Artificial motion data for navigation sensors of a submarine running in periscope depth below wave surface

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- Introduction
- Equations of motion
- Navigation data
- Simulation
- Conclusion

Introduction

❖ Background

- Submarine navigation
  - GPS cannot be used.
  - IMU: Dead reckoning
  - Secondary navigational sensor: DVL, EM-Log, Depth gauge, etc.
- Development of navigation algorithm
  - Artificial data of navigation is necessary.
  - Especially the data during alignment near wave surface

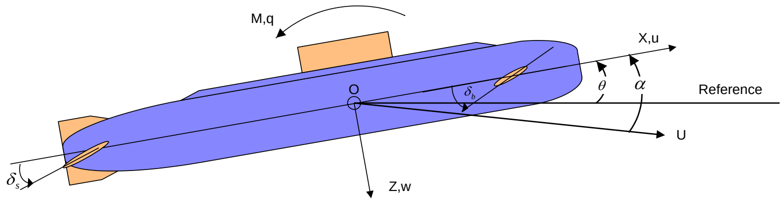
❖ Simulation program

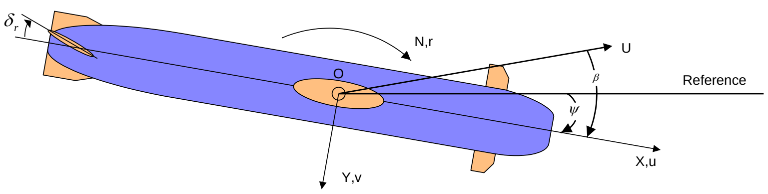
- 6 DOF submarine motion for maneuvering
- Additional seakeeping motion during running or hovering near wave surface

Equations of motion

Coordinate systems

- Earth-centered Earth-fixed: Reference and position
- NED: Position and Euler angle
- Body-fixed: Describe 6 DOF equations of motion





State variables → Velocity and Displacement

- Linear and angular velocities
- Latitude, longitude, height, and Euler angles

Equations of motion

6 DOF equations of motion

$$m\left[\underline{v}^{b\prime}+\underline{\omega}_{nb}^{b}\times\underline{v}^{b}+\underline{\omega}_{nb}^{b\,\prime}\times\underline{r}_{G}^{b}+\underline{\omega}_{nb}^{b}\times\left(\underline{\omega}_{nb}^{b}\times\underline{r}_{G}^{b}\right)\right]=\underline{f}_{HD}+\underline{f}_{HS}+\underline{f}_{G}+\underline{f}_{P}+\underline{f}_{\delta}+\underline{f}_{W}+\underline{f}_{C}$$

$$I\underline{\omega}_{nb}^{b\,\prime}+\underline{\omega}_{nb}^{b}\times\left(I\underline{\omega}_{nb}^{b}\right)+m\underline{r}_{G}^{b}\times\left(\underline{v}^{b\prime}+\underline{\omega}_{nb}^{b}\times\underline{v}^{b}\right)=\underline{m}_{HD}+\underline{m}_{HS}+\underline{m}_{G}+\underline{m}_{P}+\underline{m}_{\delta}+\underline{m}_{W}+\underline{m}_{C}$$

- External force
  - HD, HS, G: Hydrodynamic, hydrostatic, and gravity
  - P, δ: Propeller and control plane
  - W, C: Wave and current

Kinematic relations

$$\underline{v}^{n}=C_{b}^{n}\underline{v}^{b},\quad \underline{\dot{\eta}}=D_{b}^{n}\underline{\omega}_{nb}^{b}$$

$$\dot{\Phi}=\frac{v_N}{R_m+h},\quad \dot{\Theta}=\frac{v_E}{\left(R_t+h\right)\cos\phi},\quad \dot{h}=-v_D$$

External force

❖ Hydrodynamic force

- Feldman model (1979, NSRDC)

$$X_{HD} = X_{\dot{u}}\dot{u} + X(u) + X_{vr}vr + X_{wq}wq + X_{rp}rp + X_{vv}v^2 + X_{ww}w^2 + X_{qq}q^2 + X_{rr}r^2$$

$$Z_{HD} = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_0 + Z_w w + Z_q q + Z_{vp}vp + Z_{|w|}\left|w\right| + Z_{ww}\left|w\sqrt{v^2+w^2}\right|$$
$$+\frac{\rho}{2}C_D\int_l b(x)w(x)\sqrt{w^2(x)+v^2(x)}dx + \frac{\rho}{2}L\bar{C}_L\int_{x_2}^{x_1} v(x)\bar{v}_{FW}\left(t-\tau[x]\right)dx$$

$$M_{HD} = M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_0 + M_w w + M_q q + M_{rp}rp + M_{|w|}\left|w\right| + M_{ww}\left|w\sqrt{v^2+w^2}\right| + M_{w|w|}w\sqrt{v^2+w^2}$$
$$+\frac{\rho}{2}C_D\int_l xb(x)w(x)\sqrt{w^2(x)+v^2(x)}dx + \frac{\rho}{2}L\bar{C}_L\int_{x_2}^{x_1} xv(x)\bar{v}_{FW}\left(t-\tau[x]\right)dx$$

❖ Propeller and control force

$$X_P = \rho n^2 D_P^4 K_T\left(J_P\right)$$
$$K_P = \rho n^2 D_P^5 K_Q\left(J_P\right)$$

$$X_\delta = X_{\delta_r\delta_r}\delta_r^2 + X_{\delta_s\delta_s}\delta_s^2 + X_{\delta_b\delta_b}\delta_b^2$$
$$Z_\delta = Z_{\delta_s}\delta_s + Z_{\delta_b}\delta_b + Z_{\delta_s\eta}\delta_s\left(\eta - \frac{1}{C}\right)C$$
$$M_\delta = M_{\delta_s}\delta_s + M_{\delta_b}\delta_b + M_{\delta_s\eta}\delta_s\left(\eta - \frac{1}{C}\right)C$$

External force

Hydrostatic and gravitational force

$$X_{HS} + X_G = -(W - B)\sin\theta$$
$$Z_{HS} + Z_G = (W - B)\cos\theta\cos\phi$$
$$M_{HS} + M_G = -(z_G W - z_B B)\sin\theta - (x_G W - x_B B)\cos\theta\cos\phi$$

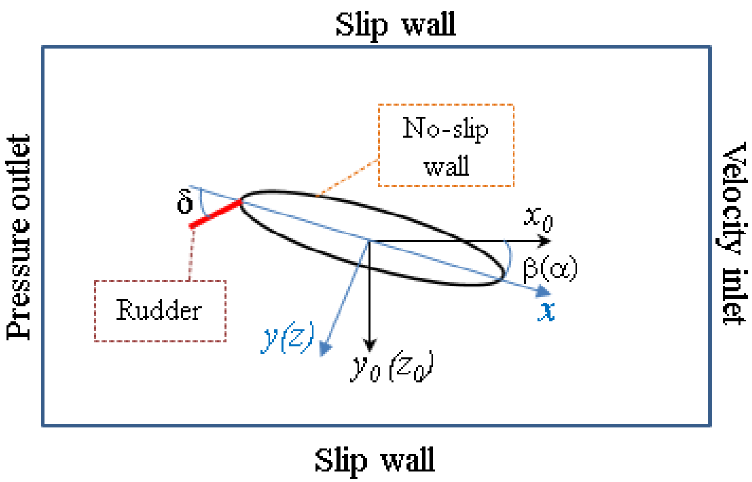
Wave effect

- Superpose wave induced acceleration to maneuvering one
  - Smooth change of motion value → Acceleration considered
  - Response amplitude operator and ITTC wave spectrum

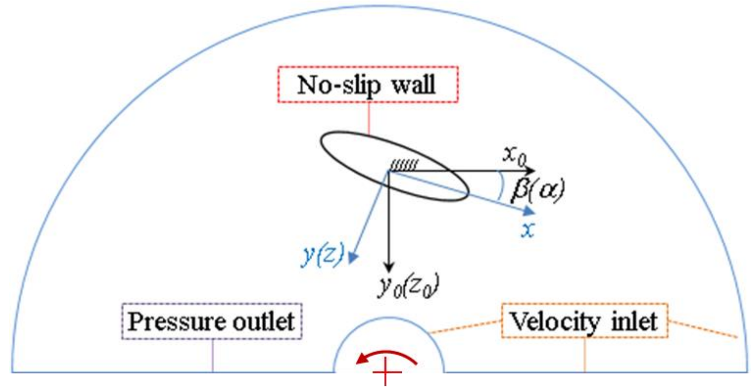
$$\dot{u}_W = -\sum_{i=1}^{N} \omega_i^2 RAO_x \varsigma_i \cos\left[k_i\left(X\cos\alpha + Y\sin\alpha\right) - \omega_i t + \varepsilon_{x_i} + \delta_i\right]$$
$$\dot{w}_W = -\sum_{i=1}^{N} \omega_i^2 RAO_z \varsigma_i \cos\left[k_i\left(X\cos\alpha + Y\sin\alpha\right) - \omega_i t + \varepsilon_{z_i} + \delta_i\right]$$
$$\dot{q}_W = -\sum_{i=1}^{N} \omega_i^2 RAO_\theta k_i \varsigma_i \cos\left[k_i\left(X\cos\alpha + Y\sin\alpha\right) - \omega_i t + \varepsilon_{\theta_i} + \delta_i\right]$$

Hydrodynamic coefficient

❖ Numerical PMM test



Drift test

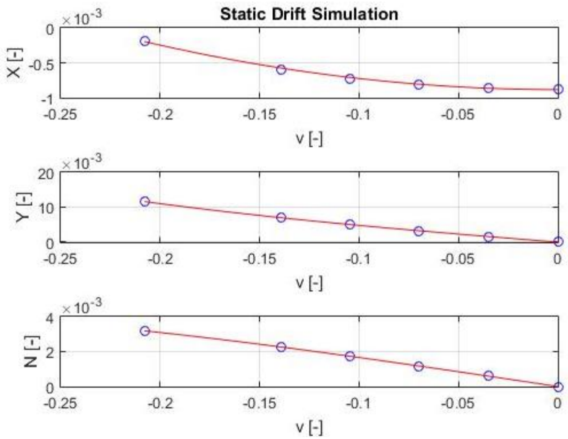


Rotating arm test

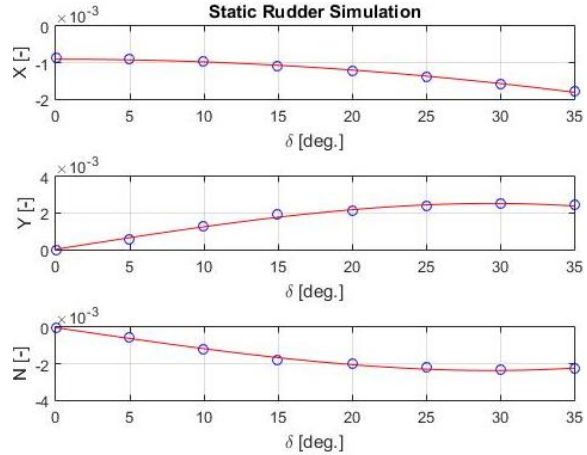
Test	α [°]	β [°]	δ [°]	r'
Static drift	0	2, 4, 6, 8, 12	0	0
Static angle of attack	0, ±2, ±4, ±6, ±8	0	0	0
Static control plane	0	0	0, 5, 10, 15, 20, 25, 30, 35	0
Turn	0	0	0	0.12, 0.17, 0.21, 0.25, 0.29
Drift and turn	0	±3, ±5, ±7, ±9	0	0.21, 0.25, 0.29
Angle of attack and turn	3, 5, 7, 9	0	0	0.21, 0.25, 0.29

Hydrodynamic coefficient

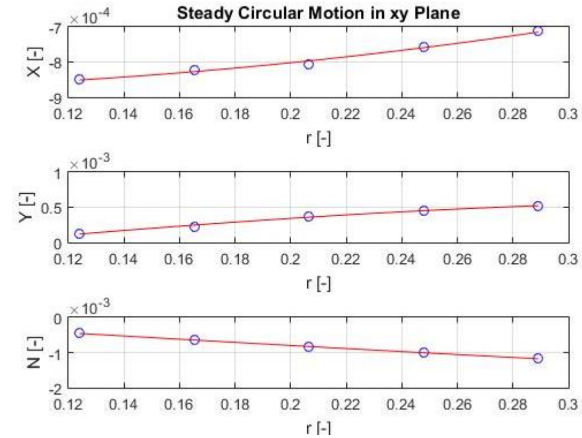
❖ Horizontal plane



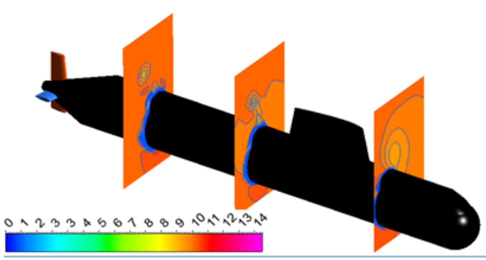
Static drift

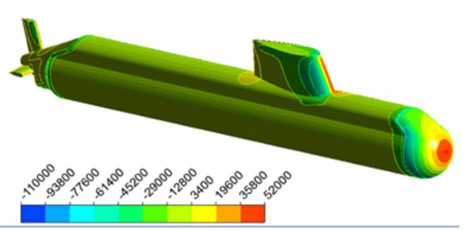


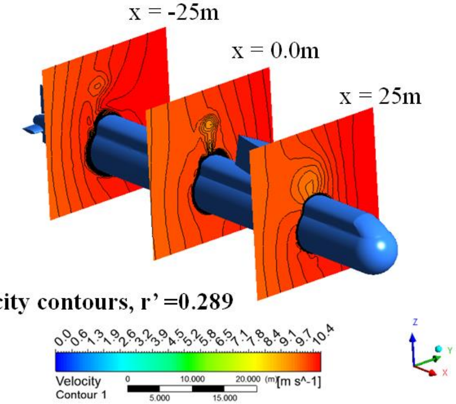
Static rudder



Turning







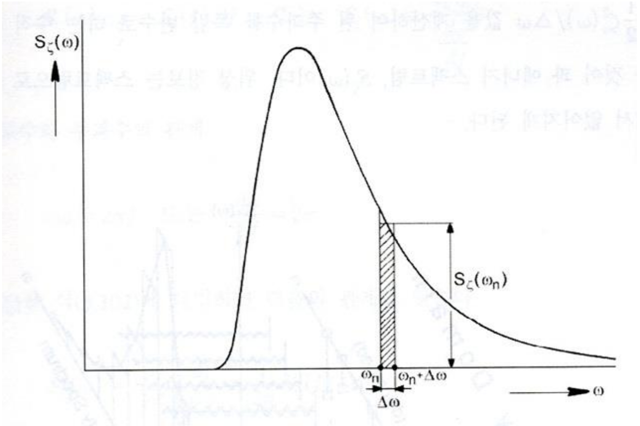
Wave effect

RAO (Response Amplitude Operator)

- ANSYS AQWA (3D panel method based on potential theory)
- Pre-calculation and interpolation for speed and heading
  - Speed: 2~20 knots, 2 knots interval
  - Wave heading: 0~180 degrees, 45 degrees interval
  - Wave frequency: 0.2~3.0 rad/s → Long-crested irregular wave

Wave

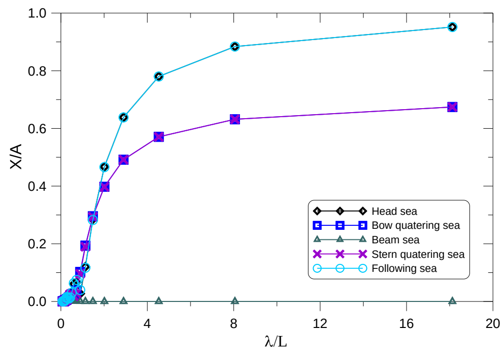
- Long-crested irregular wave
  - Superpose various regular waves
  - ITTC wave spectrum → Wave height
  - Random phase



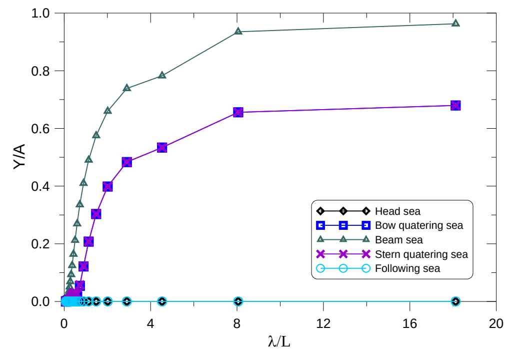
Wave effect

❖ RAO

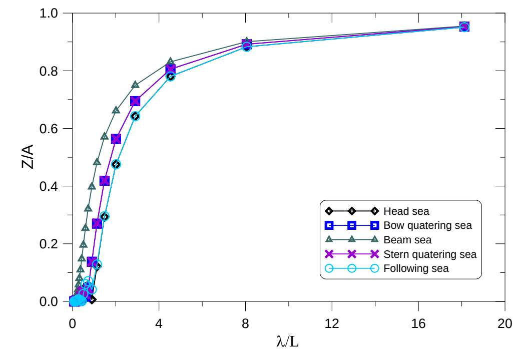
- Stationary case



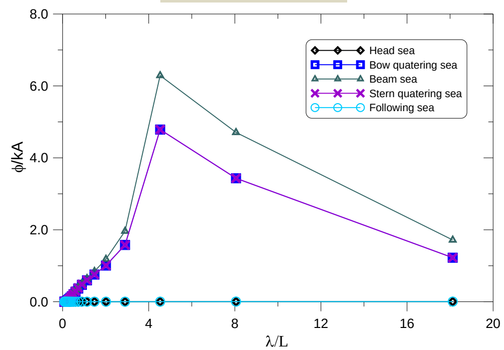
Surge



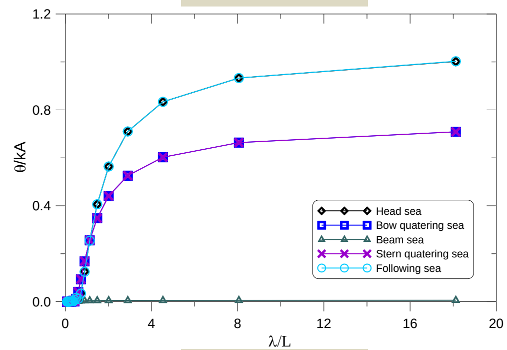
Sway



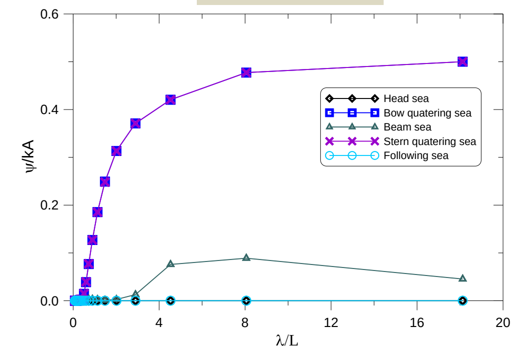
Heave



Roll



Pitch

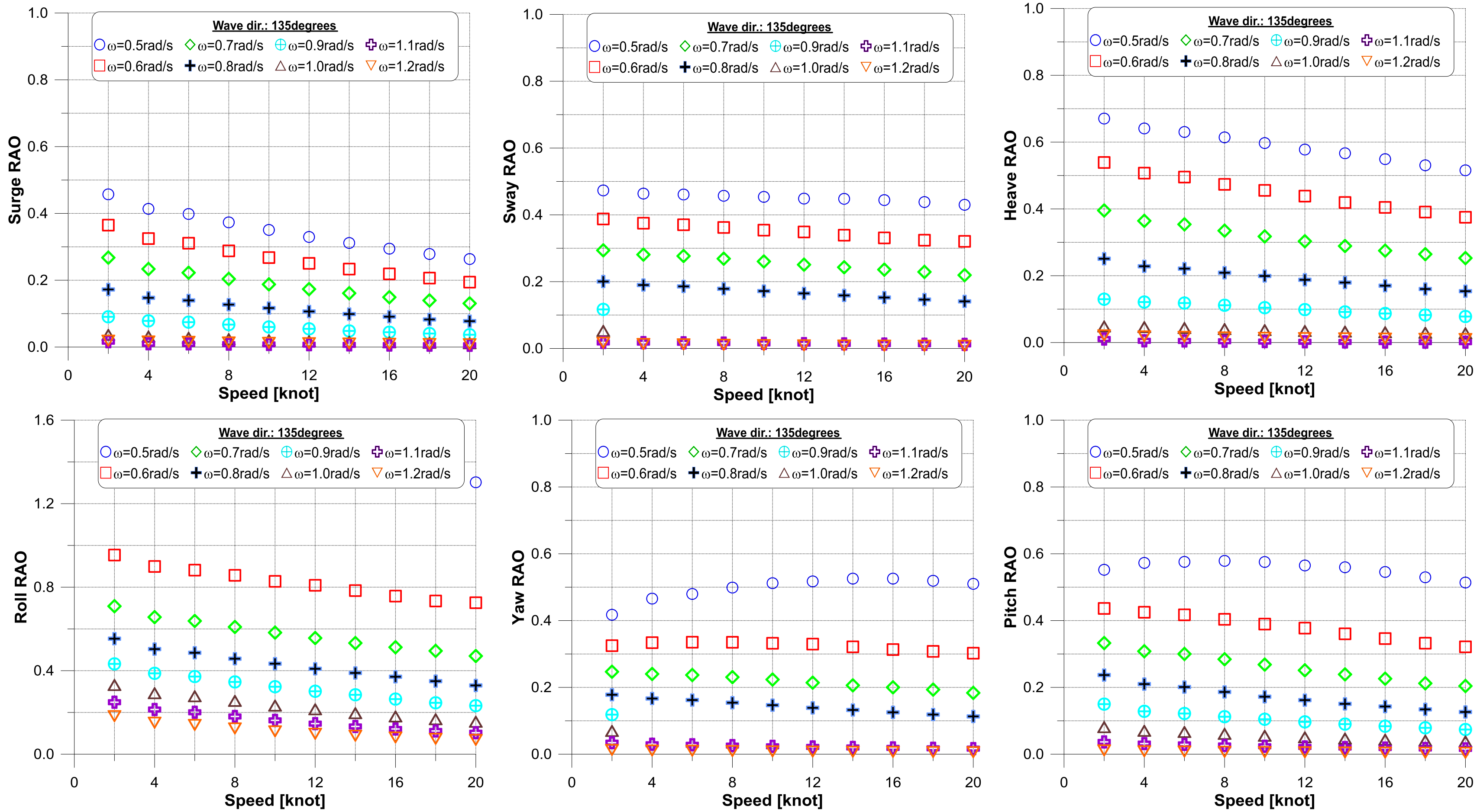


Yaw

Wave effect

RAO (Beam sea)

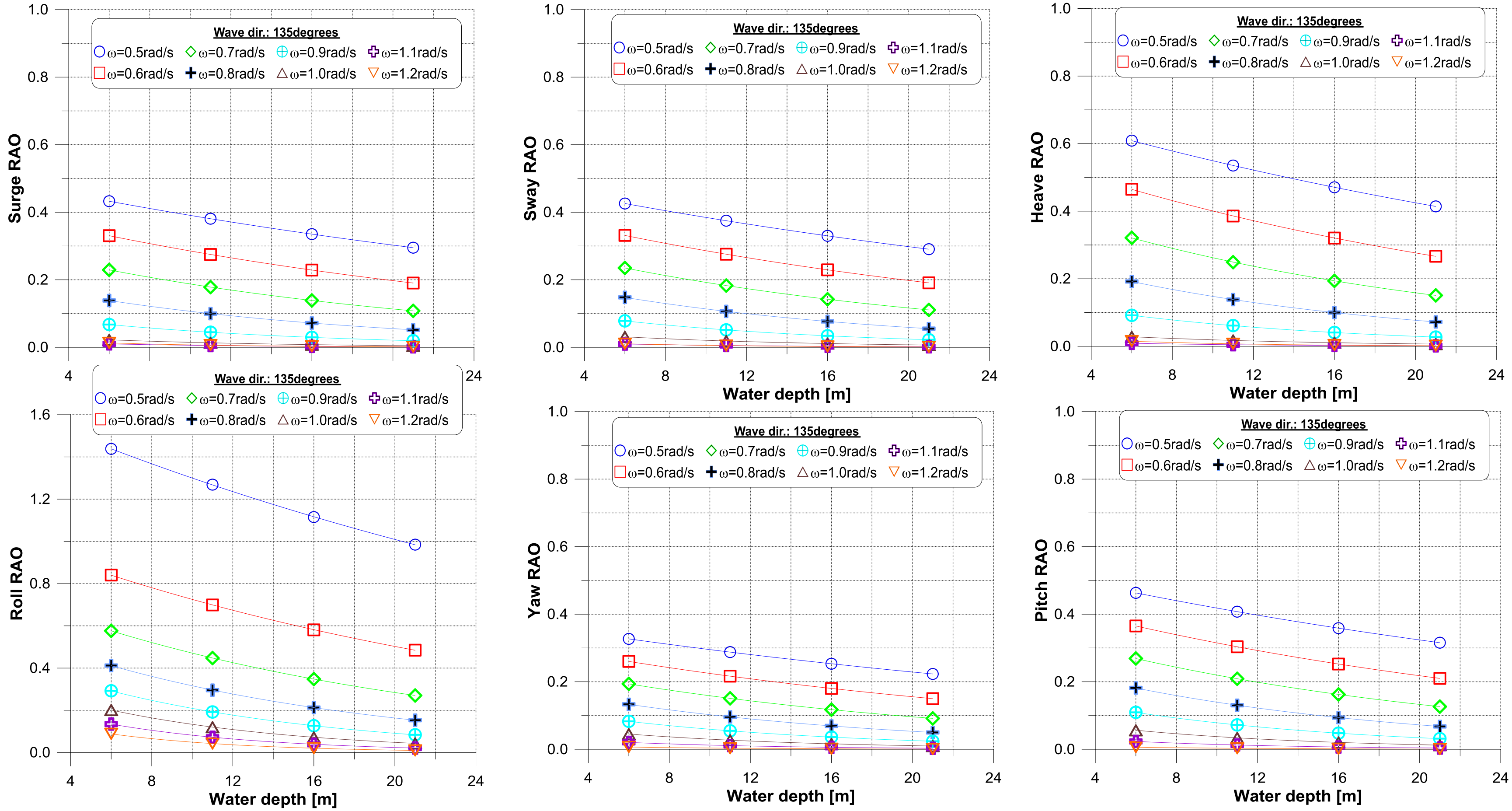
- Speed change



Wave effect

RAO (Bow quartering sea)

- Depth change → modeling using Exp(-kz)



Navigational data

❖ Data stored in navigation sensors

- Measured or calculated values
- Earth's rotation and curved surface effect included

Sensor	Item	Unit	Reference
INS	Position(Θ, Φ, h)	rad, m	Earth-fixed
	Velocity(v_N, v_E, v_D)	m/s	Earth-fixed
	Attitude(ϕ, θ, ψ)	rad	Earth and Body-fixed
	Angular rate($\omega_x, \omega_y, \omega_z$)	rad/s	Body-fixed
	Acceleration(a_x, a_y, a_z)	m/s^2	Body-fixed
DVL	Velocity(u_r, v_r, w_r)	m/s	Body-fixed
DM-Log	Forward speed(V)	m/s	Body-fixed
Depth gauge	Depth(-h)	m	Earth-fixed

Navigational data

IMU (Gyro and accelerometer)

- Earth's rotation and curved surface effect (Transport rate)

$$\underline{\omega}_{ib}^{b} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T = \underline{\omega}_{nb}^{b} + C_n^b \underline{\omega}_{in}^{n}, \quad \text{where, } \underline{\omega}_{in}^{n} = \underline{\omega}_{ie}^{n} + \underline{\omega}_{en}^{n}$$

$$\underline{a}^{b} = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix}^T = C_n^b \left[\underline{\dot{v}}^{n} + \left(2\underline{\omega}_{ie}^{n} + \underline{\omega}_{en}^{n}\right) \times \underline{v}^{n} - \underline{g}^{n} \right]$$

$$\underline{\omega}_{ie}^{n} = \begin{bmatrix} \Omega_{ER} \cos\Phi & 0 & -\Omega_{ER} \sin\Phi \end{bmatrix}^T$$

$$\underline{\omega}_{en}^{n} = \begin{bmatrix} \dfrac{v_E}{R_t + h} & -\dfrac{v_N}{R_m + h} & -\dfrac{v_E \tan\Phi}{R_t + h} \end{bmatrix}^T$$

- Sensor position

$$\underline{\dot{v}}_{s}^{b} = \underline{v}'^{b} + \underline{\omega}_{nb}^{b} \times \underline{v}^{b} + \underline{\omega}'^{b}_{nb} \times \underline{r}_{s}^{b} + \underline{\omega}_{nb}^{b} \times \left(\underline{\omega}_{nb}^{b} \times \underline{r}_{s}^{b} \right)$$

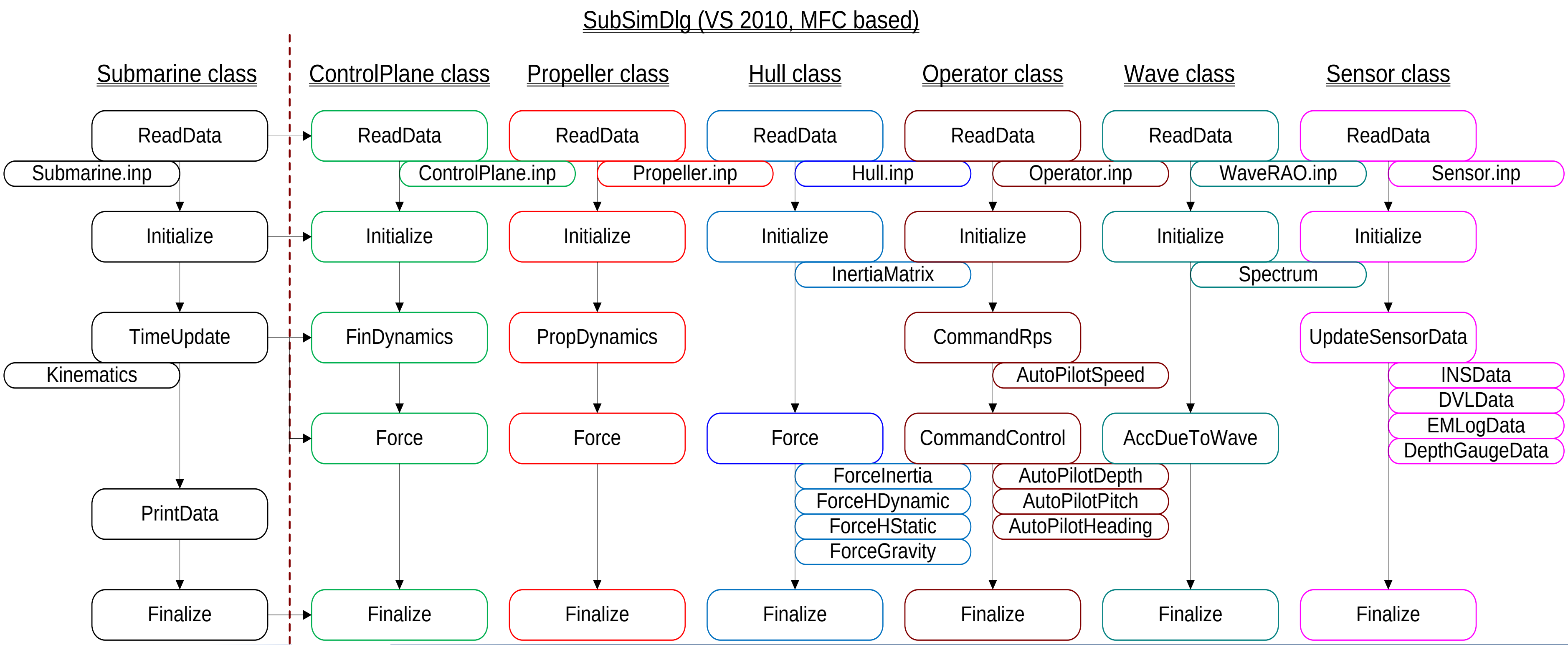
Noise effect

$$z = \left(1 + \varepsilon_{SF}\right) x + \varepsilon_{bias} + \varepsilon_{noise}$$

Simulation

❖ Computer program

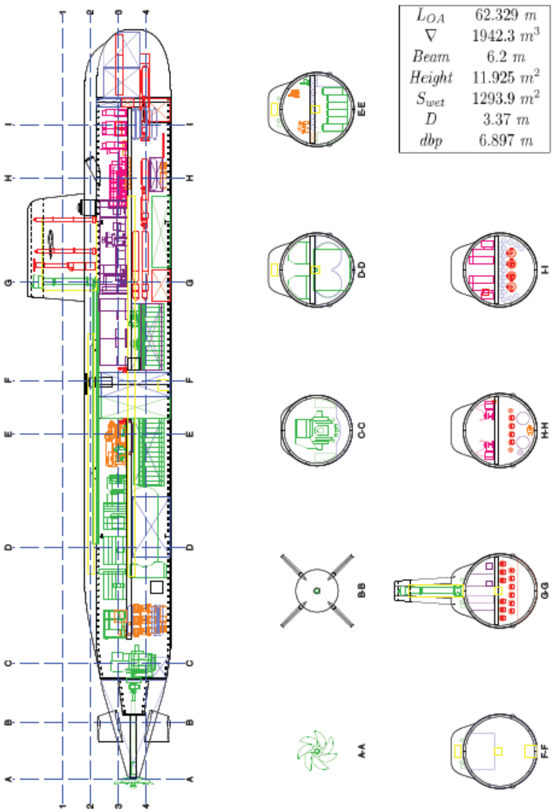
- Visual Studio 2010 MFC based dialog program
- Main class: Submarine
- Subclass: Hull, Propeller, ControlPlane, Operator, Sensor, Wave



Simulation

❖ Sample submarine

- Thune, S., “Simulation of Submarine Manoeuvring”, Master thesis, Royal Institute of Technology, Sweden, 2015



L_{OA}	62.329 m
∇	1942.3 m^3
Beam	6.2 m
Height	11.925 m^2
S_{wet}	1293.9 m^2
D	3.37 m
dbp	6.897 m

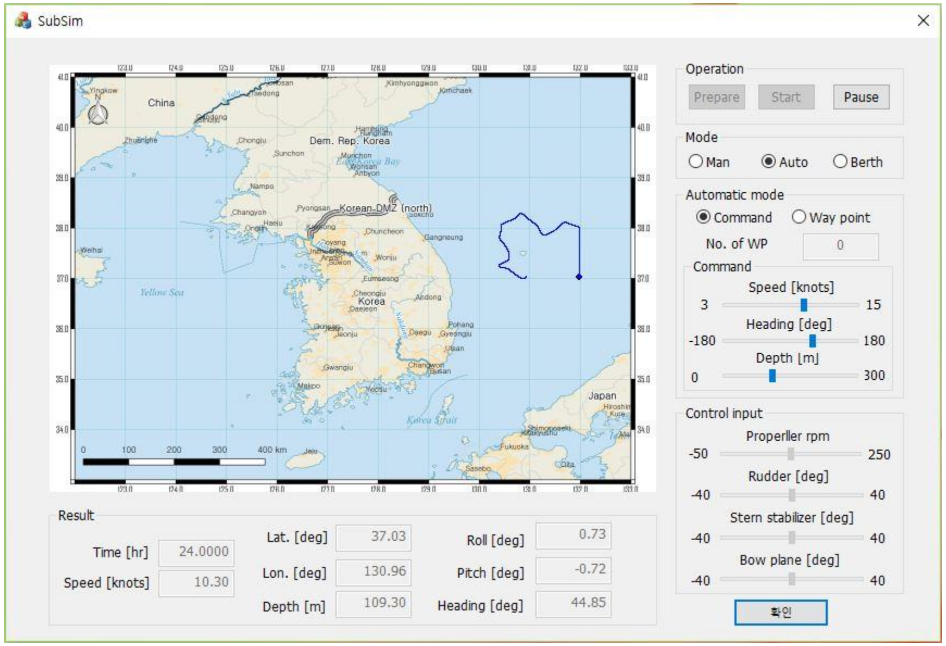
x_G	$= 0$	[m]
y_G	$= 0$	[m]
z_G	$= -0.36697$	[m]
x_B	$= 0$	[m]
y_B	$= 0$	[m]
z_B	$= -0.54848$	[m]
k_{xx}	$= 0.04176$	[-]
k_{yy}	$= 0.24012$	[-]
k_{zz}	$= 0.23858$	[-]
k_{xy}	$= 0.0010303$	[-]
k_{zx}	$= 0.031494$	[-]
k_{yz}	$= 0.0021967$	[-]
S_1	$= 1.17$	[-]
S_2	$= -1.281$	[-]
x_1	$= 10.825$	[m]
x_{FW}	$= 10.825$	[m]
z_{FW}	$= 0$	[m]
β_{ST}	$= 0.133$	[rad]
x_{ap}	$= -33.978$	[m]

X	Y	Z
$X'_{\dot{u}} = -0.00048129$	$Y'_{\dot{p}} = -0.00049893$	$Z'_{\dot{q}} = -0.00020374$
$X'_{rp} = 0.00049893$	$Y'_{\dot{r}} = -0.0016656$	$Z'_{\dot{w}} = -0.01334$
$X'_{qq} = 0.00080214$	$Y'_{\dot{v}} = -0.01744$	$Z'_{vp} = -0.01744$
$X'_{q\|q\|} = 0$	$Y'_{p} = -0.0012749$	$Z'_{q} = -0.0040505$
$X'_{rr} = 0.001123$	$Y'_{pq} = 0.00020374$	$Z'_{q\|q\|} = 0$
$X'_{vr} = 0.016132$	$Y'_{wp} = 0.01334$	$Z'_{rr} = 0$
$X'_{uu} = -0.0011095$	$Y'_{r} = -0.00082411$	$Z'_{vr} = 0$
$X'_{vv} = 0.011293$	$Y'_{r\|r\|} = 0$	$Z'_{vv} = 0$
$X'_{ww} = 0.0037018$	$Y'_{v\|r\|} = 0$	$Z'_{vw} = 0$
$X'_{w\|w\|} = 0$	$Y'_{\|v\|r} = 0$	$Z'_{w} = -0.023841$
$X'_{wq} = -0.012339$	$Y'_{wr} = 0$	$Z'_{\|w\|} = 0$
$X'_{w\|q\|} = 0$	$Y'_{v} = -0.061469$	$Z'_{ww} = 0.0033377$
$X'_{\delta_r\delta_r} = -0.0015181$	$Y'_{v\|v\|} = -0.063314$	$Z'_{w\|w\|R} = 0$
$X'_{\delta_r\delta_r\eta} = 0$	$Y'_{vw} = 0$	$Z'_{w\|q\|} = 0$
$X'_{\delta_s} = 0$	$Y'_{\delta_r} = 0.0034403$	$Z'_{wq} = 0$
$X'_{\delta_s\delta_s} = -0.0015181$	$Y'_{\delta_r\|\delta_r\|} = 0$	$Z'_{\delta_s} = -0.0034403$
$X'_{\delta_s\delta_s\eta} = 0$	$Y'_{\delta_r\eta} = 0.00034403$	$Z'_{\delta_s\|\delta_s\|} = 0$
$X'_{\delta_b} = 0$	$Y'_{\|r\|\delta_r} = 0$	$Z'_{\delta_s\eta} = -0.00034403$
$X'_{\delta_b\delta_b} = -0.0017798$	$Y'_{*} = 0$	$Z'_{\|q\|\delta_s} = 0$
$X'_{rr\xi} = 0$	$Y'_{r\xi} = 0$	$Z'_{\delta_b} = -0.003852$
$X'_{vv\xi} = 0$	$Y'_{v\xi} = 0$	$Z'_{\delta_b\|\delta_b\|} = 0$
		$Z'_{*} = -0.00029985$
		$Z'_{rr\xi} = 0$
		$Z'_{vv\xi} = 0$
		$Z'_{\xi} = 0$
		$Z'_{\xi\|\theta\|} = 0$

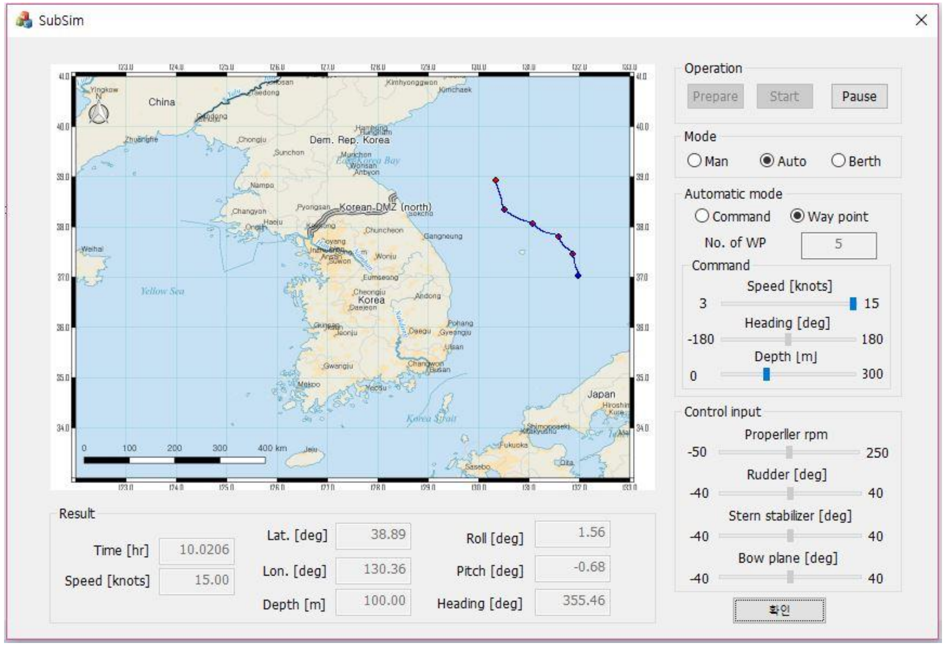
Simulation

❖ GUI to control a submarine

- Manual and automatic mode
  - Automatic mode: Command and way point



Command mode

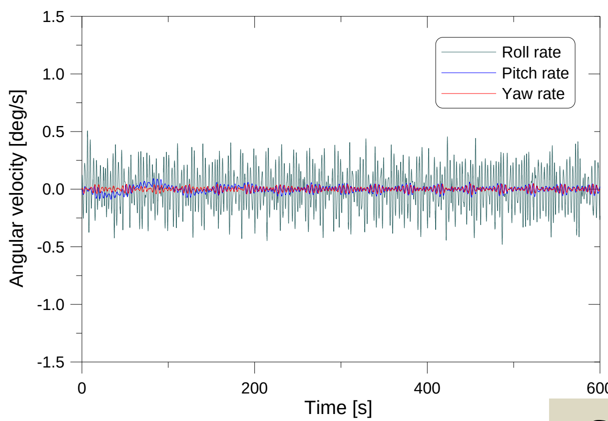


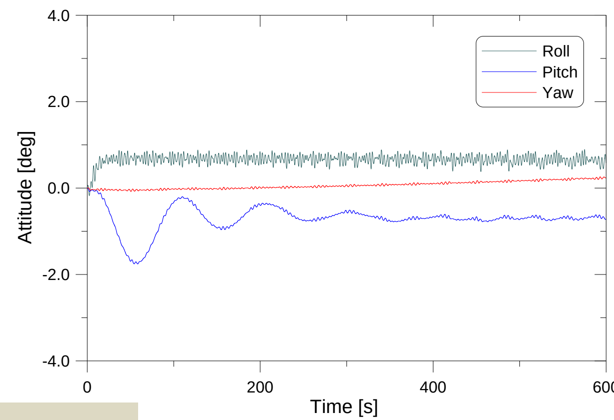
Way point mode

Simulation

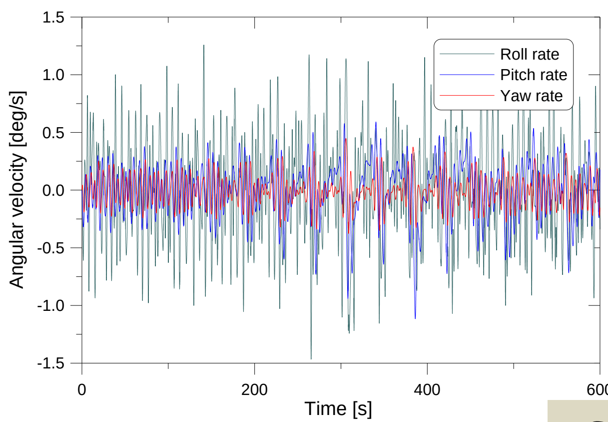
❖ IMU data

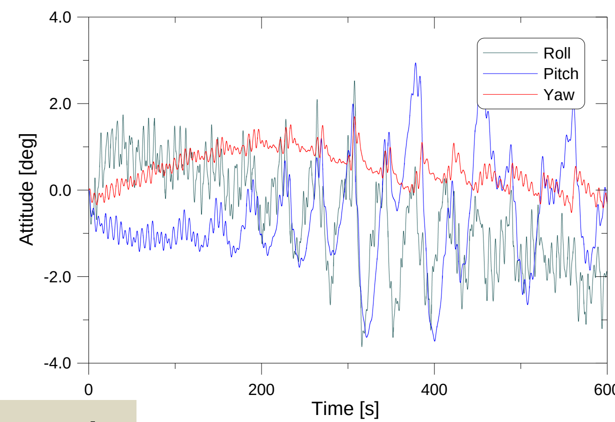
- Angular velocity and attitude





Sea state 3





Sea state 4

Conclusion

❖ Submarine 6 DOF equations of motion

- Maneuvering motion based on Feldman model
- Wave effect added by RAO calculated by ANSYS AQWA
- Hydrodynamic coefficient and RAO
  - Numerical PMM test and RAO for various regular wave

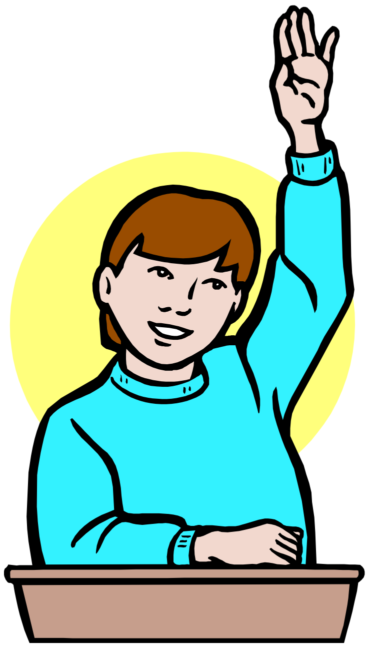
❖ Navigational data

- IMU data including Earth's rotation and transport rate

❖ Simulation

- MFC based GUI program to manage submarine motion
- Binary output data file for confirming navigational algorithm

Thank you for your kind attention



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