Estimation of Nonlinear Greybox Models for Marine Applications

Presentation of licentiate thesis at LINK-SIC workshop

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Research motivation

Why do we need marine models?

- Facilitation of development.
- Achieving satisfactory model-based control.

Main modelling challenges:

- Nonlinear dynamic forces and moments.
- Environmental disturbances, like wind, waves and ocean currents (often non-additive).

Problem description

Definition. *A second-order modulus function is a function,* $f : \mathbb{R}^{n+p} \to \mathbb{R}^m$ *that can be written as*

$$f(\boldsymbol{x}, \theta) = \Phi^T(\boldsymbol{x})\theta,$$

where each element of the $p \times m$ *matrix* $\Phi(\boldsymbol{x})$ *is on one of the forms* x_i, $|x_i|$, $x_i x_j$, $x_i|x_j|$ *for* $i, j \leq n$ *or zero and* $\theta \in \mathbb{R}^p$ *is a vector of coefficients.*

Main objective

Obtaining consistent estimators of θ for the class of models that can be expressed as second-order modulus functions, which are robust to:

- Measurement uncertainty.
- Non-additive environmental disturbances.

Contributions

1. The suggestion of an experiment design where the input signal has a static offset of sufficient amplitude and the instruments in an IV method are forced to have zero mean.
2. A method to estimate the first-order moments of system disturbances alongside the model parameters.
3. Experimental work.

F. Ljungberg, M. Enqvist.
Obtaining Consistent Parameter Estimators for Second-Order Modulus Models.
IEEE Control Systems Letters, 3(4):781–786, 10 2019.

F. Ljungberg, M. Enqvist.
Consistent Parameter Estimators for Second-order Modulus Systems with Non-additive Disturbances.
In Proceedings of the 21st IFAC World Congress, Berlin, Germany, 2020 (to appear).

Marine modelling: Undisturbed equations of motion

$$\dot{\eta} = J(\eta)\nu,$$
$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau_{\text{act}}.$$

6-DOF models:
(surge, sway, heave, roll, pitch, yaw)

$$\eta = \begin{bmatrix} x_n & y_n & z_n & \phi & \theta & \psi \end{bmatrix}^T$$
$$\nu = \begin{bmatrix} u & v & w & p & q & r \end{bmatrix}^T$$
$$\tau_{\text{act}} = \begin{bmatrix} F_x & F_y & F_z & M_x & M_y & M_z \end{bmatrix}^T$$

Maneuvering models:
(surge, sway, yaw)

$$\eta = \begin{bmatrix} x_n & y_n & \psi \end{bmatrix}^T$$
$$\nu = \begin{bmatrix} u & v & r \end{bmatrix}^T$$
$$\tau_{\text{act}} = \begin{bmatrix} F_x & F_y & M_z \end{bmatrix}^T$$

Marine modelling: Environmental disturbances

Disturbed equations of motion:

$$\dot{\eta} = J(\eta)\nu,$$
$$M_{RB}\dot{\nu} + M_A\dot{\nu}_r + C_{RB}(\nu)\nu + C_A(\nu_r)\nu_r + D(\nu_r)\nu_r + F(\nu_q)\nu_q = \tau_{\text{act}}.$$

- $\nu_r = \nu - \nu_c$, where ν_c is the velocity of an ocean current.
- $\nu_q = \nu - \nu_w$, where ν_w is the wind velocity.

Disturbances:

$$\nu_c = J^{-1}(\eta)\nu_{c,n},$$
$$\nu_w = J^{-1}(\eta)\nu_{w,n}.$$

More about this on my poster!

Note: Disturbance effects depend on the ship's attitude.

Eliminating disturbances: Problem description

Challenge: Estimate θ when

$$\text{System:} \quad \begin{cases} \mathbf{x}(k+1) = \Phi^T\left(\begin{bmatrix}\mathbf{x}^T(k)+\mathbf{v}^T(k) & \mathbf{u}^T(k)\end{bmatrix}^T\right)\theta_0 + \mathbf{w}(k), \\ \mathbf{y}(k) = \mathbf{x}(k) + \mathbf{e}(k), \end{cases}$$

$$\text{Model:} \quad \hat{\mathbf{y}}(k) = \Phi^T\left(\begin{bmatrix}\mathbf{y}^T(k-1) & \mathbf{u}^T(k-1)\end{bmatrix}^T\right)\theta.$$

Main assumptions:

- $f = \Phi^T(.)\theta$ is a second-order modulus function.
- $\mathbf{v}(k)$, $\mathbf{w}(k)$ and $\mathbf{e}(k)$ are disturbance signals.
- $\mathbf{v}(k)$ is independent of $\mathbf{x}(l)$ for $k \geq l$ (non-physical for ships).

Eliminating disturbances: Solutions

Main result

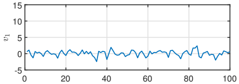
Challenge: Developing estimators of θ which are consistent despite measurement uncertainty and process disturbances.

Solution 1. Experiment design with excitation offset and zero-mean instruments.

Solution 2. Utilizing disturbance measurements ($\mathbf{y}_2(k) = \mathbf{v}(k)$).

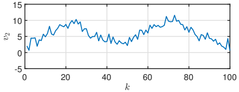
Non-add. dist. $\mathbf{v}(k)$

Case 1.



Requires: Solution 1 (by Lemma 4.1).

Case 2.



Requires: Solution 1 and 2 (by Lemma 4.2).

Estimating disturbances: Problem description

Second-order modulus system in surge:

$$u(k+1) = u(k) + \mathcal{X}_u u_r(k) + \mathcal{X}_{|u|u} \left| u_r(k) \right| u_r(k) + \mathcal{W}_{|u|u} \left| u_q(k) \right| u_q(k) + \mathcal{X}_\mu \tilde{\tau}_x(k),$$
$$y_u(k) = u(k) + e_u(k),$$
$$y_\psi(k) = \psi(k) + e_\psi(k).$$

Here $u_r(k) = u(k) - u_c(k)$ and $u_q(k) = u(k) - u_w(k)$.

Sought parameters:

$$\theta = \begin{bmatrix} 1 + \mathcal{X}_u & \mathcal{X}_{|u|u} + \mathcal{W}_{|u|u} & \mathcal{X}_\mu \end{bmatrix}^T.$$

Disturbances:

$$u_c(k) = \cos\big(\psi(k)\big)\, \nu_{c,NS}(k) + \sin\big(\psi(k)\big)\, \nu_{c,EW}(k),$$
$$u_w(k) = \cos\big(\psi(k)\big)\, \nu_{w,NS}(k) + \sin\big(\psi(k)\big)\, \nu_{w,EW}(k).$$

Estimating Disturbances: Solutions

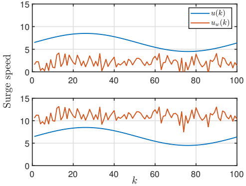
Main result

Challenge: Developing estimators of θ which are consistent despite non-additive environmental disturbances in the forms of ocean currents and wind.

Solution 1. Augment the predictor with heading-angle dependent regressors.

Solution 2. Utilize disturbance (wind) measurements.

Vessel/wind speed



Case 1. Requires: Solution 1.

Case 2. Requires: Solution 1 and 2.

Experimental study: Experiment description

The studied ship

Size:
- Roughly 30 meters long

Actuation:
- 2 azimuth thrusters (along centerline)

Sensing:
- GNSS receiver (with two antennas)
- Propeller-based anemometer on weather vane

The collected data

Day 1:
- Light breeze (≈ 3 m/s)
- Data used for validation

Day 2:
- Fresh breeze (≈ 10 m/s)
- Data used for estimation

Additional:
- 6 shorter experiments per day ($6 - 10$ min. each)
- No ocean currents
- No excitation offset

Experimental study: Results using sway data

Estimators:

- Regular LS ($\hat{\theta}_N^{LS_1}$)
- Regular IV ($\hat{\theta}_N^{IV_1}$)
- IV with heading-angle dependent regressors ($\hat{\theta}_N^{IV_2}$)
- IV utilizing wind measurements ($\hat{\theta}_N^{IV_3}$)

Average fit for each estimator:

Estimator	Fit - Sway
$\hat{\theta}_N^{LS_1}$	50.3056 ± 4.4771
$\hat{\theta}_N^{IV_1}$	63.3711 ± 8.3876
$\hat{\theta}_N^{IV_2}$	71.9800 ± 2.8652
$\hat{\theta}_N^{IV_3}$	70.3522 ± 3.4760

Conclusion and future work

Main result

- A framework for estimation of second-order modulus models has been suggested.
- The methods have been analyzed and show promising results in simulations.
- Some ideas have also been tested on real data.

Possible future work and ideas

- More focused study on experiment design.
- Connection to disturbance observers.
- Compare with blackbox approach.

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