Modelling and Simulation of Marine Surface Vessel Dynamics

(Module 1: Motivation and Overview)

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Tutorial Goals

- Model vessels and environmental loads in 6 DOF.
- Use state-of-the-art hydrodynamic codes to compute model parameters: added mass, potential damping, 1st and 2nd-order wave loads.
- Derive control plant models by postprocessing data from hydrodynamic codes (Matlab GNC toolbox).
- Use system identification to fit hydrodynamic data to state-space models.
- Add viscous effects/manoeuvring terms.
- Time-domain simulation in Matlab Simulink.
Applications
Modelling and Control

- System designers make decisions to satisfy conflicting requirements based on some knowledge of the system they intend to design: this knowledge is represented in a mathematical model.

- Modelling is an essential part of control design and preliminary testing, which can consume up to 60% of effort in these tasks.
Modelling of Marine Structures

- Models of marine structures are complex.

- Control engineers often base their models on models used by naval architects, which sometimes are not control-design oriented.

- In this tutorial, we will look at the models commonly used in naval architecture and ship theory from the control system’s perspective.
 Obtaining Models

Data-base

Scaling

Model testing

System Identification

Mathematical Models
(Simulation, GNC-design, HIL-testing, Diagnosis)

System Identification

Numerical Hydrodynamics

Main focus of this tutorial

System Identification

Full-scale Experiments
Manoeuvring and Seakeeping

Ship theory has traditionally been separated into two main areas

<table>
<thead>
<tr>
<th>Manoeuvring</th>
<th>Sea-keeping</th>
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<tr>
<td>The aim is to study steering characteristics of vessels with forward speed and the response to the command of propulsion systems and control surfaces. This is done in calm water.</td>
<td>The aim is to study the behavior of the vessel in waves while keeping a constant speed and course.</td>
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Although both areas are concerned with the study of motion, stability and control, the separation allows one making assumptions that simplify the study in each case.
Manoeuvring Models

- Nonlinear parametric models (classical and Lagrangian):
  \[
  \dot{x} = f(x, u) \\
  M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau
  \]
- Obtained by fitting data from scaled model experiments.
- Calm water models.
- Horizontal motion models (surge-sway-yaw).
- Not commonly available.
- Restricted to a few speeds/loading conditions of the experiment.
Seakeeping Models

Linear non-parametric models

\[ H(j\omega) \]

Obtained from hydrodynamic calculations based on simplifying assumptions:

- Constant course and speed.
- Linear wave loads.
- Potential theory.
- Viscous effects can be added.

For the design of control systems, seakeeping models are very useful.

They provide preliminary models based on little data of the ship.
Recent Results on a Unified Manoeuvring and Seakeeping Model


Unified Manoeuvring and Seakeeping Model for Time-Domain Simulation

The Force-Transfer-Functions are computed using hydrodynamic SW (WAMIT, VERES or SEAWAY).

\[ M\ddot{v} + C_{RB}v + Dv + d_n(\Theta, v) + \mu + g(\eta) = \tau_{env} + \tau \]

\[ \dot{\eta} = J(\Theta)v \]

\[ \dot{\chi} = A_r\chi + B_r\delta v, \quad \chi(0) = 0 \]

\[ \mu = C_r\chi + D_r\delta v \]

For 6 DOF this model will typically be represented by 6 + 6 + 90 = 102 ODEs which are computed using hydrodynamic SW (WAMIT, VERES or SEAWAY).

These terms are found using experimental results/curve fitting or semi-empirical methods.
Hull supported by mostly by hydrostatic pressure (forces)

Aero and hydrodynamic forces; strong flow separation

\[ F_n = \frac{U}{\sqrt{gL}} \]
The 3 Speed Regimes for Control

Dynamic positioning systems
- 3D potential theory
- 2D potential theory (strip theory)

Maneuvering/motion damping
- 2D potential theory (strip theory) up to Froude numbers of 0-3-0.4
- 2.5 D potential theory for high-speed craft

Low-speed maneuvering

Station-keeping

Maneuvering at moderate speed (transit)

Maneuvering at high speed (high-speed craft)

\[ U = 0.3 \sqrt{Lg} \]

Speed

0 1.5 m/s (3 knots)
Motion in Waves

Motions and loads of floating structures due to waves can be separated into

- **Wave-frequency**: linearly excitations and motion in the wave frequency range. Periods in the range 5-20s

- **Higher than wave frequency (ringing & springing)**: nonlinear effects, which can produce resonance in TLPs, with natural periods of 2-4s.

- **Slow and mean drift**: nonlinear effects with mean value and sub harmonic excitation that can produce oscillations with natural periods of 20-30s.
Motion and Control

Then, motion control problems can have different objectives:

- **Control only the non-oscillatory motion (wave filtering needed)**
  - Autopilots,
  - Dynamic positioning (DP)
  - Thruster assisted position mooring (TAPMOOR)

- **Control only the oscillatory motion**
  - Ride control of high speed vessels (roll and pitch stabilisation)
  - Heave compensation of offshore structures

- **Control both**
  - Dynamic positioning in extreme seas (DP + roll & pitch stabilisation)
  - Autopilots with rudder roll stabilisation
  - Unmanned Surface Vehicles USV
### The Road Ahead

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<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
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<tr>
<td>09:00</td>
<td><strong>M1: Motivation and overview</strong></td>
<td>TIF</td>
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<tr>
<td>09:20</td>
<td>M2: Hydrodynamics for control engineers</td>
<td>TP</td>
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<tr>
<td>10:00</td>
<td>M3: Kinematics and kinetic models of marine vessels</td>
<td>TP</td>
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<td>10:45</td>
<td>Coffee break</td>
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<tr>
<td>11:00</td>
<td>M4: Manoeuvring in calm water</td>
<td>TIF</td>
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<td>11:30</td>
<td>M5: Environmental disturbances</td>
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<td>12:00</td>
<td>Lunch break</td>
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<td>13:00</td>
<td>M6: Motion in waves a frequency-domain approach</td>
<td>TP</td>
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<tr>
<td>13:30</td>
<td>M7: Motion in waves a time-domain approach</td>
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<tr>
<td>14:00</td>
<td>M8: Manoeuvring in a seaway</td>
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<td>M9: Models and marine control problems</td>
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<td>15:00</td>
<td>M10: Software, and rapid model prototyping</td>
<td>TIF</td>
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