On predicting the hydrodynamic coefficients and environmental loads for a free-running vessel in waves

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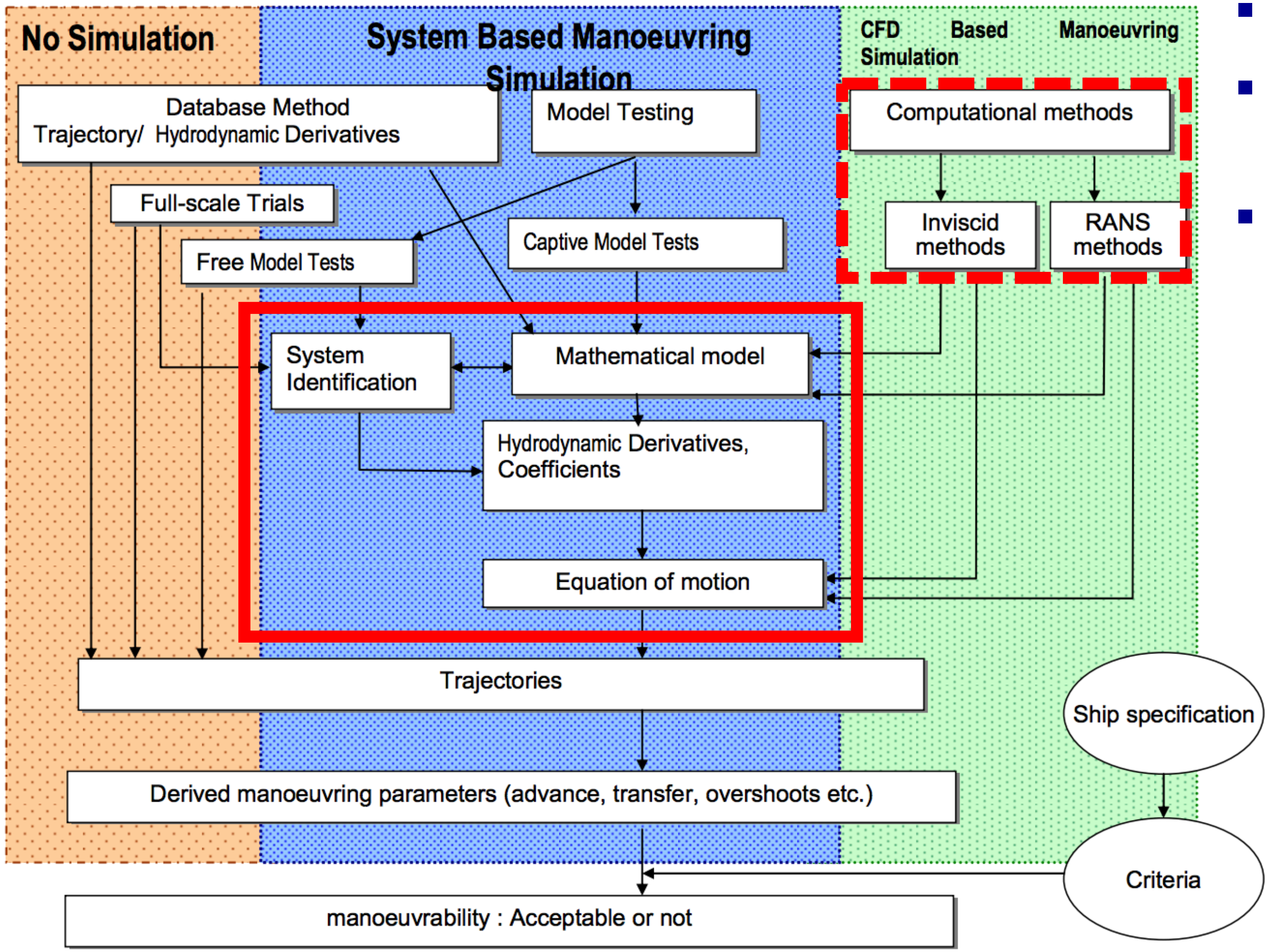
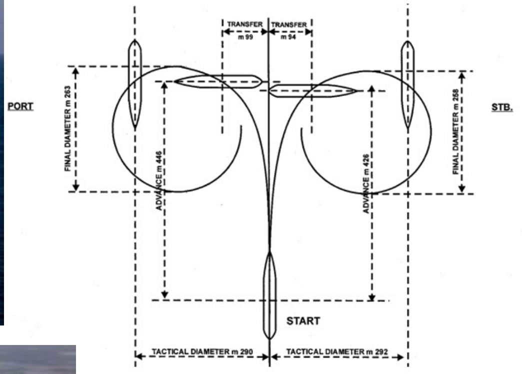
Parameterising a Vessel's Manoeuvrability



Source: Proceedings of 25th ITTC Vol 1

- Sea trials generally conducted in relatively calm seas
- Experienced mariners (e.g. pilots) perform certain sets of manoeuvres to get a 'feel' of vessel's manoeuvrability
- System-based modelling methods most appropriate for real-time simulations/predictions


Source: Marine Insight



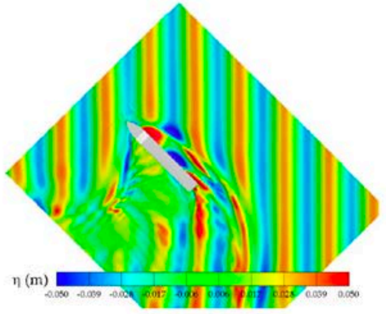

Source: Daily Mail


Source: BAE Systems

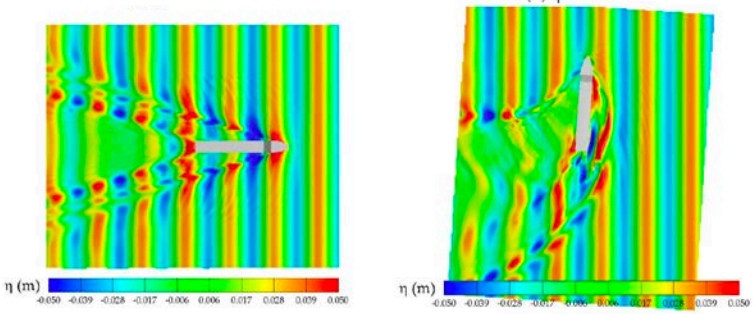
Numerical Modelling – URANS CFD

- Vessel: KRISO Container Ship (KCS)
- Model scale URANS simulations using Star-CCM+
- Simulation parameters:
  - Dynamic Fluid Body Interaction, 6DOF motion solver
  - Overset regions: hull, rudder, propeller
  - Momentum disk/body force propeller model
  - Turning circle and zigzag in calm water and in regular waves (λ/L = 0.5 and 1.1)

Scale	1	31.6
Length between perpendiculars L [m]	230	7.28
Breadth at waterline B [m]	32.2	1.02
Draft T [m]	19	0.6
Mass m [kg]	53,330,750	1,690
Block coefficient C_b	0.651	0.651
Radius of gyration R_{zz}/L	0.25	0.25

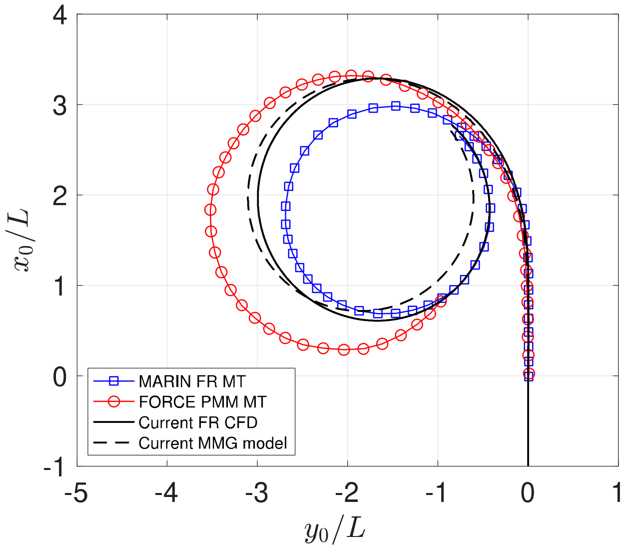


(b) φ= 135°

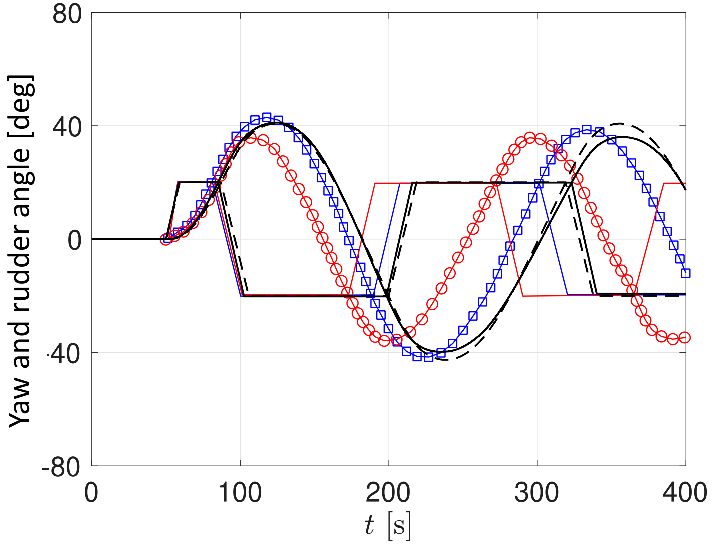


(c) φ= 0°
(d) φ= 85°

Turning circle, 35° PT rudder, Fn_0 = 0.26



20°/20° zigzag, Fn_0 = 0.26



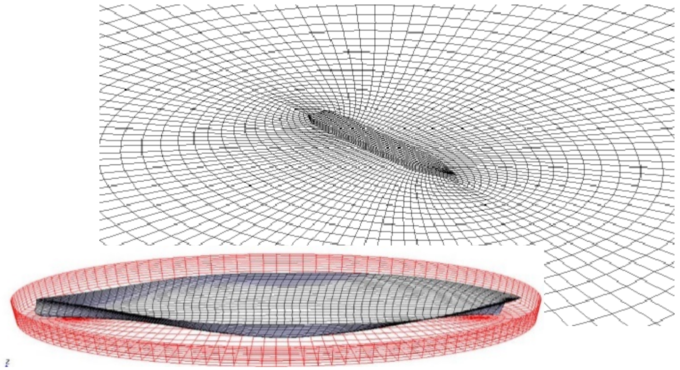
Calm water comparisons with:
- Free-running (FR) model tests (MT)[1]
- Planar motion mechanism (PMM) derived model[2]
- Mathematical MMG model[3]

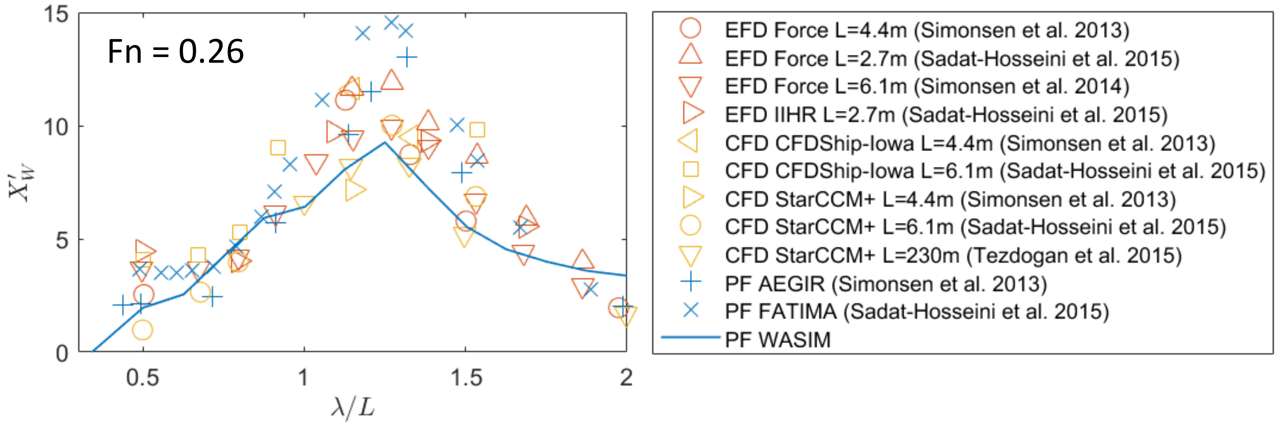
[1] SIMMAN (2014)
[2] Otzen & Simonsen (2014)
[3] Yoshimura & Masumoto (2011)

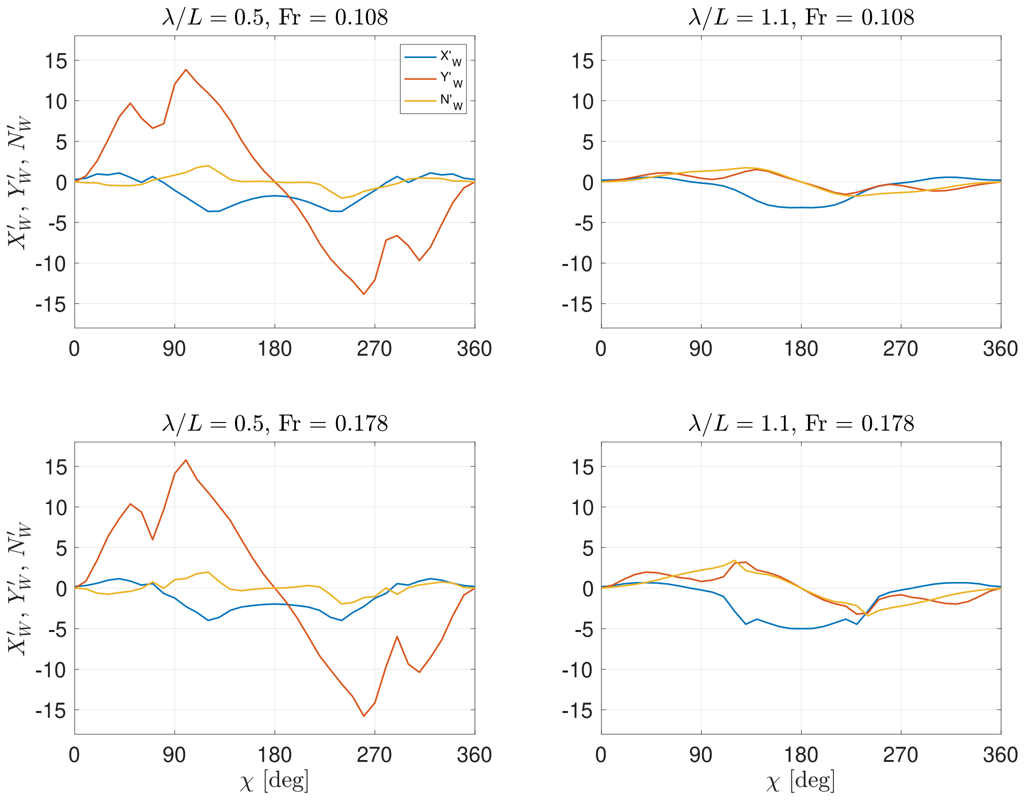
TCOMS

Numerical Modelling – Potential-Flow

- Sesam WASIM (DNV GL) to derive added resistance due to waves
- Time-domain Rankine source solver
  - Conservation of momentum on near-field fluid domain
  - Added resistance calculated by integrating the potential over a control surface
- Simulation parameters:
  - Double body linearisation of basis flow
  - Control surface: 1.3 x Lpp, 1.3 x B, 1.1 x T
  - 1040 panels on wetted hull, 5134 panels on free surface
  - Mean drift in surge, sway and yaw for 2 speeds, 2 wavelengths





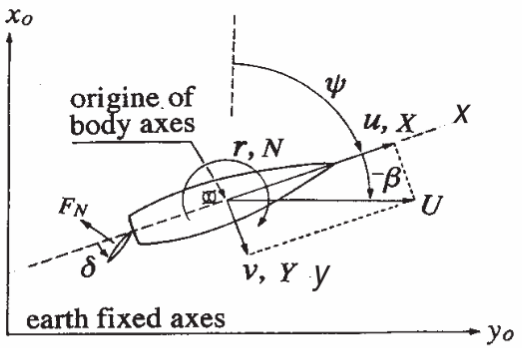


Mathematical Model

TCOMS

- MMG model* – forces and moments decomposed into hull, rudder and propeller (and wave) components
- 3 DOF equation of motions:

$$
\begin{aligned}
(m+m_x)\dot{u} &= X_H + X_R + X_P + X_W \\
(m+m_y)\dot{v} &= Y_H + Y_R + Y_P + Y_W \\
(I_{zz}+J_{zz})\dot{r} &= N_H + N_R + N_P + N_W
\end{aligned}
$$



- Hull forces and moment, functions of drift angle (β) and yaw rate (r):

$$
\begin{aligned}
X_H &= \frac{\rho}{2} LTU^2 \left[X'_0 + X'_{\beta\beta}\beta^2 + X'_{\beta r}\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta\beta}\beta^4\right] - m_y v r \\
Y_H &= \frac{\rho}{2} LTU^2 \left[Y'_\beta \beta + Y'_r r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3\right] + m_x u r \\
N_H &= \frac{\rho}{2} L^2TU^2 \left[N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr} r'^3\right]
\end{aligned}
$$

- Coefficients to solve for:

$$
X'_{\beta\beta}, X'_{\beta r}, X'_{rr}, X'_{\beta\beta\beta\beta}, Y'_\beta, Y'_r, Y'_{\beta\beta\beta}, Y'_{\beta\beta r}, Y'_{\beta rr}, Y'_{rrr}, N'_\beta, N'_r, N'_{\beta\beta\beta}, N'_{\beta\beta r}, N'_{\beta rr}, N'_{rrr}
$$

- Wave resistance and propulsion forces/models prescribed

*Yasukawa & Yoshimura (2015), Yoshimura & Masumoto (2011)

System Identification

TCOMS

- State-augmented extended Kalman filter (SAEKF)
- State transition equation and observation equations:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}(n), \boldsymbol{u}(n)) + \boldsymbol{E}\boldsymbol{w}, \qquad \boldsymbol{x} = [u, v, r, \boldsymbol{\alpha}]^\top$$

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{v}. \qquad \boldsymbol{y} = (u_m, v_m, r_m)$$

$$\boldsymbol{u} = [n_P, \delta]^\top$$

- Initial state estimate: $\bar{\boldsymbol{x}}(0) = [u_m(0), v_m(0), r_m(0), \boxed{\boldsymbol{\alpha}_\mathrm{E}}]^\top$ empirical coefficients from Yoshimura & Masumoto (2011)
- Compute Kalman gain: $\boldsymbol{K}(n) = \bar{\boldsymbol{P}}(n)\boldsymbol{H}^\top(n)[\boldsymbol{H}(n)\bar{\boldsymbol{P}}(n)\boldsymbol{H}^\top(n) + \boldsymbol{R}(n)]^{-1}$
- Update:

$$\hat{\boldsymbol{x}}(n) = \bar{\boldsymbol{x}}(n) + \boldsymbol{K}(n)[\boldsymbol{y}(n) - \boldsymbol{H}(n)\bar{\boldsymbol{x}}(n)]$$

$$\bar{\boldsymbol{P}}(0) = [(\bar{\boldsymbol{x}}(0) - \hat{\boldsymbol{x}}(0))(\bar{\boldsymbol{x}}(0) - \hat{\boldsymbol{x}}(0))^\top]$$

$$\boldsymbol{H} = [\,\boldsymbol{I}\,|\,\boldsymbol{0}\,]$$

$$\hat{\boldsymbol{P}}(n) = [\boldsymbol{I} - \boldsymbol{K}(n)\boldsymbol{H}(n)]\bar{\boldsymbol{P}}(n)[\boldsymbol{I} - \boldsymbol{K}(n)\boldsymbol{H}(n)]^\top + \boldsymbol{K}(n)\boldsymbol{R}(n)\boldsymbol{K}^\top(n)$$

- Predict:

$$\bar{\boldsymbol{x}}(n+1) \approx \hat{\boldsymbol{x}}(n) + h[\boldsymbol{f}(\hat{\boldsymbol{x}}(n), \boldsymbol{u}(n))]$$

$$\boldsymbol{\Phi}(n) \approx \boldsymbol{I} + h\left.\frac{\partial \boldsymbol{f}(\boldsymbol{x}(n), \boldsymbol{u}(n))}{\partial \boldsymbol{x}(n)}\right|_{\boldsymbol{x}(n)=\hat{\boldsymbol{x}}(n)}$$

$$\bar{\boldsymbol{P}}(n+1) = \boldsymbol{\Phi}(n)\hat{\boldsymbol{P}}(n)\boldsymbol{\Phi}^\top(n) + \boldsymbol{\Gamma}(n)\boldsymbol{Q}(n)\boldsymbol{\Gamma}^\top(n)$$

$$\boldsymbol{\Gamma}(n) \approx h\boldsymbol{E}$$

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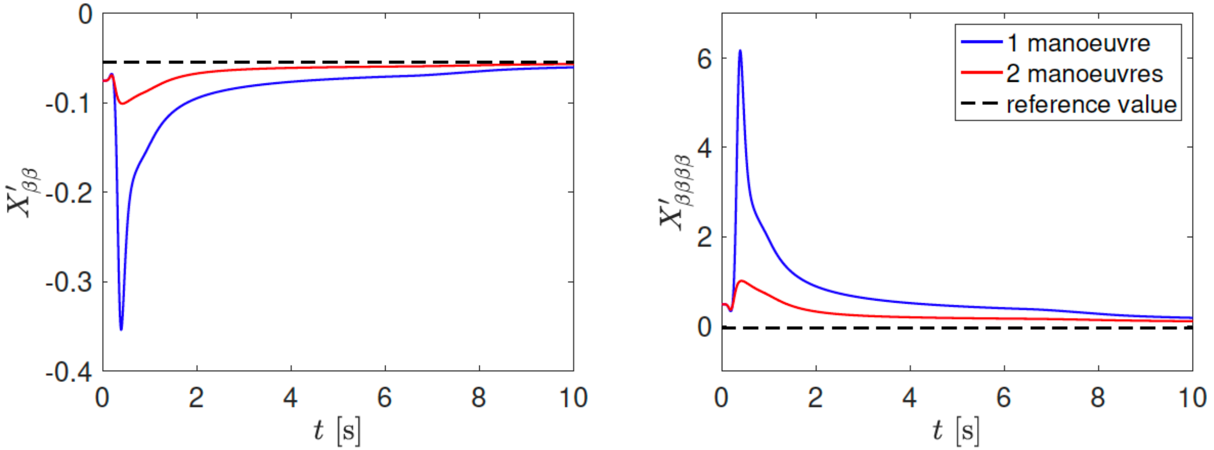
$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{v}.$$

$$\boldsymbol{x} = [u_1, v_1, r_1, u_2, v_2, r_2, \boldsymbol{\alpha}]^\top$$

$$\boldsymbol{y} = (u_m, v_m, r_m)$$

$$\boldsymbol{u} = [n_P, \delta]^\top$$

- Parallel processing of multiple manoeuvres => faster convergence of state estimates

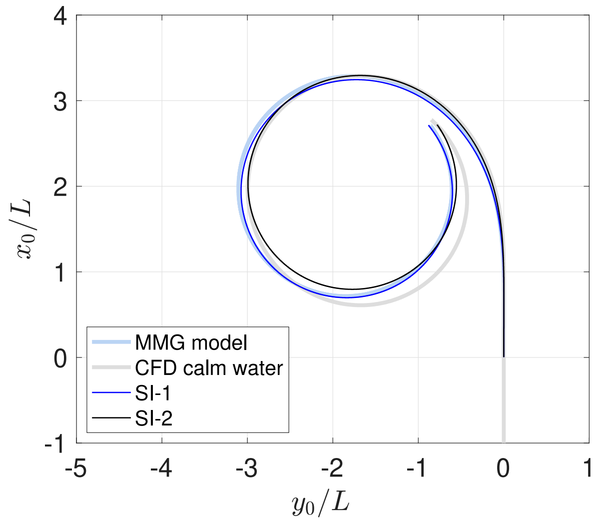


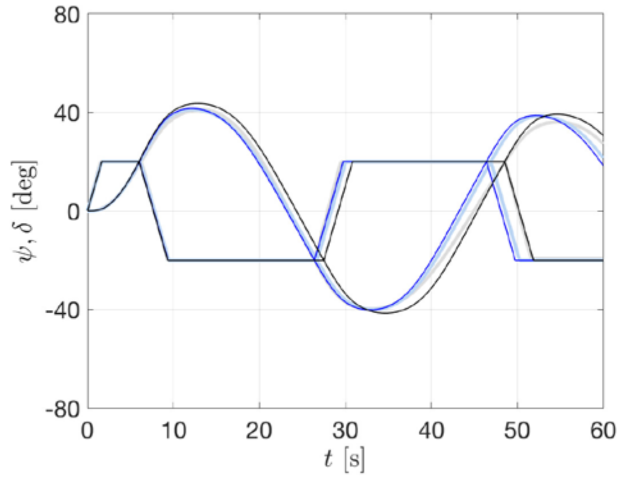
- Manoeuvres/training data: 35° port turning circle and 20°/20° zigzag

Predictions of Coefficients and Trajectories

- Comparison of predictions in calm water:

			Calm Water		In Waves	
	Reference	Empirical	MMG model	URANS	URANS λ/L = 1.1	URANS λ/L = 0.5
	KCS[21]	$\mathrm{KCS_E}$ (Δ_K%)	SI-1 (Δ_K%)	SI-2 (Δ_K%)	SI-3 (Δ_K%)	SI-4 (Δ_K%)
$X'_{\beta\beta}$	-0.0549	-0.0752 (37)	-0.0552 (0.6)	-0.0577 (5.1)	-0.0660 (20.2)	-0.0598 (8.9)
$X'_{\beta r}$	-0.1084	-0.0941 (-13.2)	-0.1090 (0.6)	-0.0994 (-8.3)	-0.1005 (-7.2)	-0.1049 (-3.2)
X'_{rr}	-0.0120	0.0003 (-102.1)	-0.0136 (12.9)	-0.0025 (-78.8)	-0.0185 (54.3)	-0.0149 (23.9)
$X'_{\beta\beta\beta\beta}$	-0.0417	0.4912 (-1277.9)	-0.0419 (0.5)	-0.0521 (24.9)	-0.0645 (54.7)	-0.0518 (24.2)
Y'_{β}	0.2252	0.2751 (22.2)	0.2278 (1.1)	0.2366 (5.1)	0.2525 (12.1)	0.2373 (5.4)
Y'_{r}	0.0398	0.0416 (4.5)	0.0402 (0.9)	-0.0065 (-116.4)	-0.0564 (-241.6)	-0.0027 (-106.8)
$Y'_{\beta\beta\beta}$	1.7179	1.8014 (4.9)	1.7179 (0.002)	1.7388 (1.2)	1.7635 (2.7)	1.7381 (1.2)
$Y'_{\beta\beta r}$	-0.4832	-0.3225 (-33.3)	-0.4832 (0.007)	-0.4430 (-8.3)	-0.3954 (-18.2)	-0.4444 (-8)
$Y'_{\beta rr}$	0.8341	0.6965 (-16.5)	0.8339 (-0.02)	0.7983 (-4.3)	0.7589 (-9)	0.8008 (-4)
Y'_{rrr}	-0.0050	-0.051 (920)	-0.0061 (22.7)	-0.0086 (71.3)	-0.0077 (55)	-0.0062 (24.3)
N'_{β}	0.1111	0.0939 (-15.5)	0.1083 (-2.6)	0.1056 (-5)	0.1017 (-8.5)	0.1069 (-3.7)
N'_{r}	-0.0465	-0.0419 (-9.9)	-0.0433 (-6.9)	-0.0467 (0.4)	-0.0440 (-5.4)	-0.0454 (-2.4)
$N'_{\beta\beta\beta}$	0.1751	0.2108 (20.4)	0.1749 (-0.1)	0.1840 (5.1)	0.1946 (11.1)	0.1837 (4.9)
$N'_{\beta\beta r}$	-0.6167	-0.4006 (-35)	-0.6172 (0.1)	-0.5622 (-8.8)	-0.4986 (-19.1)	-0.5645 (-8.5)
$N'_{\beta rr}$	0.0512	-0.0592 (-215.6)	0.0504 (-1.6)	0.0638 (24.6)	0.0792 (54.6)	0.0636 (24.2)
N'_{rrr}	-0.0387	-0.0537 (38.8)	-0.0407 (5.1)	-0.0433 (11.8)	-0.0469 (21.2)	-0.0423 (9.4)
		RMSE Δ_K:	6.9%	40.7%	67.3%	29.7%
		$\Sigma\lvert\Delta_\mathrm{K}\rvert$:	0.0165	0.2762	0.5688	0.2516
		$\Sigma\lvert\Delta_1\rvert$:		0.2743	0.5587	0.2443
		$\Sigma\lvert\Delta_2\rvert$:			0.3160	0.0382





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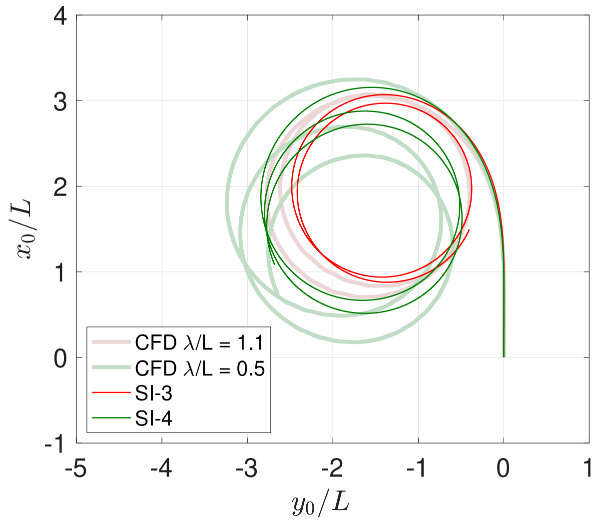
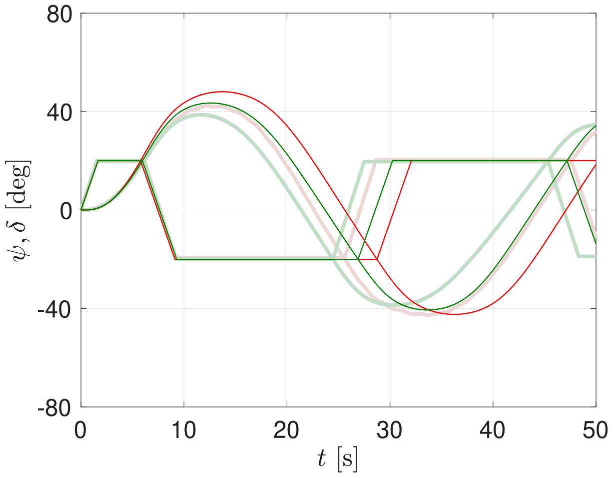
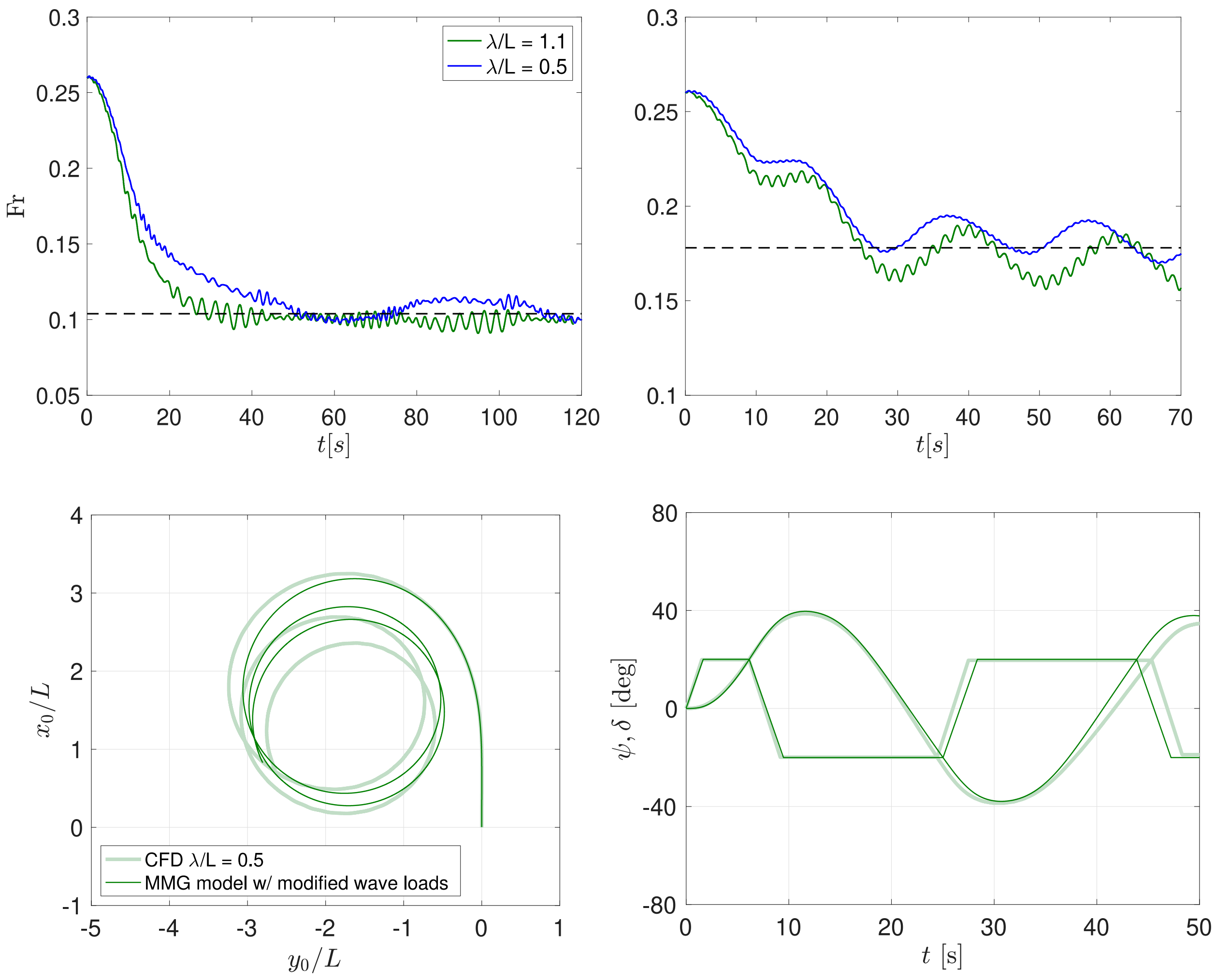
		$\Sigma\lvert\Delta_2\rvert$:			0.3160	0.0382





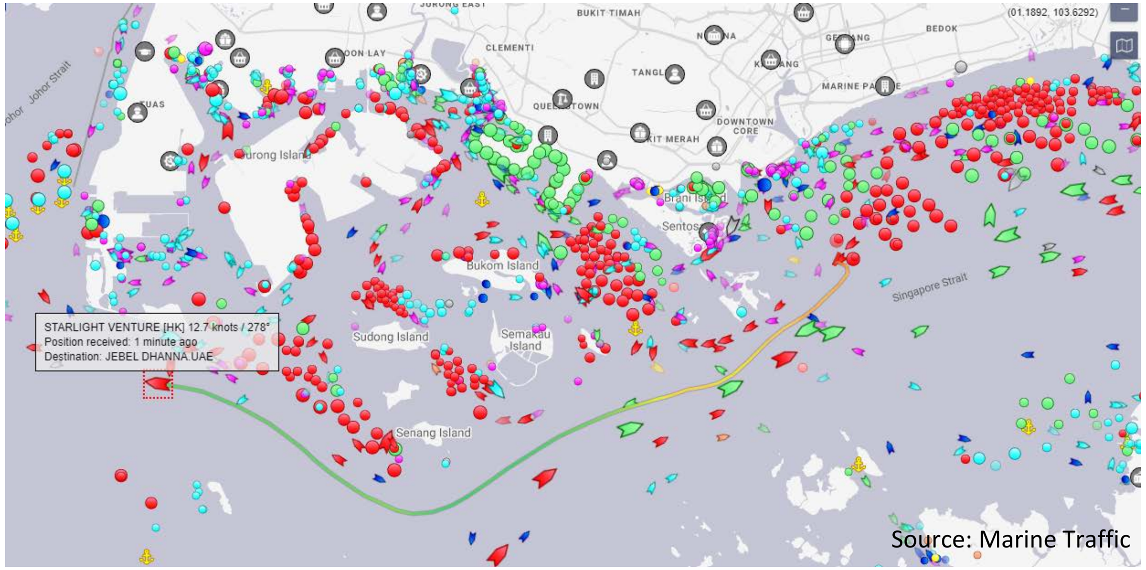
Predictions of Coefficients and Trajectories



- Amplified initial mean drift to account for higher transient speeds during initial turn
- Better predictions for turning circle and zigzag manoeuvres
- Limitations:
  - WASIM can only simulate quasi-static mean drift loads
  - Can only simulate forward speeds, i.e. cannot simulate motions with drift angle ≠ 0
  - Cannot account for instantaneous wave loads during turns
  - Effect of waves on rudder and propeller performance not yet considered

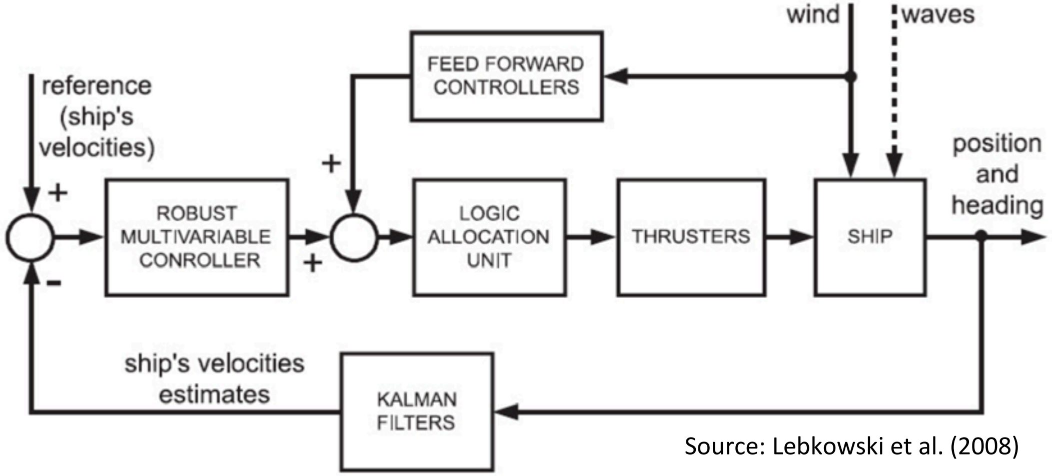
Applications for Autonomous Navigation

Source: Golden Energy Offshore



Source: Marine Traffic

- Sea trials/system identification/parameterisation of vessel manoeuvrability in less than ideal sea states
- Model in the loop can improve predictions and reduce over/under-compensation of corrective actions
- Enhanced situational awareness of operating environment, more reliable/accurate digital twins



Source: Lebkowski et al. (2008)

Thank You

Questions?