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A Hydrodynamics Simulator Developed for a Twin-Pod AUV, the Marport SQX-500

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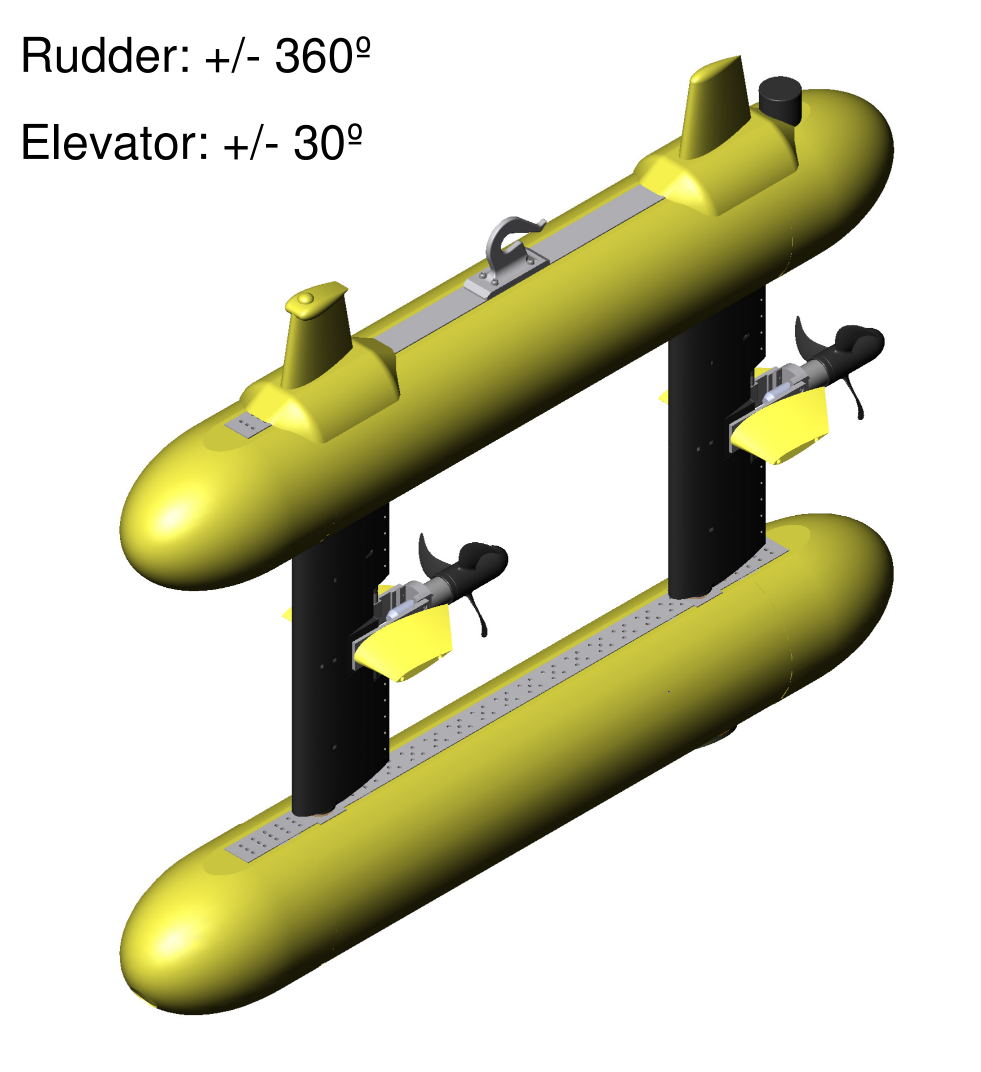
Outline

- Background
- Methodology
- Vehicle Motion Simulation
    - Added mass
    - Control forces (F) and moments (M)
    - Twin-pod F and M due to translational terms
    - Twin-pod F and M due to rotational terms
- Simulations
- Summary
- Future Work

Background

- Novel underwater vehicle configuration (Marport Canada Ltd)
  - Vertically-arranged twin-pod configuration
  - Tandem vector thrusters
  - Extremely wide operation of maneuverings, hover, crab, zero radius turning
- Highly stable platform for underwater optical and sonar systems
  - Passively stable in roll and pitch by large separation of CB and CG
  - Yaw stability improvement potentia by front-wheel drive configuration



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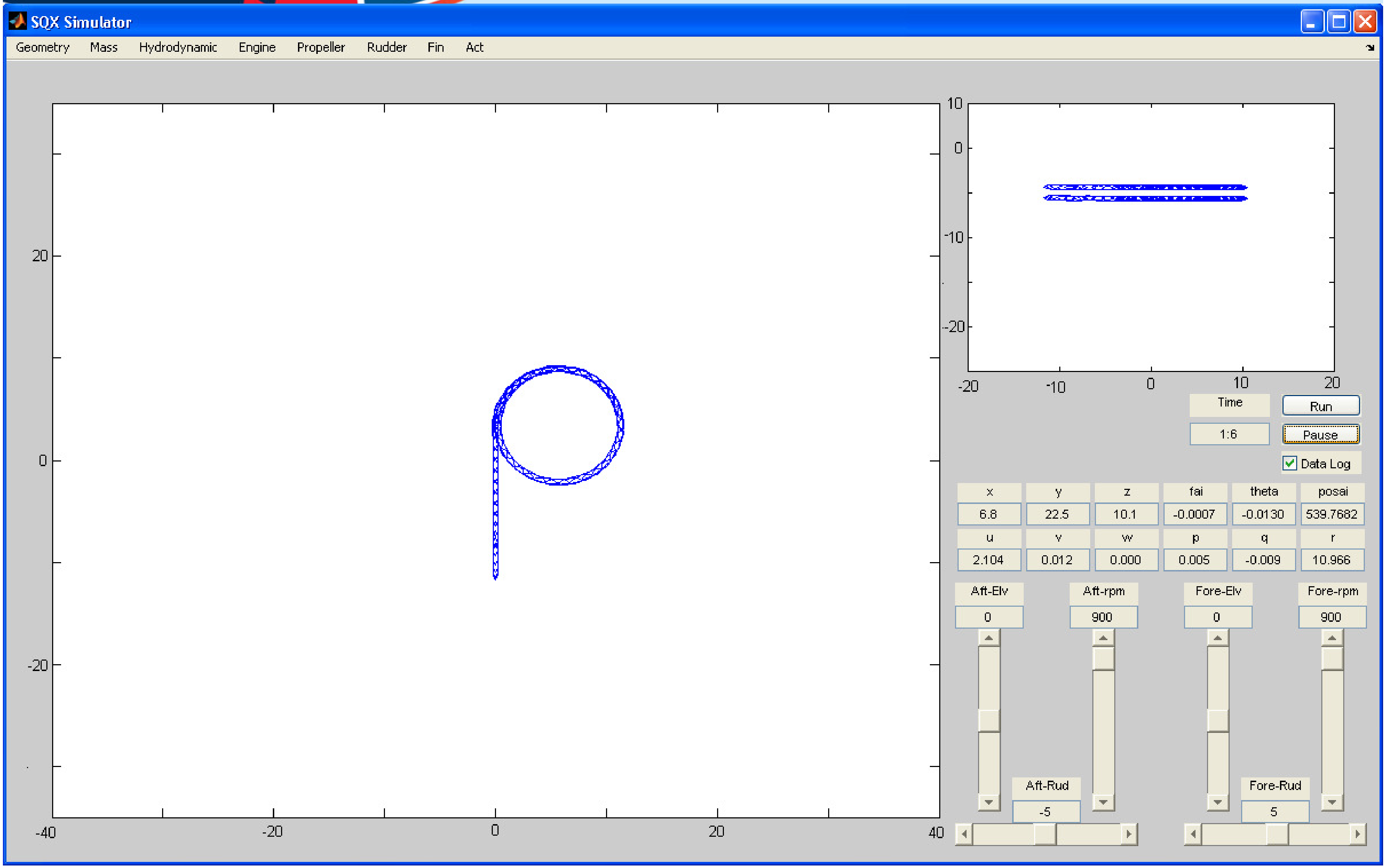
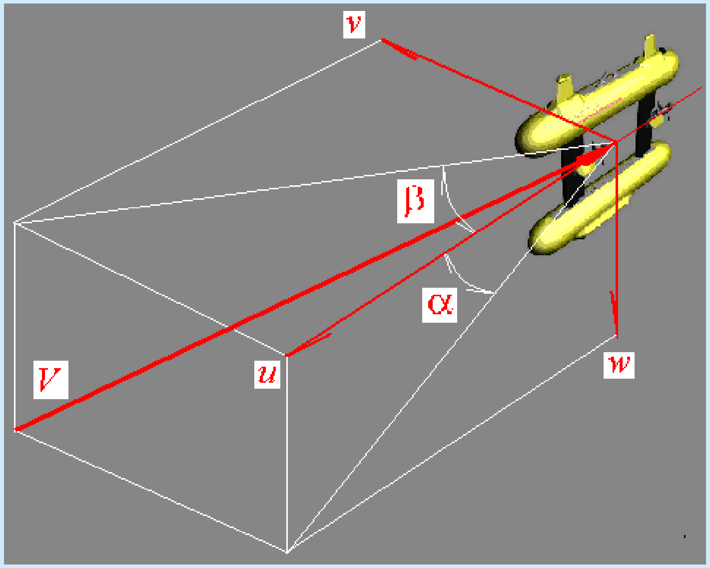
control combination
➔ motion response



How to predict and present this vehicle maneuvering in all capable operations?

- Based on simulation of a 6 DOF rigid body motion equation by Runge-Kutta Method with estimated hydrodynamic loads and control forces and moments
- Component-build-up approach was applied in estimations of hydrodynamic loads and control forces and moments
  - twin-pod hull with small appendages
  - fore rudder
  - fore propeller
  - aft rudder
  - aft propeller
  - 4 elevator fins were not considered



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Vehicle Motion Simulation

- u, v, r, p, q, and r are velocity components in surge, sway, heave, roll, pitch, and yaw
- M_r and M_a are matrices of rigid body mass and added mass
- τ is the vector of control forces and moments which consists of 2 propellers and 2 rudders
- *F* is the vector of forces and moments on the hull
- [B] is the matrix of damping coefficients
- [C] matrix for coriolis and centrifugal terms
- H_s is the vector of hydrostatic restoring forces and moments

$$\ddot{\mathbf{q}} = \left[\mathbf{M}_r + \mathbf{M}_a\right]^{-1}\left[\boldsymbol{\tau} - \mathbf{F} - [\mathbf{B}]\dot{\mathbf{q}} - [\mathbf{C}]\dot{\mathbf{q}} - \mathbf{Hs}\right]$$

Solving by Runge-Kutta Method

$$\dot{\boldsymbol{q}} = \left[u \;\; v \;\; w \;\; p \;\; q \;\; r\right]^T$$

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{rud\_f} + \boldsymbol{\tau}_{prop\_f} + \boldsymbol{\tau}_{rud\_a} + \boldsymbol{\tau}_{prop\_a}$$

$$\begin{bmatrix} X_{HS} \\ Y_{HS} \\ Z_{HS} \\ K_{HS} \\ M_{HS} \\ N_{HS} \end{bmatrix} = \begin{bmatrix} -(W-B)\sin\theta \\ (W-B)\cos\theta\sin\phi \\ (W-B)\cos\theta\cos\phi \\ -(G_yG - B_yB)\cos\theta\cos\phi - (G_zG - B_zB)\cos\theta\sin\phi \\ -(G_zG - B_zB)\sin\theta - (G_xG - B_xB)\cos\theta\cos\phi \\ -(G_xG - B_xB)\cos\theta\sin\phi - (G_yG - B_yB)\sin\theta \end{bmatrix}$$

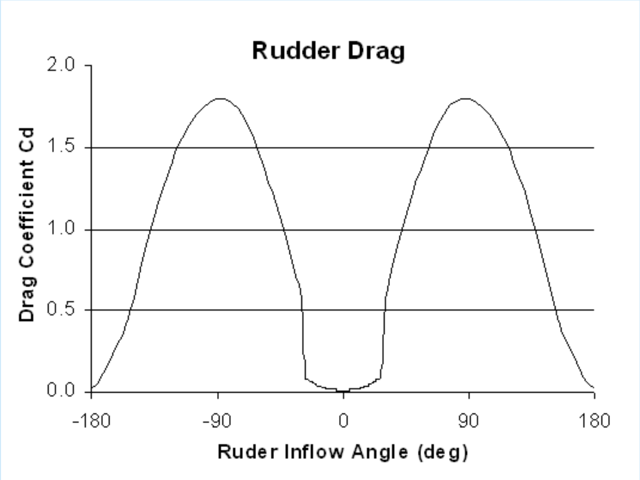
$[M_r]$ and $[C]$

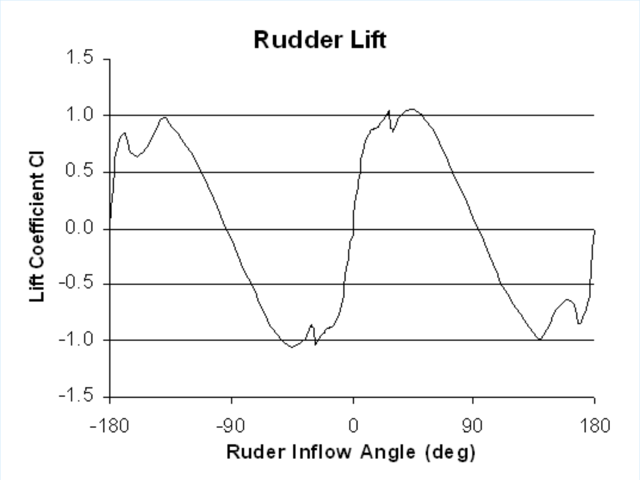
$$
\boldsymbol{M}_r = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_{xx} & I_{xy} & I_{xz} \\ mz_g & 0 & -mx_g & I_{yx} & I_{yy} & I_{yz} \\ -my_g & mx_g & 0 & I_{zx} & I_{zy} & I_{zz} \end{bmatrix}
$$

$$
\boldsymbol{C}_{rb} = \begin{bmatrix} \begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{matrix} & \begin{bmatrix} m(y_g q + z_g r) & -m(x_g q - w) & -m(x_g r + v) \\ -m(y_g p + w) & m(z_g r + x_g p) & -m(y_g r - u) \\ -m(z_g p - v) & -m(z_g q + u) & m(x_g p + y_g q) \end{bmatrix} \\ \begin{bmatrix} -m(y_g q + z_g r) & m(y_g p + w) & m(z_g p - v) \\ m(x_g q - w) & -m(z_g r + x_g p) & m(z_g q + u) \\ m(x_g r + v) & m(y_g r - u) & -m(x_g p + y_g q) \end{bmatrix} & \begin{bmatrix} 0 & -I_{zx}p - I_{zy}q + I_{zz}r & I_{yx}p - I_{yy}q + I_{yz}r \\ I_{zx}p + I_{zy}q - I_{zz}r & 0 & I_{xx}p - I_{xy}q - I_{xz}r \\ -I_{yx}p + I_{yy}q - I_{yz}r & -I_{xx}p + I_{xy}q + I_{xz}r & 0 \end{bmatrix} \end{bmatrix}
$$

τ -- Control forces and moments (rudders)

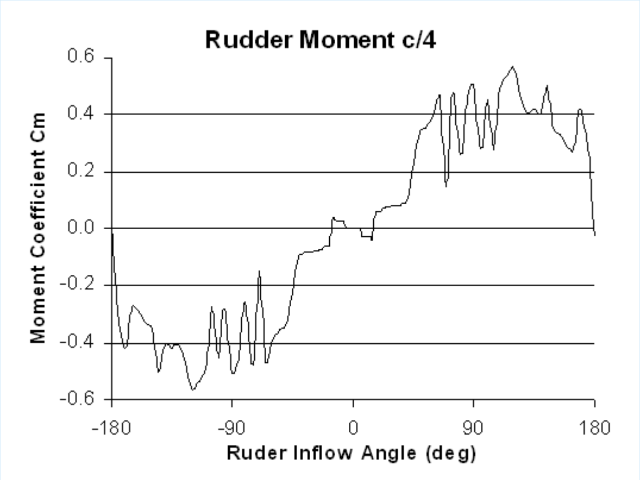
Experimental data for NACA 0025 section from Sheldahl, R. E., and Klimas, P. C. (1981)





The velocity for the rudder forces and moment calculation was estimated by the vehicle velocity and the rudder angle relative to the vehicle.

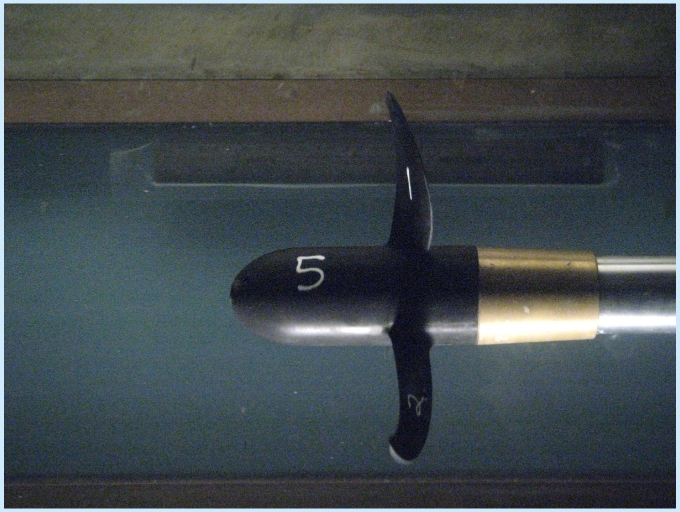
The effect of the presence of the twin pods on each rudder has not been considered in the present version.



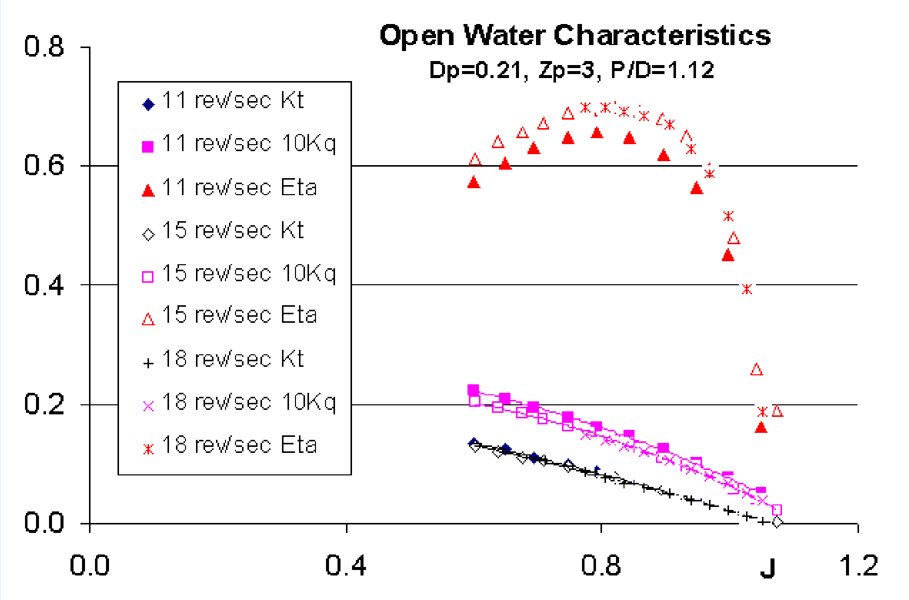
τ -- Control forces and moments (propellers)

Dp = 0.21m, P/D = 1.12, Zp = 3, BAR = 0.35, cast plastic propeller

Tested in an open-water test configuration in the NRC-IOT Cavitation Tunnel, March, 2010



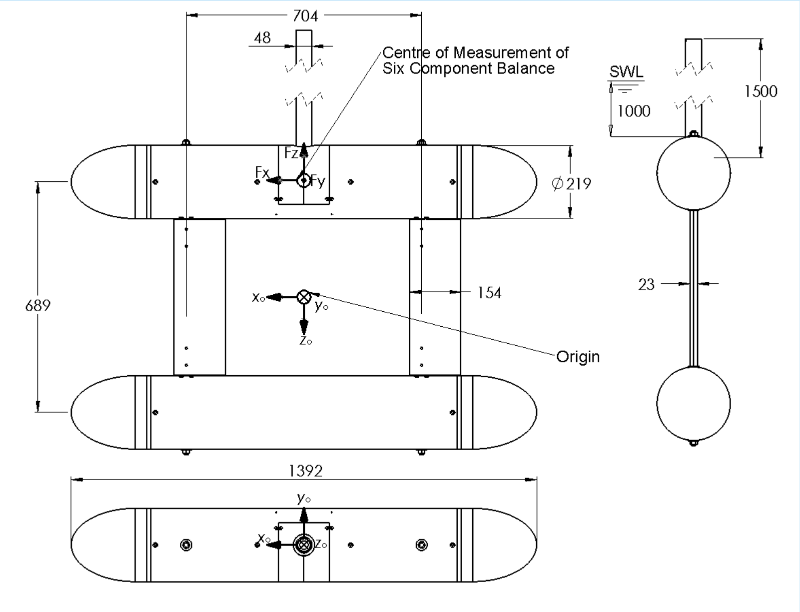
A constant wake fraction and thrust deduction were applied when calculating the thrust of the propeller behind a rudder.

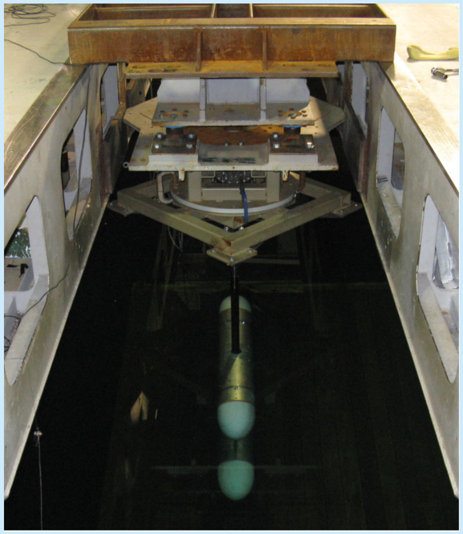


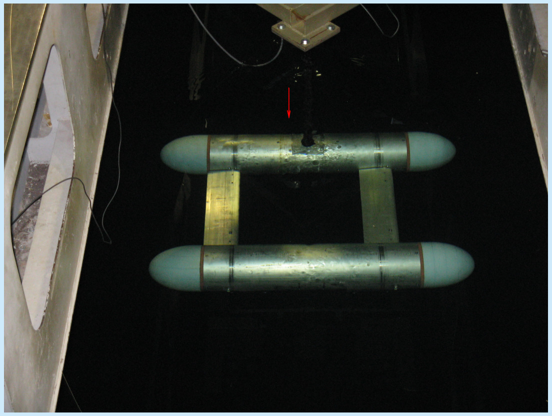
F – Hydrodynamic loads on the hull (translational terms related to u, v, w)

$$F_{twin\text{-}pod} = F_{0.88model\_exp} - F_{twin\text{-}rudder\_num}$$

- 0.88 scale simplified model (twin pod and twin rudder) tests in different yaw and pitch angles







F – Hydrodynamic loads on the hull (translational terms related to u, v, w)

Merged results from resistance, crab, and yaw tow tests

$$C_x = 0.0084 \cos\beta$$

$$C_y = 0.2326 \cdot \sin\beta$$

$$C_n = (0.0171 + 0.0032 \cdot abs(\beta)) \cdot \sin(2\beta)$$

$$-180° \le \beta \le 180°$$

Merged results from heave and pitch tow tests

$$C_x = 0.0073 \cdot \cos\alpha$$

$$C_z = 0.1159 \cdot \sin\alpha$$

$$C_m = (0.0110 + 0.0020 \cdot abs(\alpha)) \cdot \sin(2\alpha)$$

$$-30° \le \alpha \le 30°$$

F – Hydrodynamic loads on the hull (translational terms related to u, v, w)

Constructed 6 components of the twin-pod load

$$C_x = -\frac{u^2 + v^2}{u^2 + v^2 + w^2} 0.0084 \cdot \cos\beta$$

$$C_y = -\frac{u^2 + v^2}{u^2 + v^2 + w^2} 0.2326 \cdot \sin\beta$$

$$C_z = -\frac{u^2 + w^2}{u^2 + v^2 + w^2} 0.1159 \cdot \sin\alpha$$

$$C_k = 0.0$$

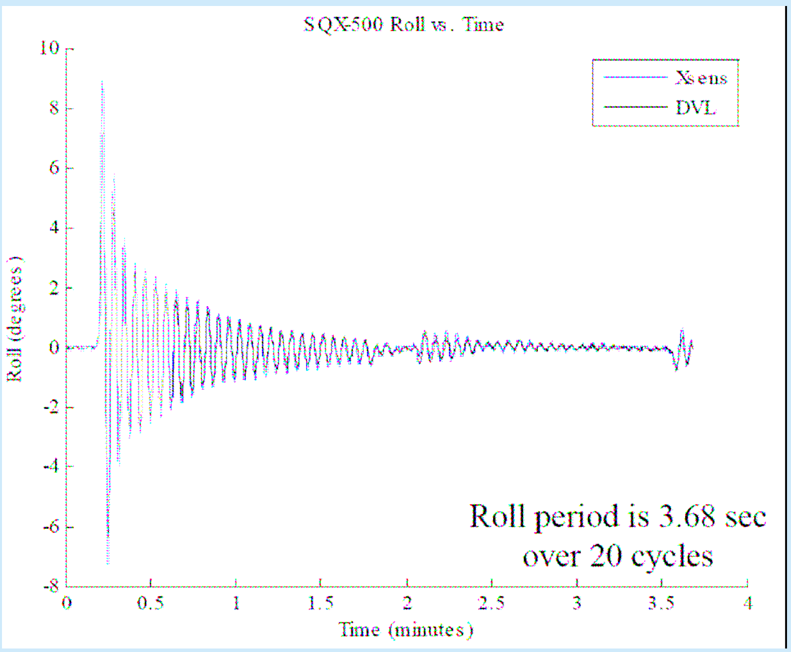
$$C_m = \frac{u^2 + w^2}{u^2 + v^2 + w^2} \left(0.0110 + 0.0020 \cdot abs(\alpha)\right) \cdot \sin(2\alpha)$$

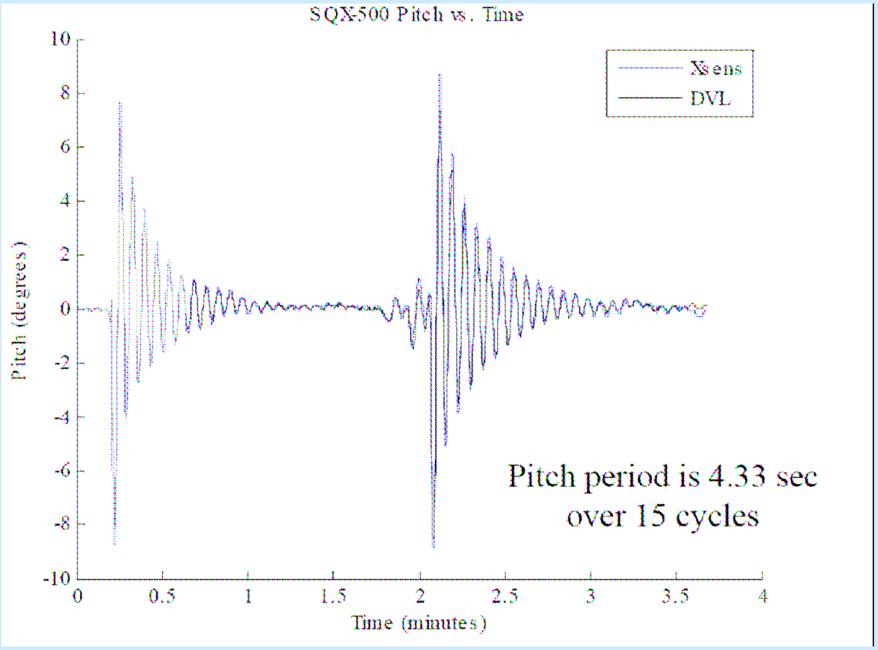
$$C_n = \frac{u^2 + v^2}{u^2 + v^2 + w^2} \left(0.0171 + 0.0032 \cdot abs(\beta)\right) \cdot \sin(2\beta)$$

$[B]\dot{q}$ – Hydrodynamic loads on the hull (terms related to p, q, r)

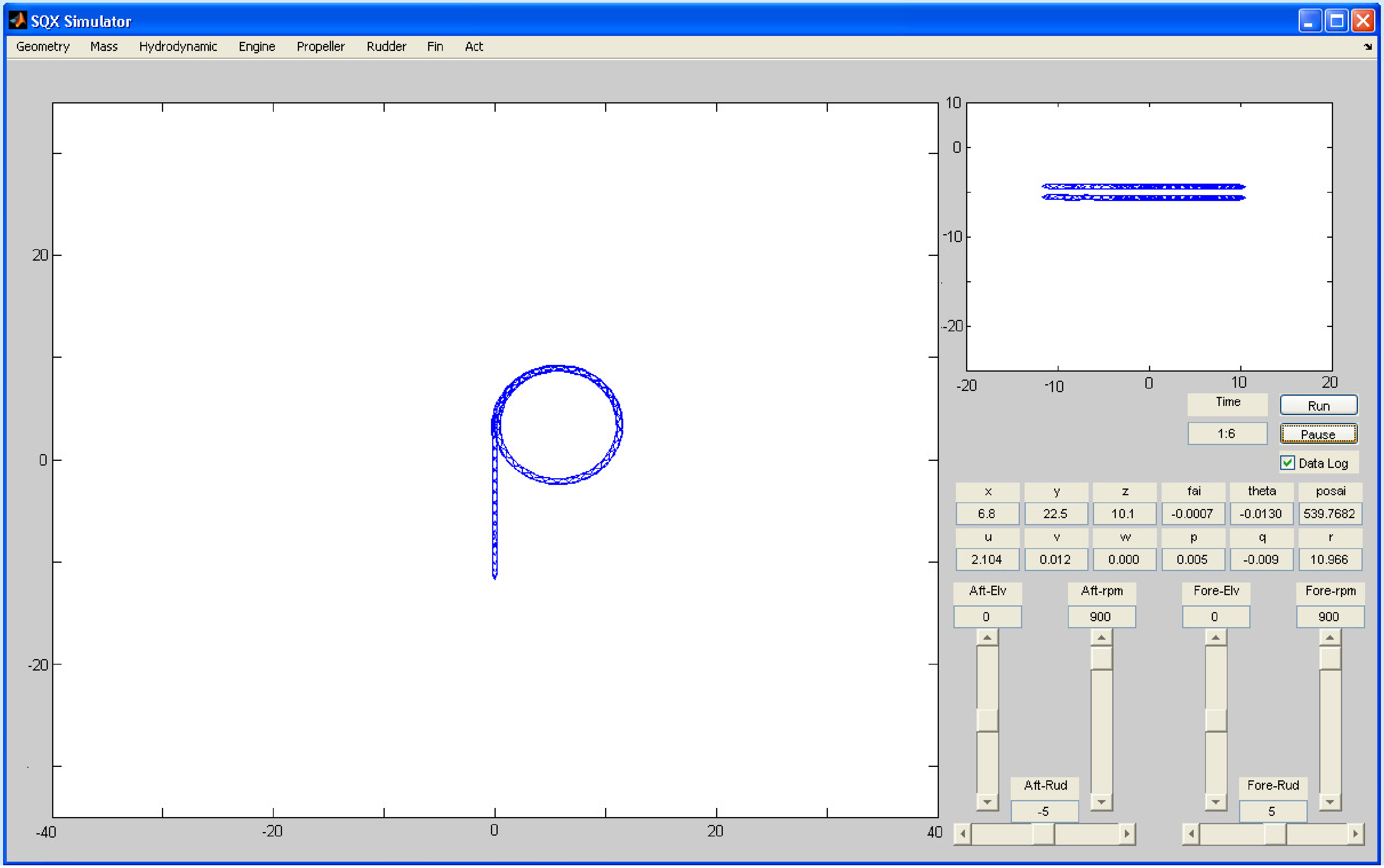
Roll and pitch damping were measured through decay tests at zero vehicle speed, linear damping for roll and pitch were measured as 0.12 and 0.24 respectively

Yaw damping was assumed to be 1.5 times the pitch damping

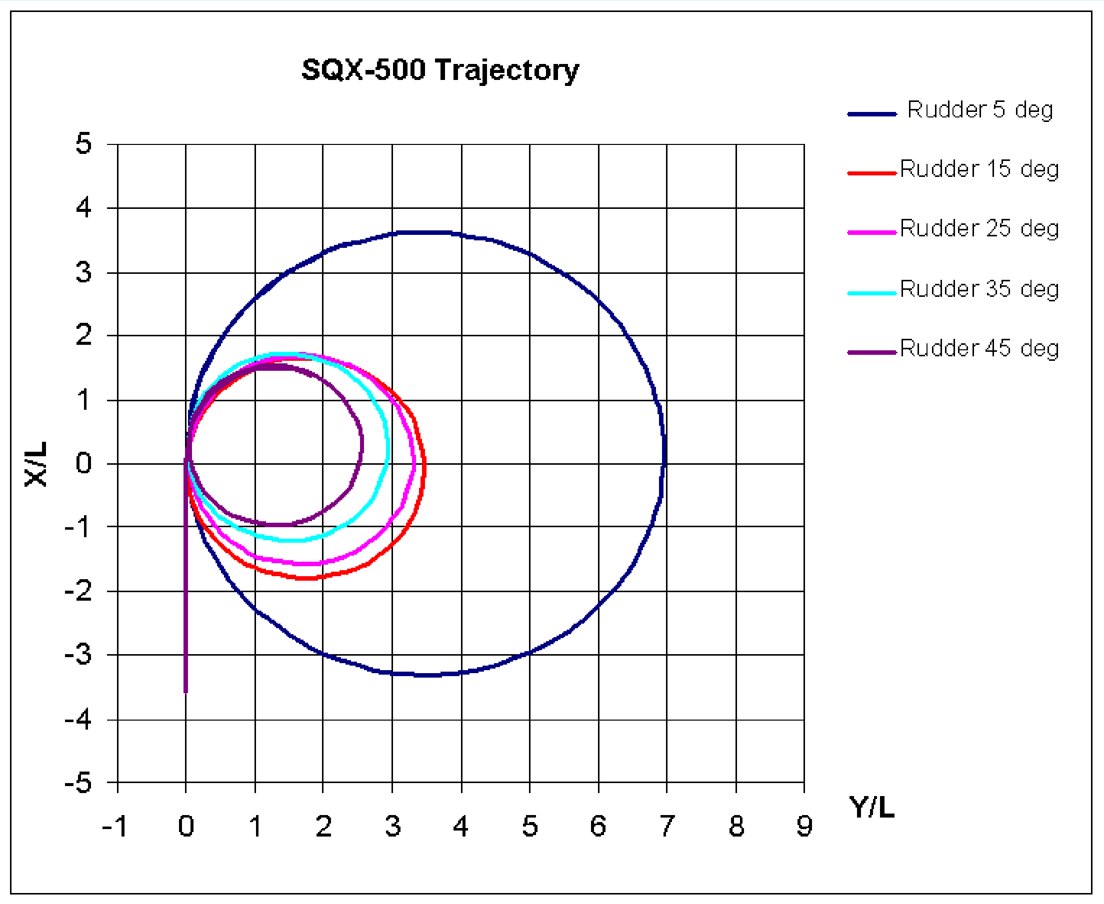


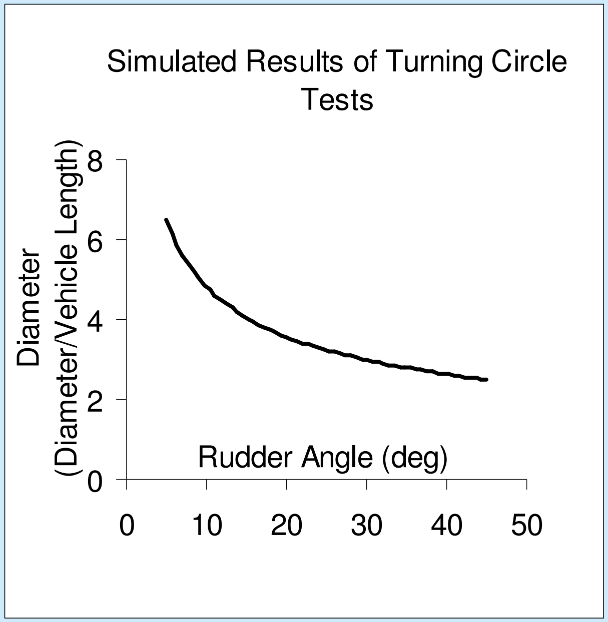


Simulations



Turning Circles





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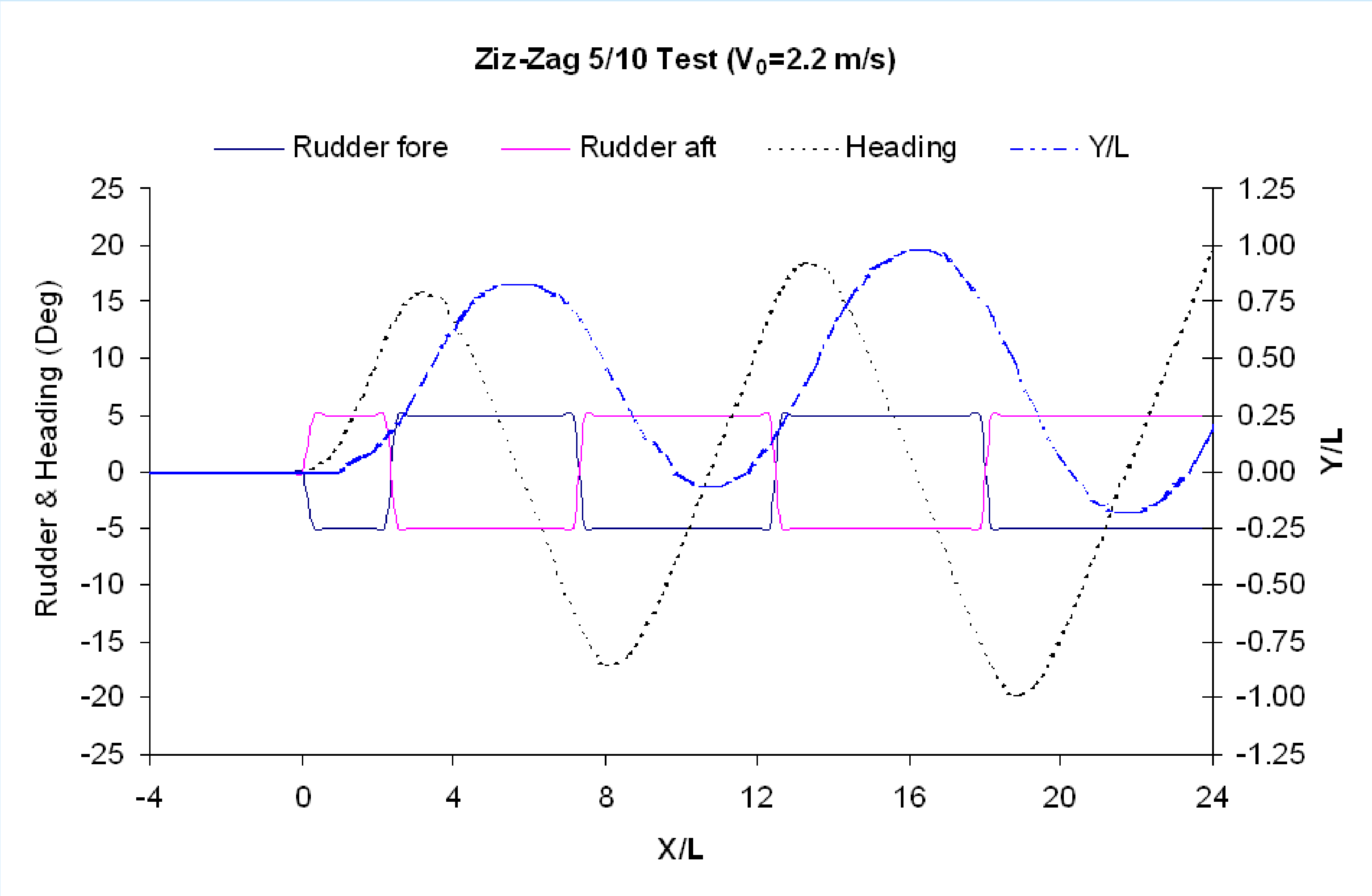


$V_0 = 2.2 \;\; m/s$

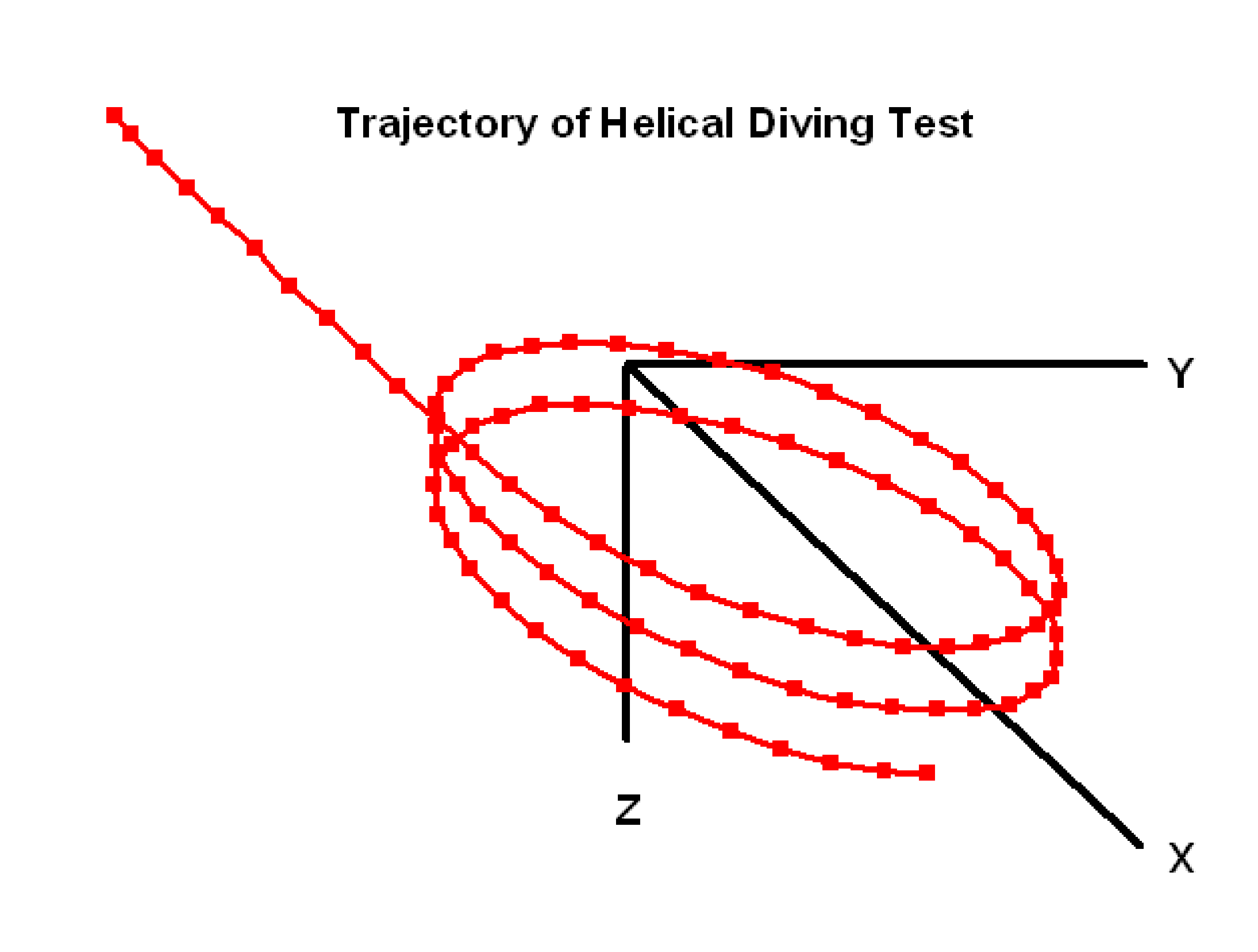
$\delta_{tf} = 0°$

$\delta_{ta} = 0°$

$\delta_{rf} = -/+5°$

$\delta_{ra} = +/-5°$

Helical Diving



$$V_0 = 2.2 \ \ m/s$$

$$\delta_{ef} = -30°$$

$$\delta_{ea} = -30°$$

$$\delta_{rf} = -15°$$

$$\delta_{ra} = +15°$$

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Summary

- A simple hydrodynamic model for a novel twin-pod, twin-thruster underwater vehicle model has been developed and implemented in a Matlab code.
- Simulations of typical vehicle manoeuvres were performed. The simulated results show that the vehicle responses as expected. It will be validated with the vehicle sea trial data when they are available.

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Future Work

- Validation the simulator when vehicle sea trial data is available
- Improve the propulsion modelling by introducing fore and aft thruster and thruster-hull interaction terms into the model.
- Include the Reynolds Number effects on propeller performance.
- Include the Reynolds Number effects on propeller performance.