorithm for level flight

Conclusions

- Hybrid glider propulsion module has been developed and integrated
- Low power requirements and small impact on existing system
- Long range navigation methods in development for use in the North Atlantic

Acknowledgements

I would like to thank my supervisor, Dr. Ralf Bachmayer, Paul Winger, George Legge and Tara Perry from the Marine Institute, Jack Foley and Craig Mitchell from Memorial University of Newfoundland (MUN), Chris Williams, Jeswin Jeyasuyra and Moqin He of the National Research Council Canada, Paul Lacroix and the Canadian Centre for Ocean Gliders for use of the glider and the Physical Oceanography Department at MUN for providing additional instrumentation and experimental support. This project is supported through funding provided by Natural Sciences and Engineering Research Council, Memorial University of Newfoundland and Suncor-Petro Canada.

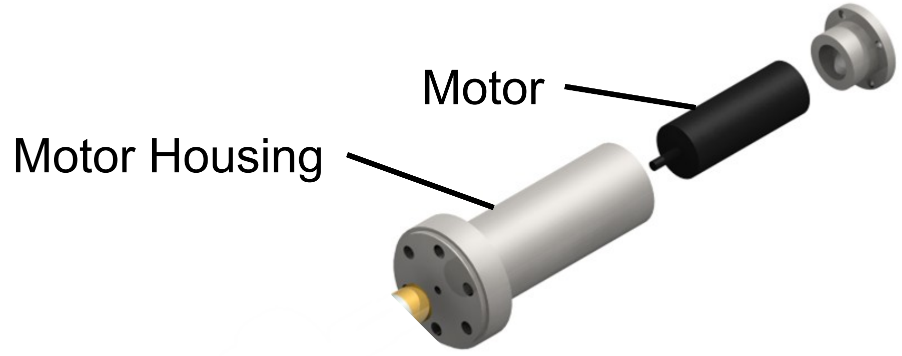
Questions

Implementation

- **Design Constraints**
  - Provide sprint mode
  - Meet or exceed upon the propulsive efficiency of buoyancy driven glider at typical speeds
  - Minimal impact on normal glider operations
  - High reliability

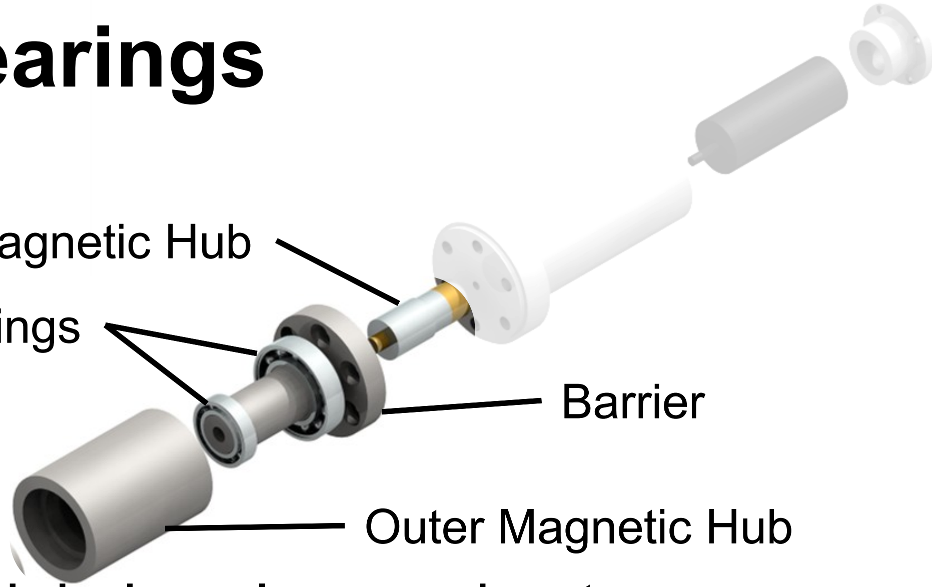
Design

- **Motor**
  - ❖ 4W Geared brushed DC motor
  - ❖ Driven directly from rail voltages of 3.3V and 15V
  - ❖ Motor operational range estimated using OpenPVL propeller scripting



Design

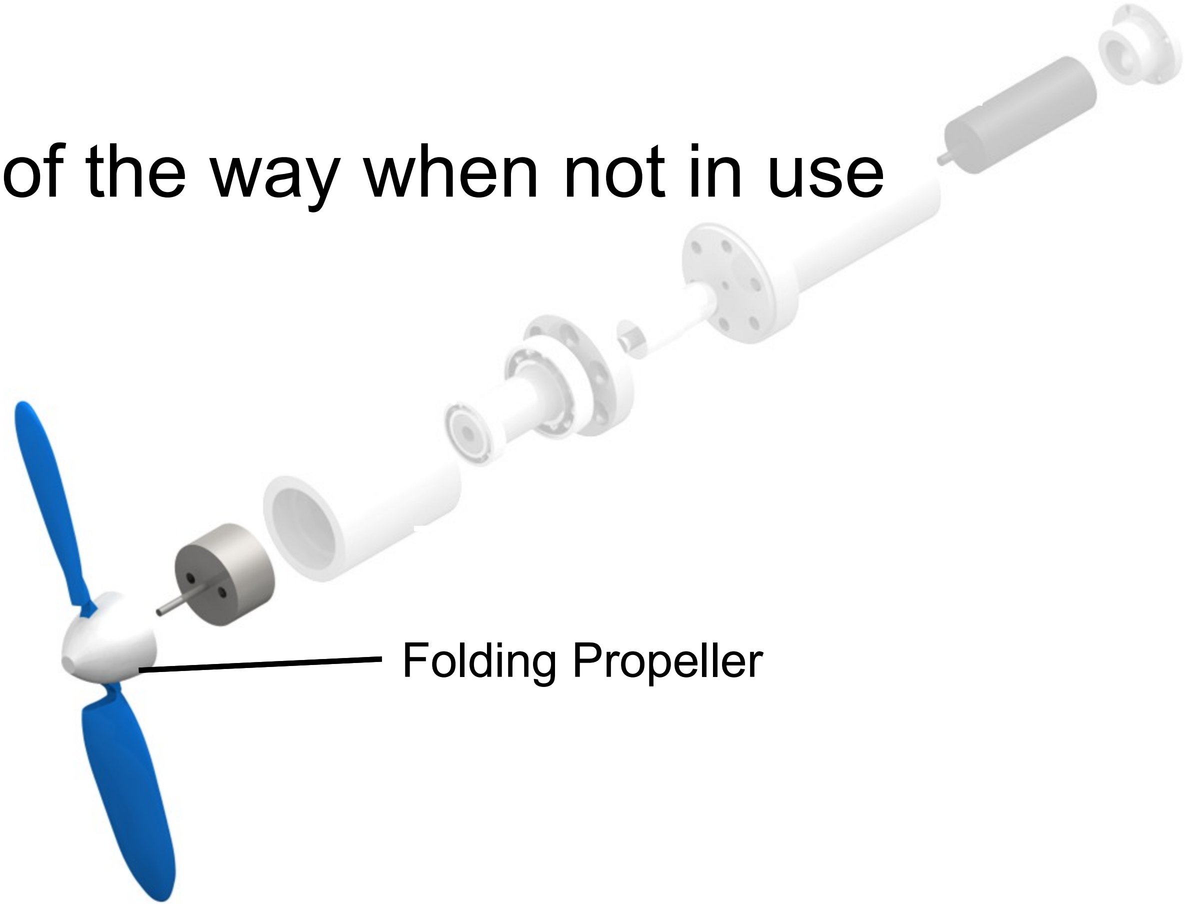
- **Coupling and Bearings**



  - Magnetic coupling minimizes losses due to mechanical shaft sealing
  - Ceramic bearings are low friction and corrosion resistant

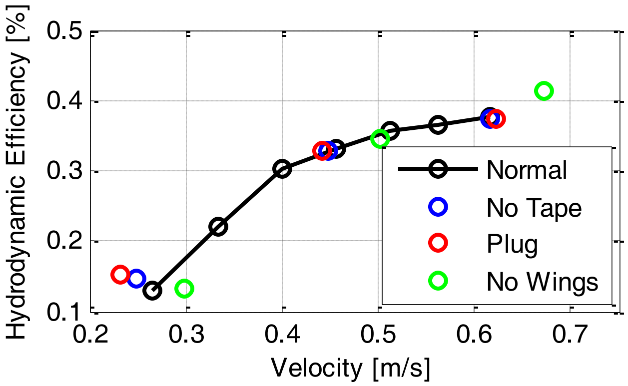
Design

- **Propeller**
  - ❖Folds out of the way when not in use



Open Water Propulsion Tests

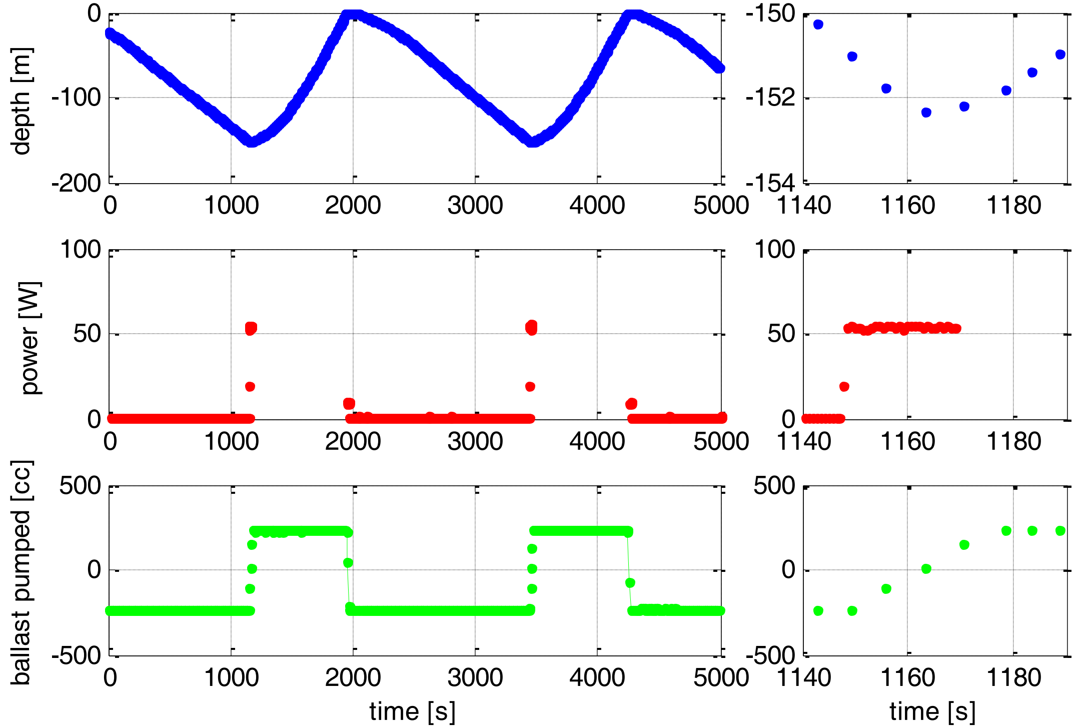
- **Estimating Efficiency**
  - Developed thrust required for calculation
  - Thrust from the previously mentioned propeller curves matched with tow tank data



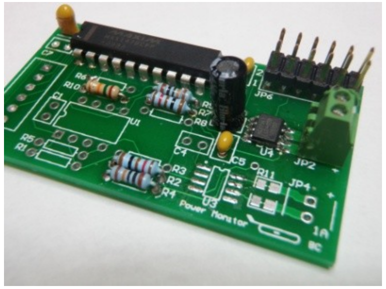
Estimated transport efficiency and of Hybrid Glider during tow tank tests

Test System Characterization

- **Ballast Pump Power Monitoring**



Glider 48 on Deployment out of Bonavista July ‘09



Power Monitoring Board

Test System Characterization

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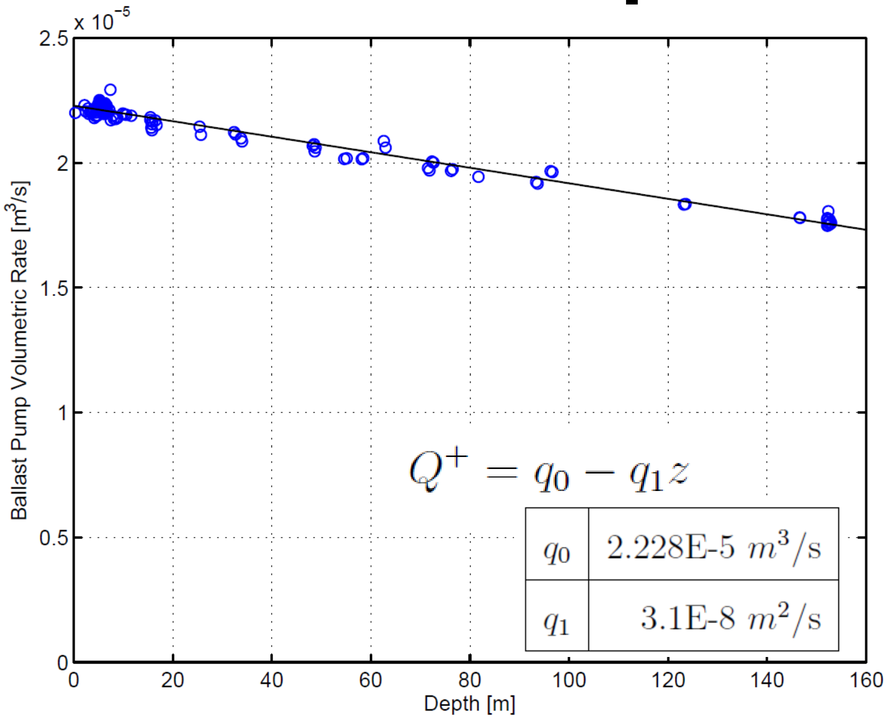
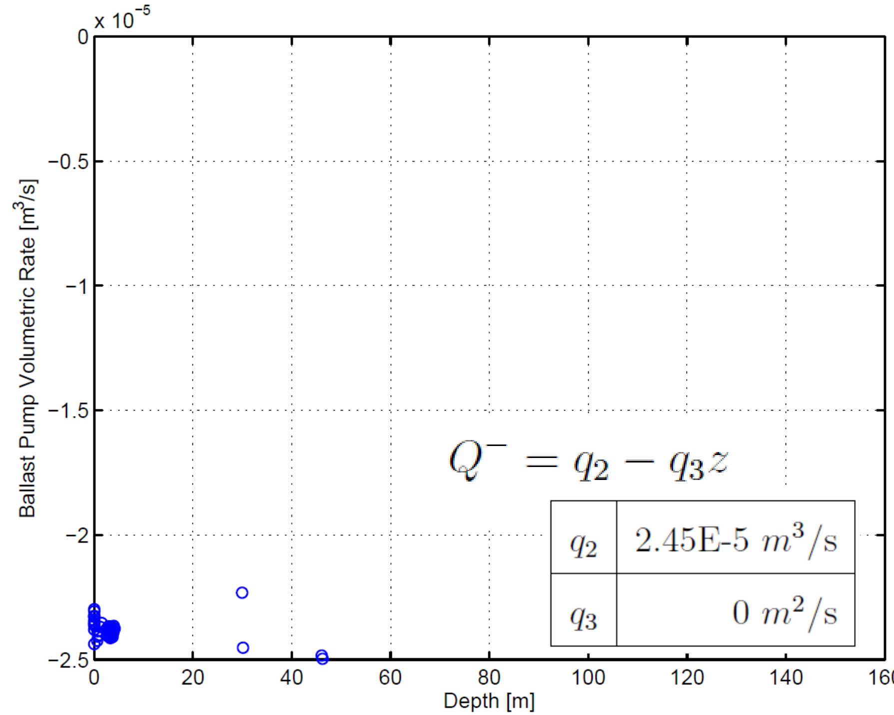
- **Ballast Pump Mechanical Power**



Positive Volumetric Rate



Negative Volumetric Rate

$$P_{bpm} = p(z)Q \qquad Q = \frac{d}{dt}V \qquad p = p_o + \rho g z$$

Test System Characterization

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- **Ballast Pump Electrical Power**

$$P_{bpi} = P_0 z + P_1$$

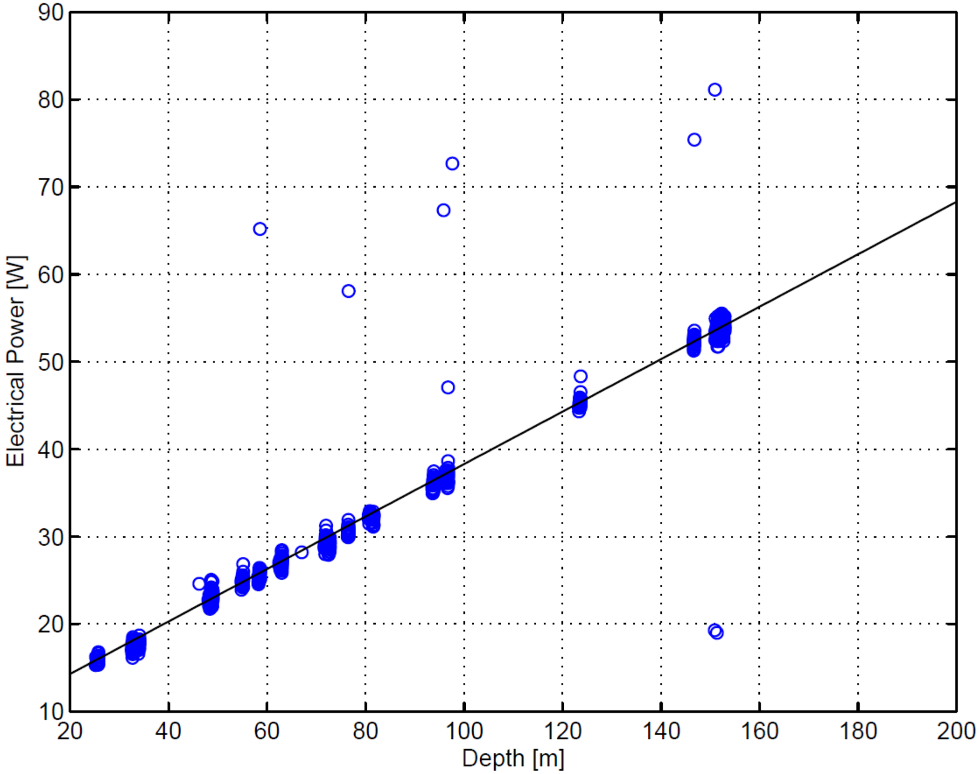
P_0	0.3 W/m
P_1	8.2 W

$$E_{bpe} = (P_0 z + P_1)\frac{V_B}{Q^+} + P_1\frac{V_B}{Q^-}$$

$$t_{bp} = \frac{\dot{z}}{z}$$

$$P_{bpe} = \frac{E_{bpe}}{t_{bp}}$$

$V_B = 4.50E-4m^3 \quad \dot{z} = 0.1922$ m/s



Instantaneous Ballast Pump Power at Depth

Test System Characterization

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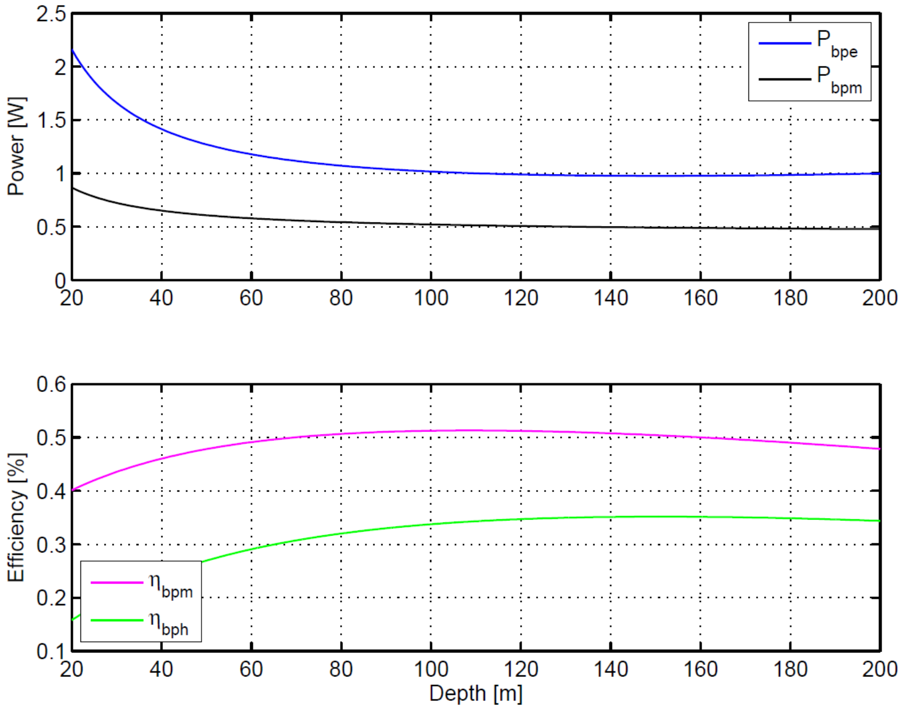
- **Power and Efficiency**



Glider 48 transport efficiency results

$$P_{hyd} = F_D v_A$$

$$v_A = \frac{\dot{z}}{sin(\xi)}$$

$$F_D = \frac{1}{2}\rho A C_D(\alpha) v_A^2$$ [1]

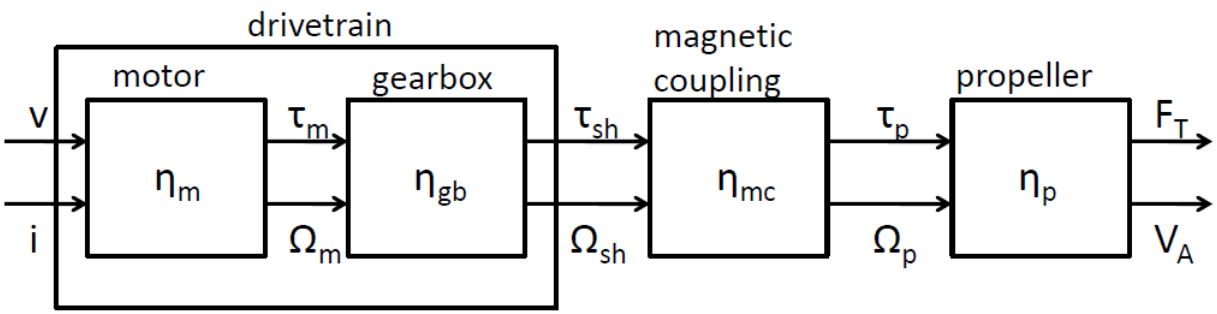
$$C_D = c_2 + c_3\alpha^2$$ [1]

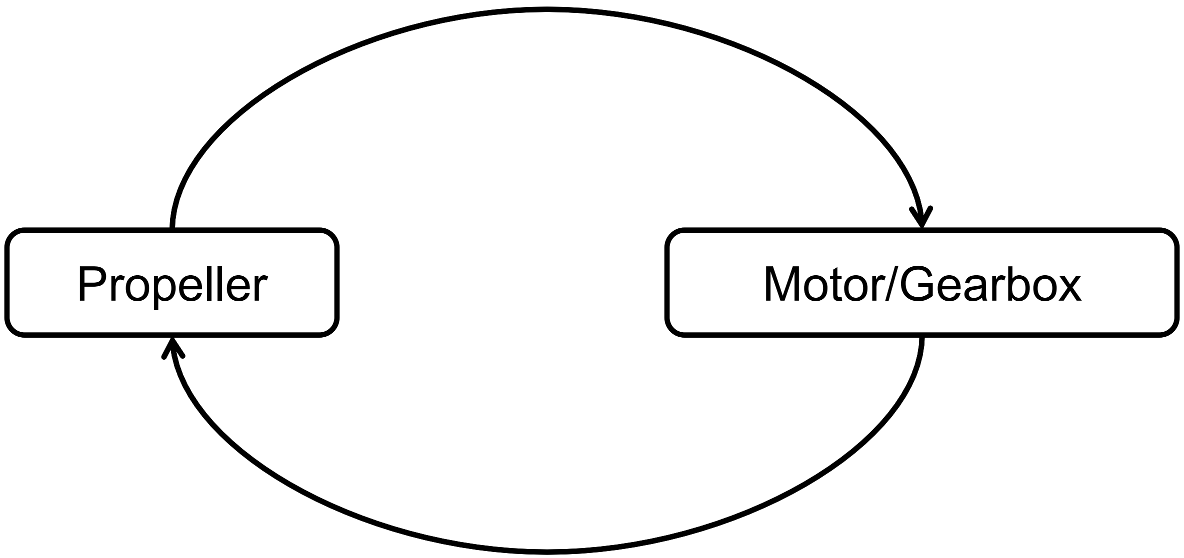
c_2	0.214
c_3	32.3

$$\eta_{bph} = \frac{P_{hyd}}{P_{bpe}} \qquad \eta_{bpm} = \frac{P_{bpm}}{P_{bpe}}$$

1. Graver et al. “Underwater Glider Model Parameter Identification,” UUST, 2003.

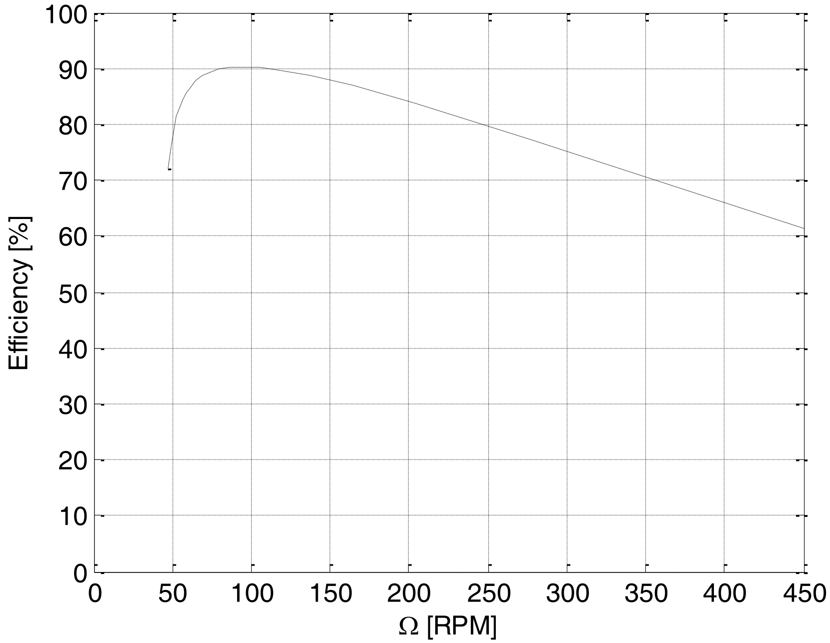
Propulsion Module Design





Initial Propeller Design

- **OpenProp Matlab codes**
  - $F_T = 0.4$ N
  - $v_A = 0.35$ m/s
  - $\Omega_p = 100$ RPM
  - Small blade area ratio propeller
- **Output**
  - $K_T = 0.0051$
  - η_p



Propeller Efficiency from OpenProp

$$\tau_p = K_\tau \rho (\frac{\Omega_p}{60})^2 d_p^5$$

Motor/Gearbox Selection

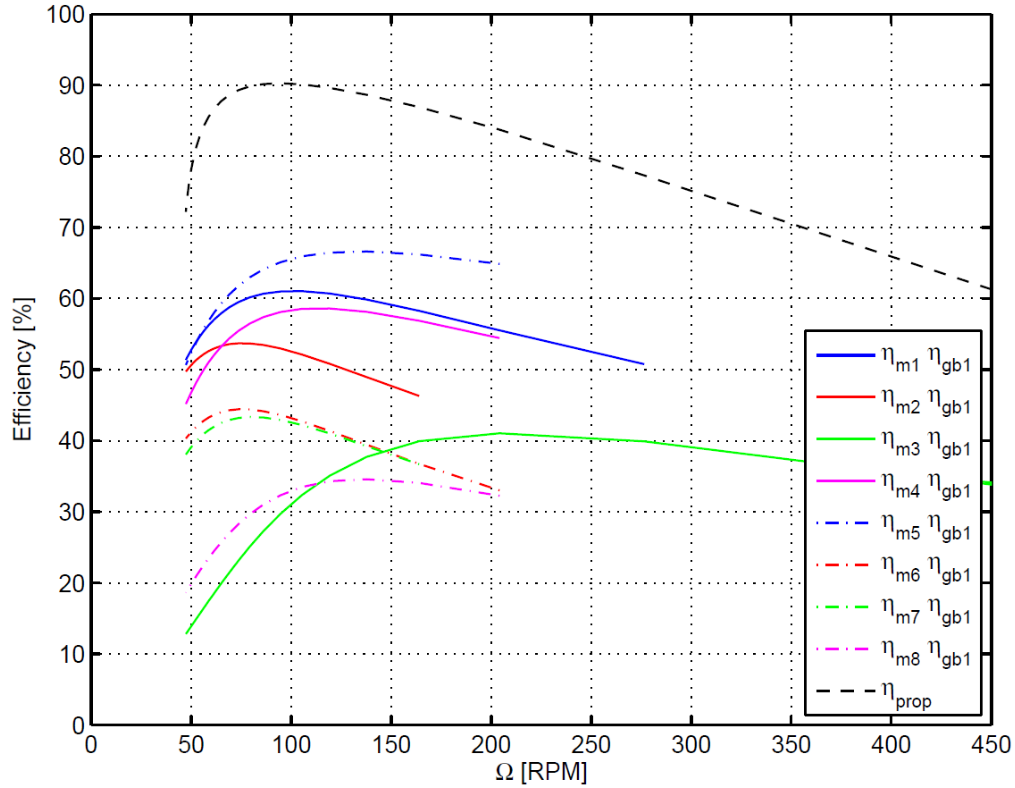
- **Propeller outputs into motor model**

$$\eta_m = \frac{\tau_m \Omega_m}{iu} \frac{2\pi}{60}$$

$$\tau_m = k_1(i - i_o)$$

$$\Omega_m = uk_2 - k_3\tau_m$$

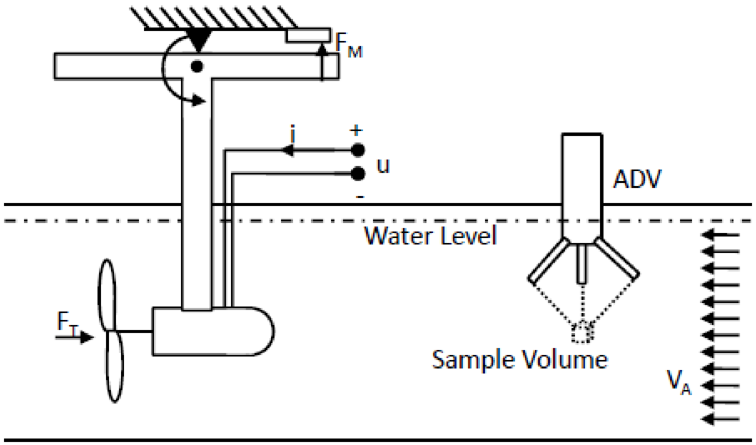
$$\Omega_m = uk_2 - k_3k_1(i - i_o)$$



Motor and propeller efficiency matching

Propeller Selection

- **University Flume Tank Tests**
  - Measure v_A, i, u, F_T
  - Characterize small blade area series of propellers



University flume tank experimental setup

$$\hat{\eta}_{sys} = \frac{F_T v_A}{iu}$$

$$\eta_p = \frac{F_T v_A}{\tau_m \Omega_m} \frac{60}{2\pi}$$

Propeller Selection

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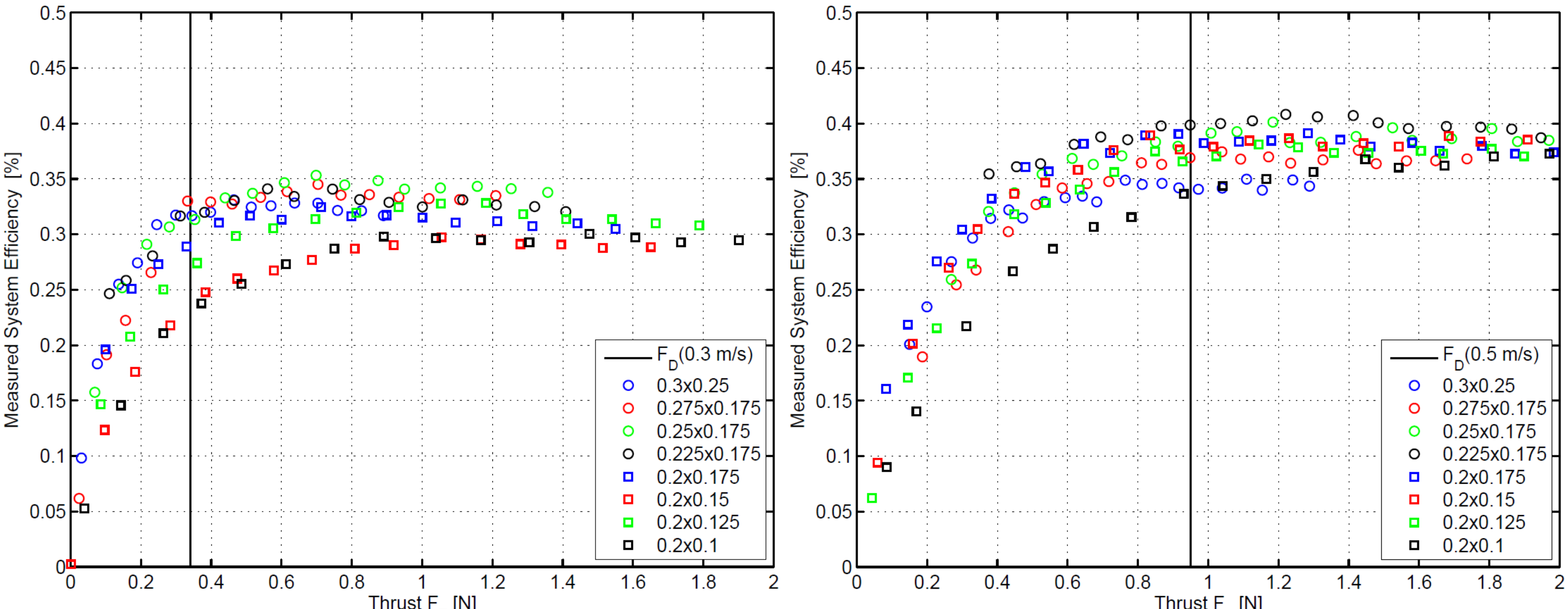
- **Test results**
  - Predicted vehicle drag overlaid

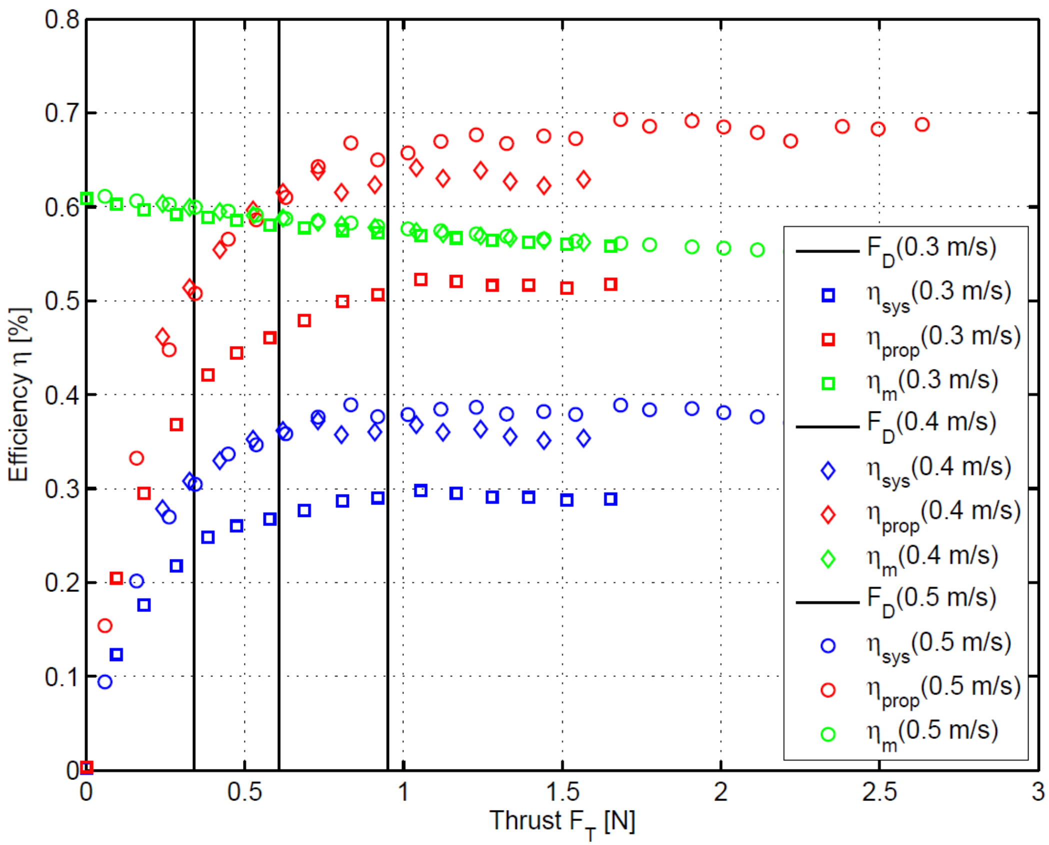


System Efficiency at 0.3 m/s

System Efficiency at 0.5 m/s

Propeller Selection

- **Selected Propeller**
  - Diameter = 0.2 m
  - Pitch = 0.15 m



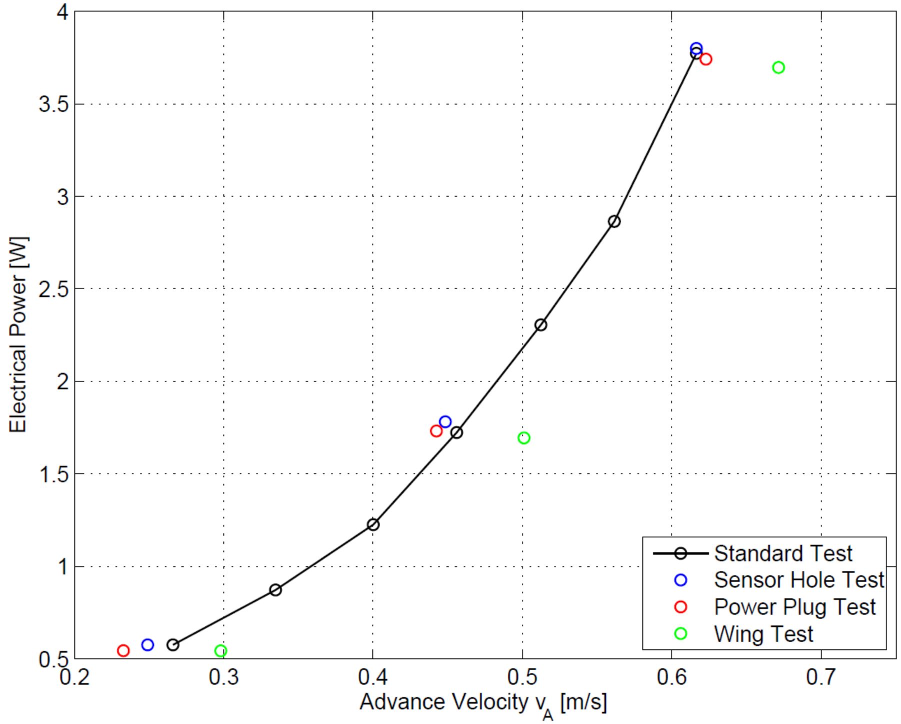
Self Propulsion Tests

- **University Tow Tank**
  - Glider driven along guide wire
  - V_A, i and v recorded

Hybrid Glider driving down tow tank on guide wire

Self Propulsion Tests

- Results

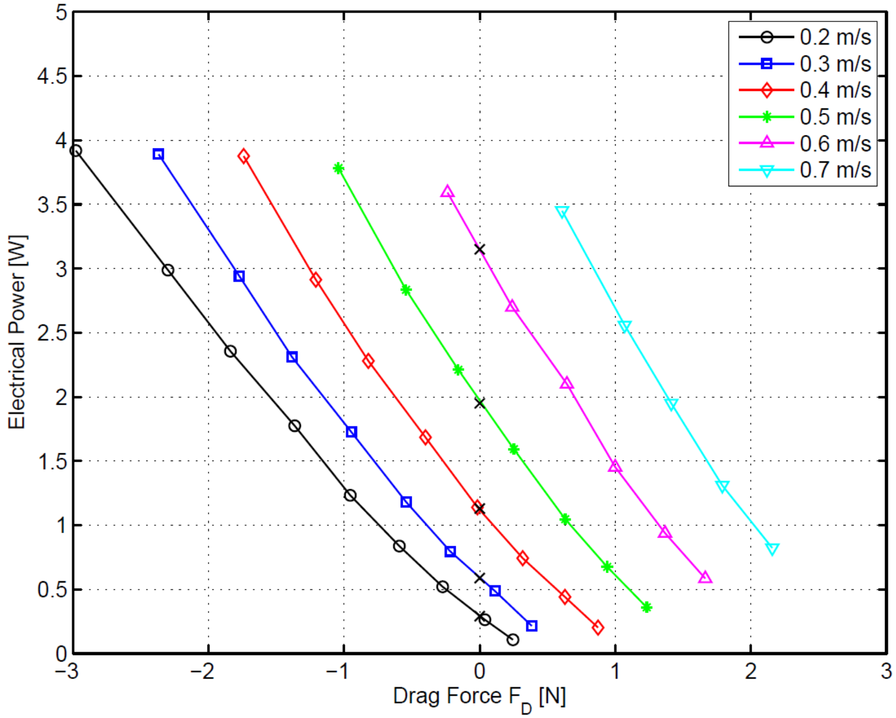


Hybrid Glider propulsion device power during self propulsion tests

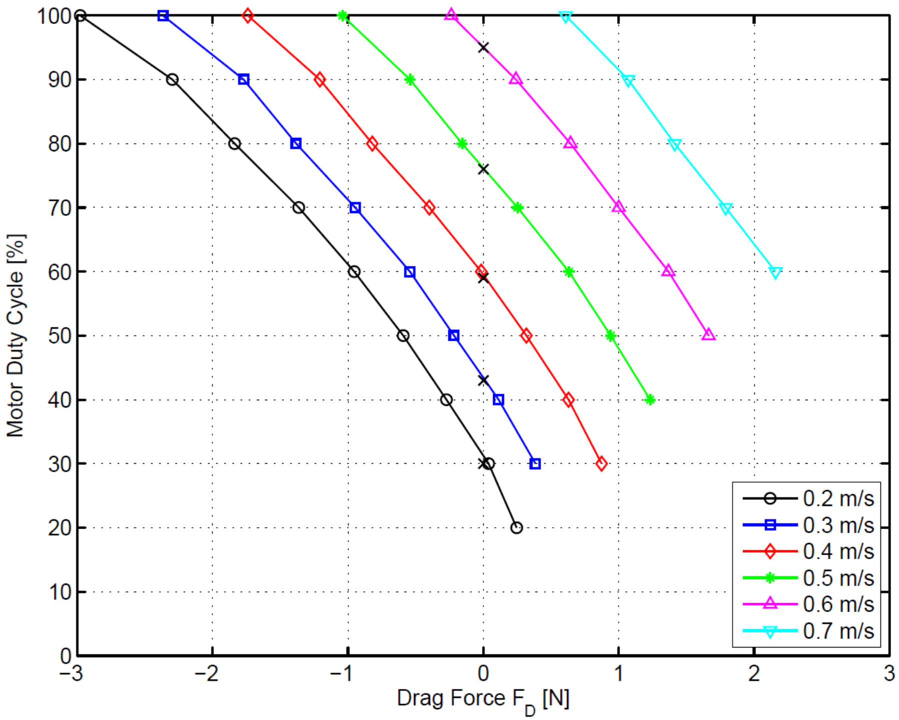
Tail section of Hybrid Glider showing the ‘Standard Configuration’

Full Scale Flume Tank Tests

- **Results**



Electrical Power for Self Propulsion



Motor Duty Cycle for Self Propulsion

Range Estimates

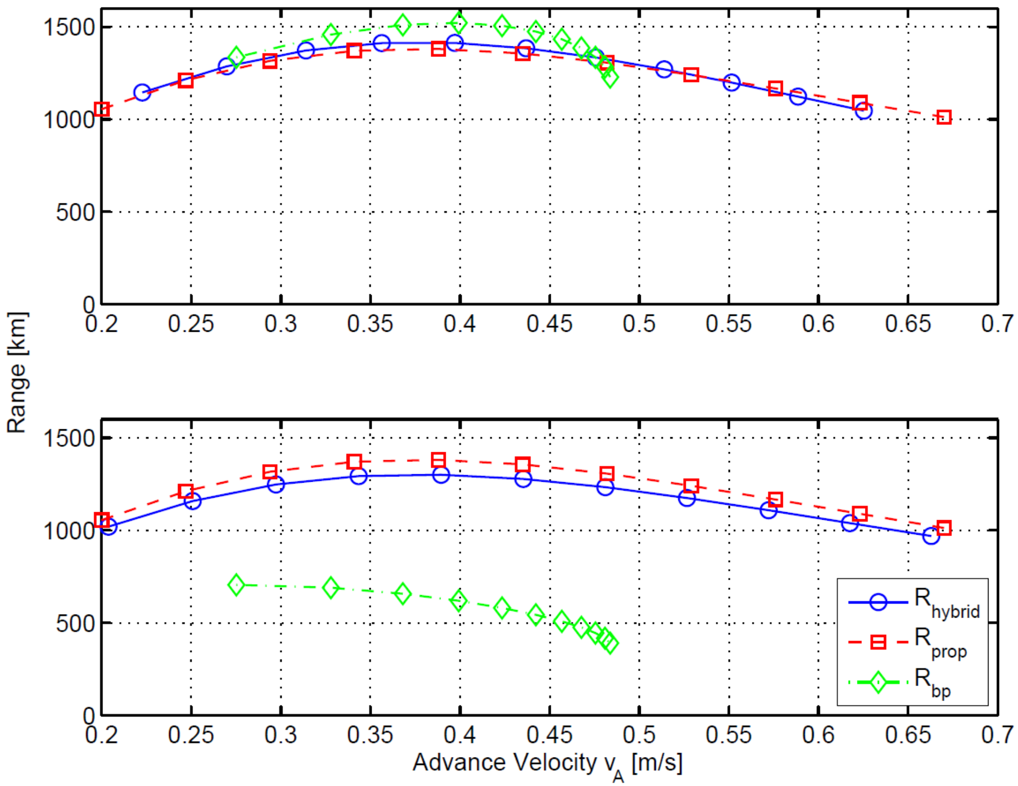
- **Buoyancy Driven Glider**
  - ~1000 km
  - ~30 days
- **How does the hybrid compare**

Range Estimates

Buoyancy driven	$$R_{bp} = \frac{E\dot{x}}{P_{bpe} + P_h + P_l}$$
Propeller driven	$$R_{prop} = \frac{Ev_A}{P_{prop} + P_h + P_l}$$
Propeller/buoyancy driven	$$R_{hybrid} = \frac{E(\dot{x}\Delta_{bp} + v_A\Delta_{prop})}{P_{bpe}\Delta_{bp} + P_{prop}\Delta_{prop} + P_h + P_l}$$ $$\Delta_{prop} = \frac{t_{prop}}{2t_{bp} + t_{prop}} \qquad \Delta_{bp} = \frac{2t_{bp}}{2t_{bp} + t_{prop}}$$ $$t_{prop} = \frac{d_{prop}}{v_A} \qquad t_{bp} = \frac{\dot{z}}{z}$$

Range Estimates

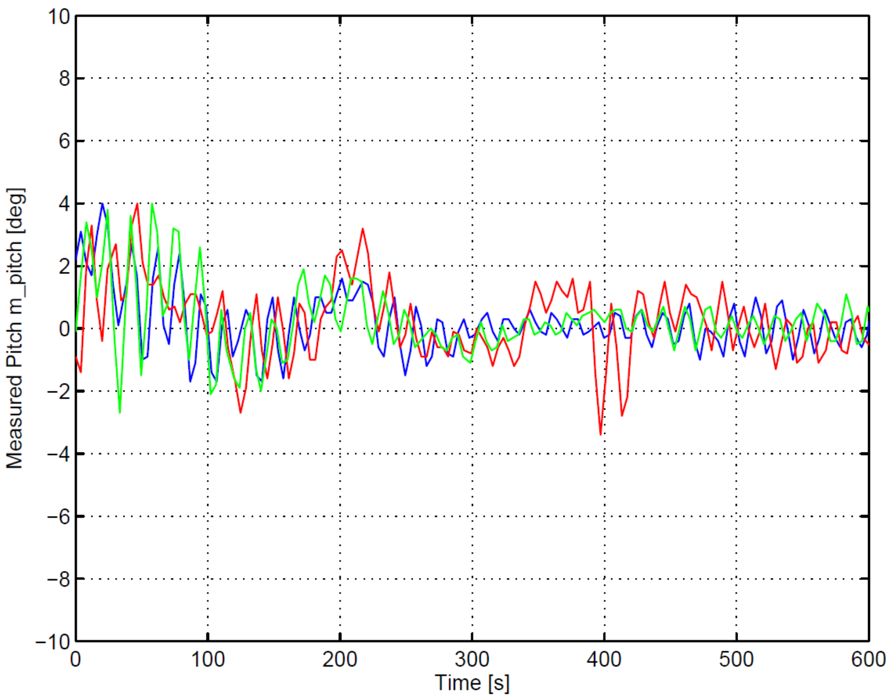
- **Assume**
  - d_{prop} = 2.5 km
  - Depth
    - z = 200 m top
    - z = 10 m bottom



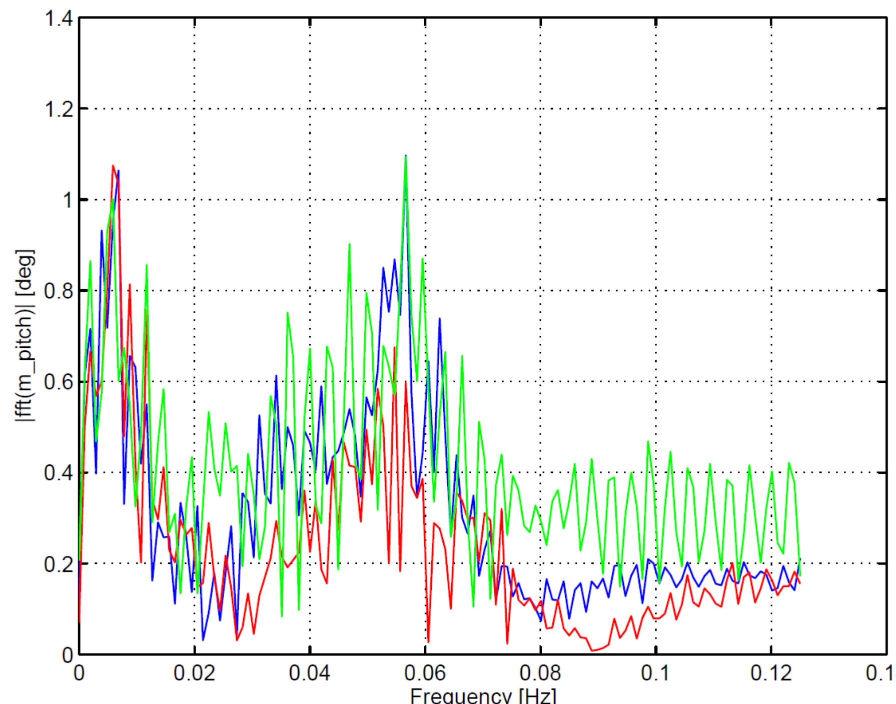
Range Comparisons

Pitch Controller

- **Pitch control with mass shifting at zero velocity**
  - ❖ Oscillations potential issue for vehicle at speed due to lift



Pitch measurements from repeated tests



FFT of pitch measurements

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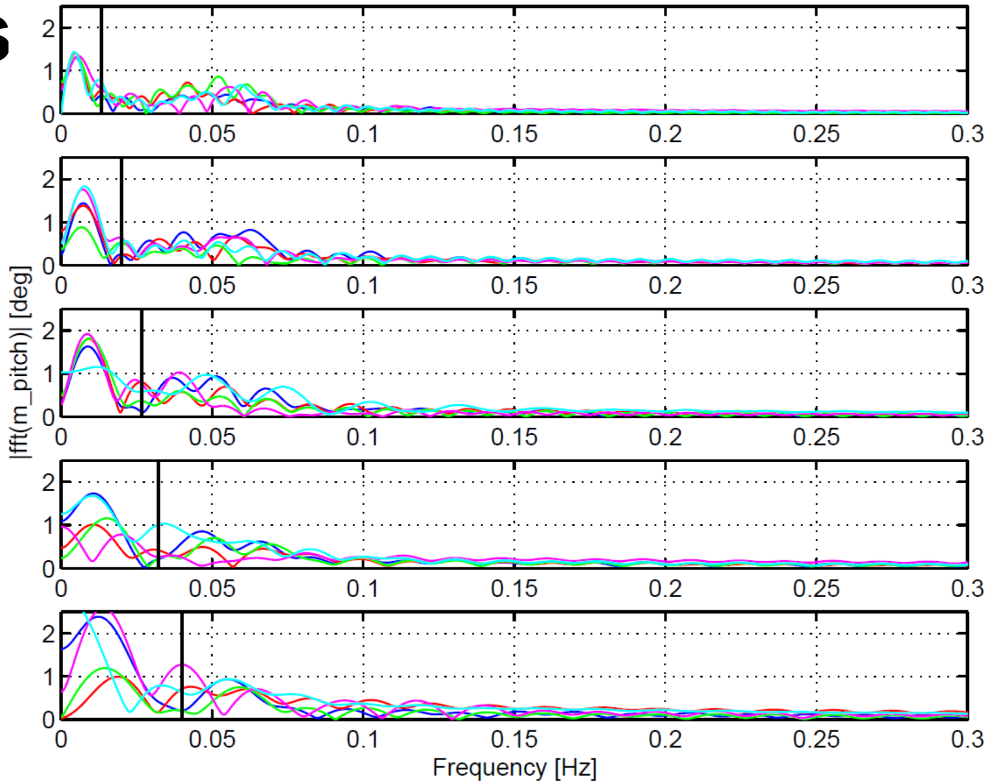
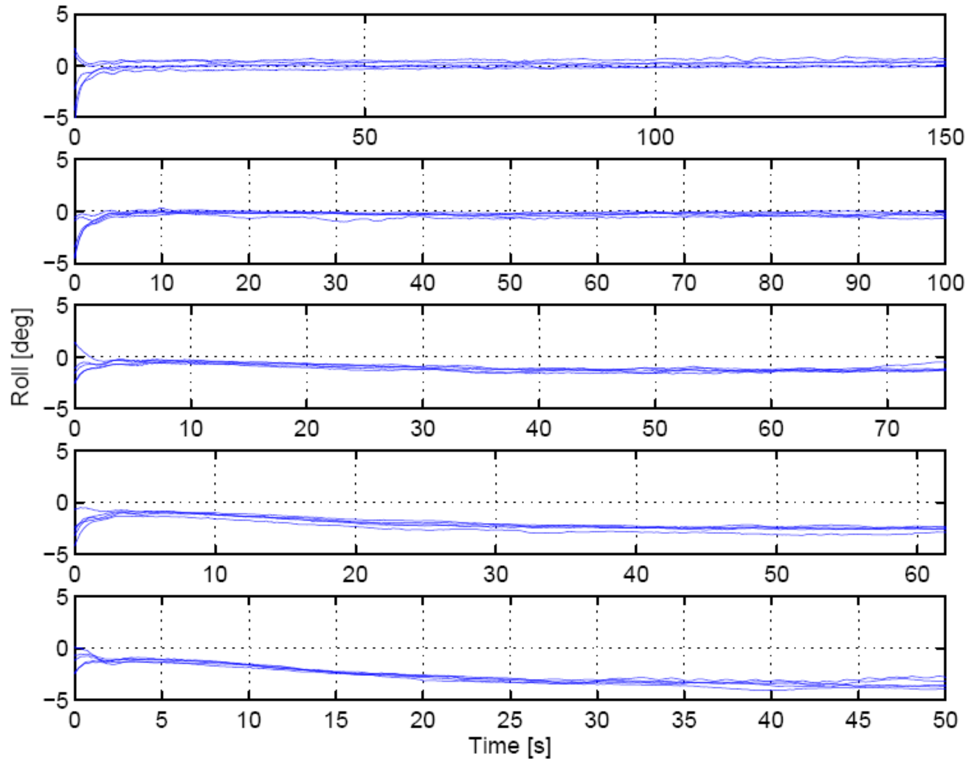
- Pitch oscillations still present
- Tests not long enough



Ocean Engineering Basin

- **Roll results**
  - Increase from top to bottom due to increase in applied torque



Top to Bottom 0.3 – 0.6 m/s