Modelling and Simulation of Marine Surface Vessel Dynamics

(Module 1: Motivation and Overview)

Dr Tristan Perez

Centre for Complex Dynamic Systems and Control (CDSC)

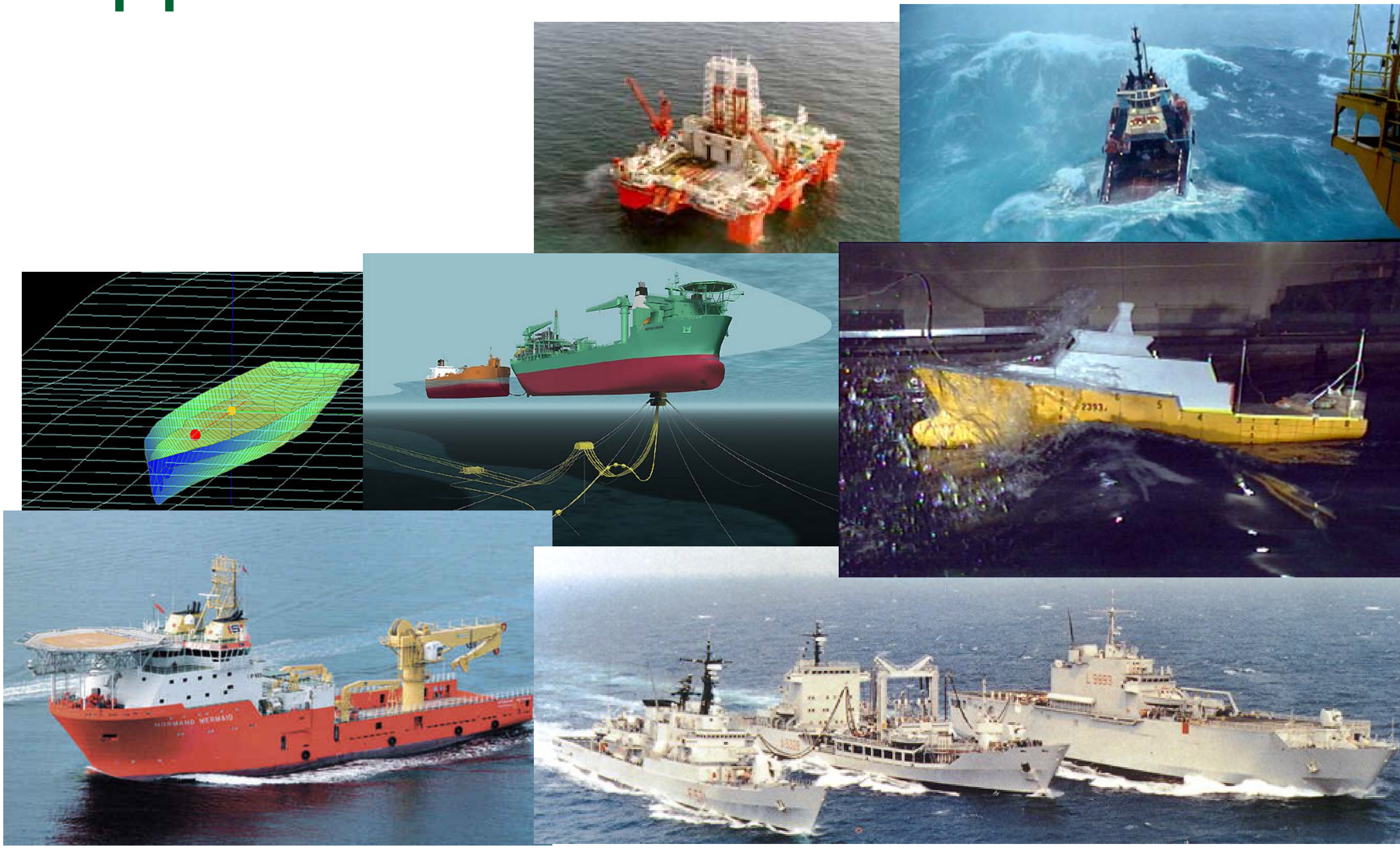
Professor Thor I Fossen

Department of Engineering Cybernetics

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.

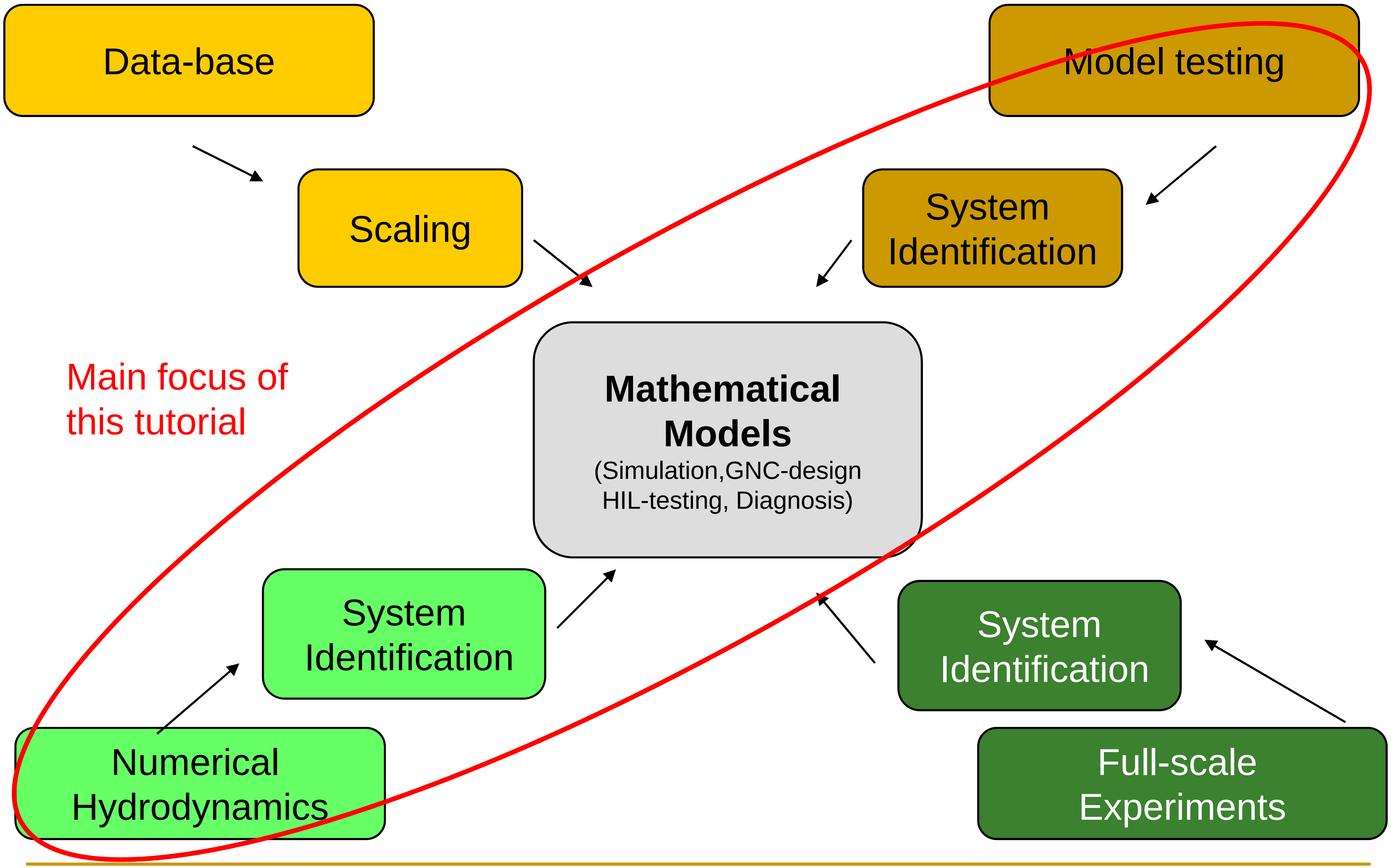
Modelling of Marine Structures

- 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



Manoeuvring and Seakeeping

Ship theory has traditionally been separated into two main areas

Manoeuvring	Sea-keeping
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**.	The aim is to study the behavior of the vessel **in waves** while keeping a <u>constant speed</u> and <u>course</u>.

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.

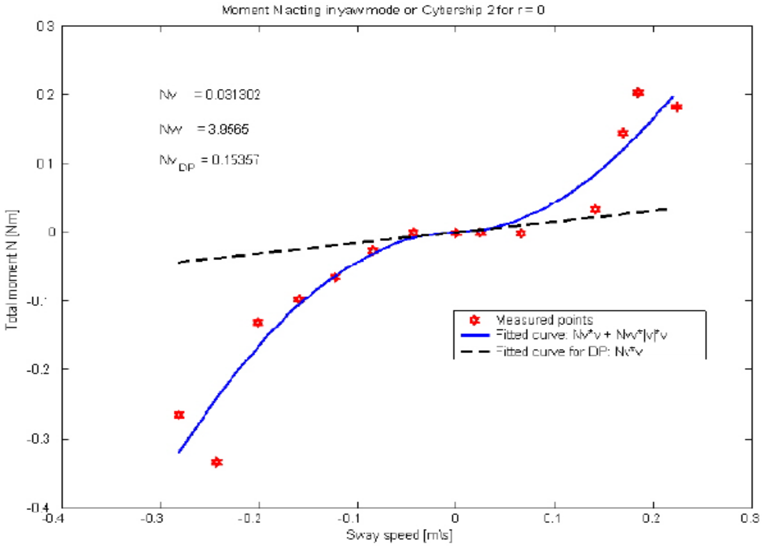
Manoeuvring Models

- Nonlinear parametric models (classical and Lagrangian):

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$$

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}$$

- 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.



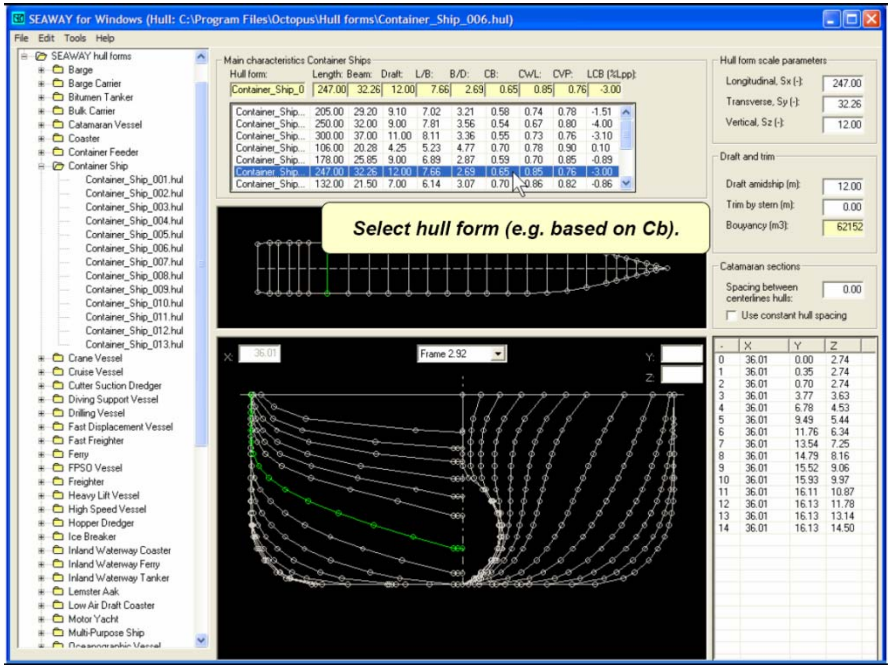
Seakeeping Models

Linear non-parametric models

$$\mathbf{H}(j\omega)$$

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.

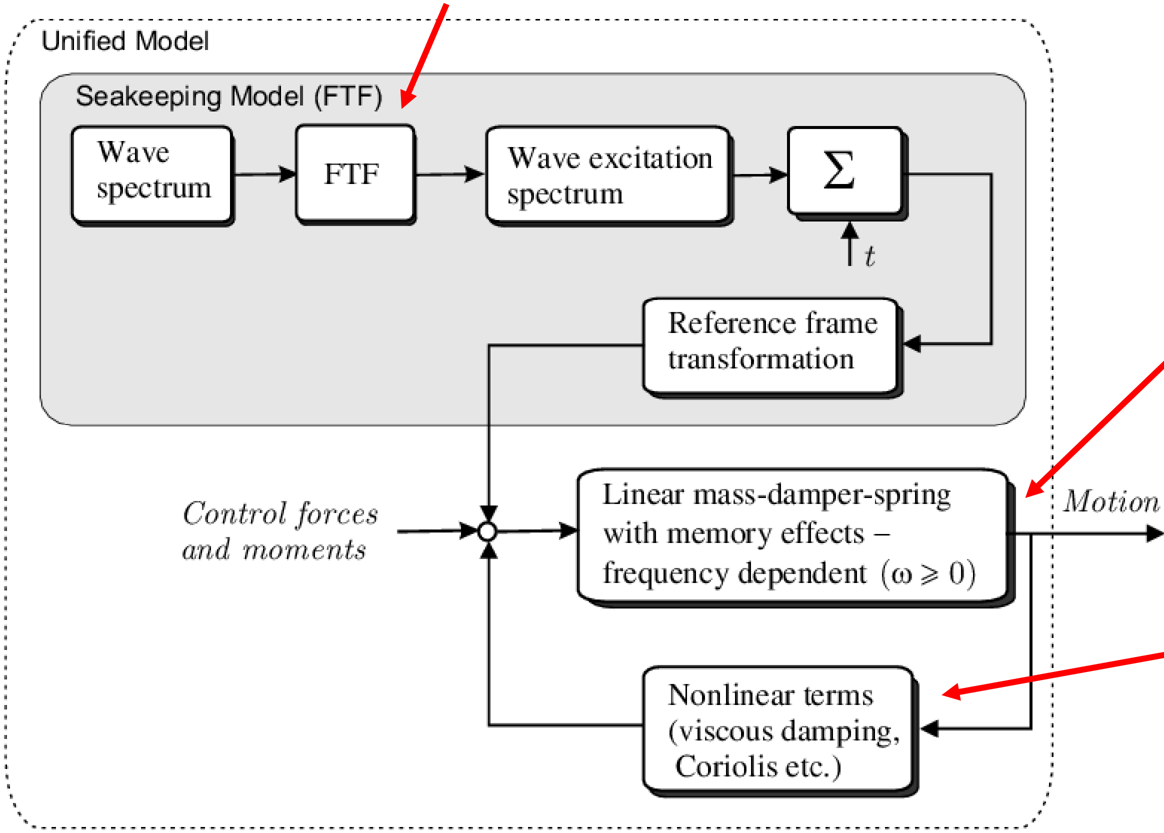
They provide preliminary models based on little data of the ship.

Recent Results on a Unified Manoeuvring and Seakeeping Model

- **Fossen, T. I. and Ø. N. Smogeli.** Nonlinear Time-Domain Strip Theory Formulation for Low-Speed Manoeuvring and Station-Keeping, *Modelling, Identification and Control,* **MIC-25**(4):201:221, 2004.
- **Fossen, T. I.** A Nonlinear Unified State-Space Model for Ship Manoeuvring and Control in a Seaway, *Journal of Bifurcation and Chaos*, September 2005. (Plenary Talk ENOC'05, Eindhoven, The Netherlands).
- **Perez, T. and T. I. Fossen.** Kinematic Models for Sea-keeping and Manoeuvring of Marine Vessels. Modelling, Identification and Control, **MIC-28**(1):1-12, 2007.
- **Perez, T. and T. I. Fossen.** Time-Domain Models of Marine Surface Vessels for Simulation and Control Design Based on Sea-keeping Computations (Plenary Talk). *Proc. of the IFAC MCMC'06, Lisbon, Portugal, September 20-22, 2006.*
- **Ross, A., T. Perez and T. I. Fossen .** A Novel Manoeuvring Model Based on Low-Aspect Ratio Lift Theory and Lagrangian Mechanics. Proc. of the IFAC CAMS'07, Croatia.

Unified Manoeuvring and Seakeeping Model for Time-Domain Simulation

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



$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}\boldsymbol{\nu} + \mathbf{D}\boldsymbol{\nu} + \mathbf{d}_n(\boldsymbol{\Theta}, \boldsymbol{\nu}) + \boldsymbol{\mu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{env} + \boldsymbol{\tau}$$

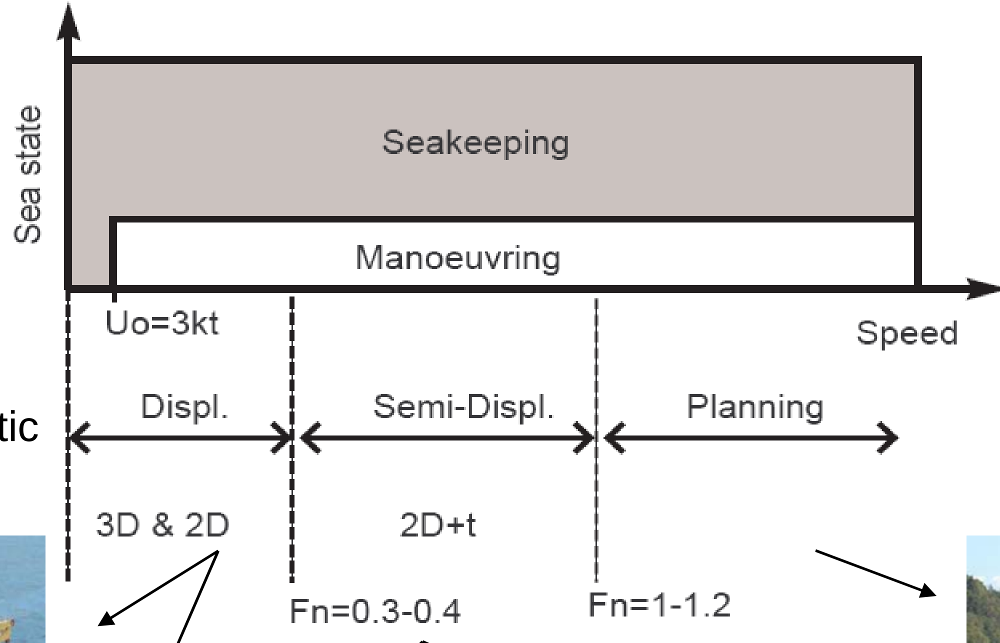
$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\Theta})\boldsymbol{\nu}$$

$$\dot{\boldsymbol{\chi}} = \mathbf{A}_r\boldsymbol{\chi} + \mathbf{B}_r\delta\boldsymbol{\nu}, \qquad \boldsymbol{\chi}(0) = \mathbf{0}$$
$$\boldsymbol{\mu} = \mathbf{C}_r\boldsymbol{\chi} + \mathbf{D}_r\delta\boldsymbol{\nu}$$

*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

Speed–Environment Envelope



$$F_n = \frac{U}{\sqrt{gL}}$$

Hull supported by mostly by hydrostatic pressure (forces)

Hydrostatic and hydrodynamic forces; Lift

Aero and hydrodynamic forces; strong flow separation

The 3 Speed Regimes for Control

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

Manoeuvring/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	Manoeuvring at moderate speed (transit)	Manoeuvring at high speed (high-speed craft)
Station-keeping		

Speed

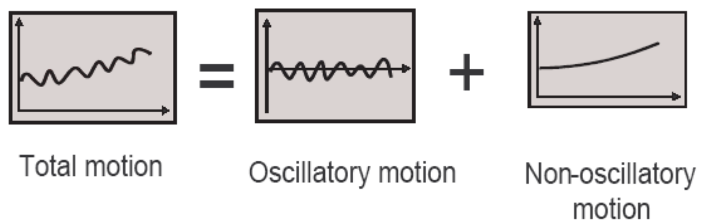
0 — 1.5 m/s (3 knots) — ···· $U = 0.3\sqrt{Lg}$ ·····

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

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