Module 6

Marine Systems – Advanced Programming with MATLAB

Table of Contents

Overview

Marine systems are operating in marine environment. There are many dynamic systems in maritime industry and engineering. They are:

- Marine electrical and electronic systems;
- Generators, turbo generator sets;
- Piping, liquid tank systems and liquid level control systems;
- HVAC systems;
- Pumping systems;
- Pressure, temperature and flow process systems and their controllers
- Ship systems and subsystems (for examples, controllable pitch propellers, ship hull dynamics, rudder steering machines);
- Marine control systems (for examples, autopilot, roll stabilisation systems and dynamic positioning systems); and
- Ship propulsion systems and governors.

Learning Outcomes

After completing this module you should be able to

- Describe reference frames for marine vehicles;
- Model ship systems (ship manoeuvring systems, steering machines);
- Explain dynamics of marine vehicles;
- Model marine electrical systems; and
- Simulate marine systems with MATLAB under various conditions.

Focus Questions

- What is the relationship between the rudder angle of a vessel and ship course angle?
- How do ships' control systems affect the marnoeuvring performance of a vessel?
- How are the marine systems simulated in various scenarios?
- How are the simulation programs used for analysis and learning of dynamics of marine vehicles?

1. Overview of Marine Systems

Maritime industry includes many branches such as oil and gas industry, sea transport industry, fish and aquaculture, subsea and underwater exploration and other industries. It is in relation with other shore-based engineering and an integration of disciplines as shown in **Fig. 1**. In each branch of maritime industry there are many marine systems and subsystems. Marine systems are mixed systems containing many components such as mechanical, thermal, electrical, hydraulic and pneumatic subsystems. They work in severe conditions and salty water and corrosion environment. They are affected by external disturbances such as wind, waves and ocean current.

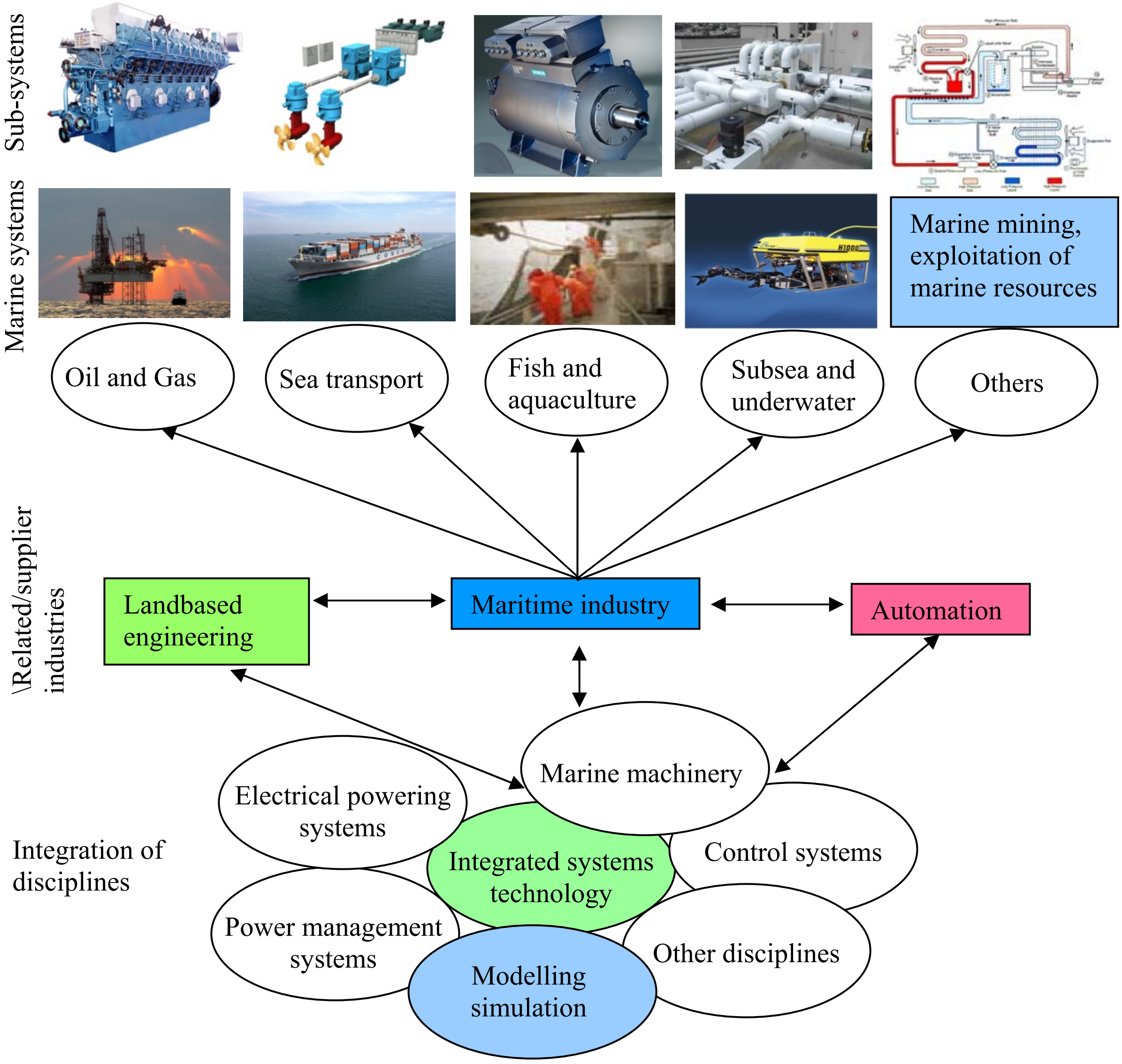


Figure 1 Marine systems and subsystems with integrated disciplines

Some examples of marine systems and subsystems are given below:

- Marine electrical and electronic systems;
- Generators, turbo generator sets;
- Piping, liquid tank systems and liquid level control systems;
- HVAC (heating, ventilating and air-conditioning) systems;
- Pipe and pumping systems;
- Pressure, temperature and flow process systems and their controllers

- Ship systems and subsystems (for examples, controllable pitch propellers, ship hull dynamics, rudder steering machines);
- Marine control systems (for examples, autopilot, roll stabilisation systems and dynamic positioning systems); and
- Ship propulsion systems and governors.

In this course we will deal with modelling and simulation of some typical marine systems and subsystems such as marine vehicles, marine electrical systems and propulsion systems and their components.

2. Marine Vehicles

Marine vehicles including surface vessels, submarines, and small vehicles like ROVs/AUVs are operating on the Earth's surface.

2.1 Reference Frames

In modelling, simulation, design and control of marine vehicles, some reference frames for descriptions of kinematics and kinetics of marine vehicles are often used. **Fig. 2** shows Earth-centred reference frames (the Earth-centred Earth-fixed frame $x_e y_e z_e$, and the Earth-centred inertial frame $x_i y_i z_i$), and geographic reference frames (the North-East-Down coordinate system $x_n y_n z_n$ and the body-fixed reference frame $x_b y_b z_b$) (Fossen, 1994 and 2002).

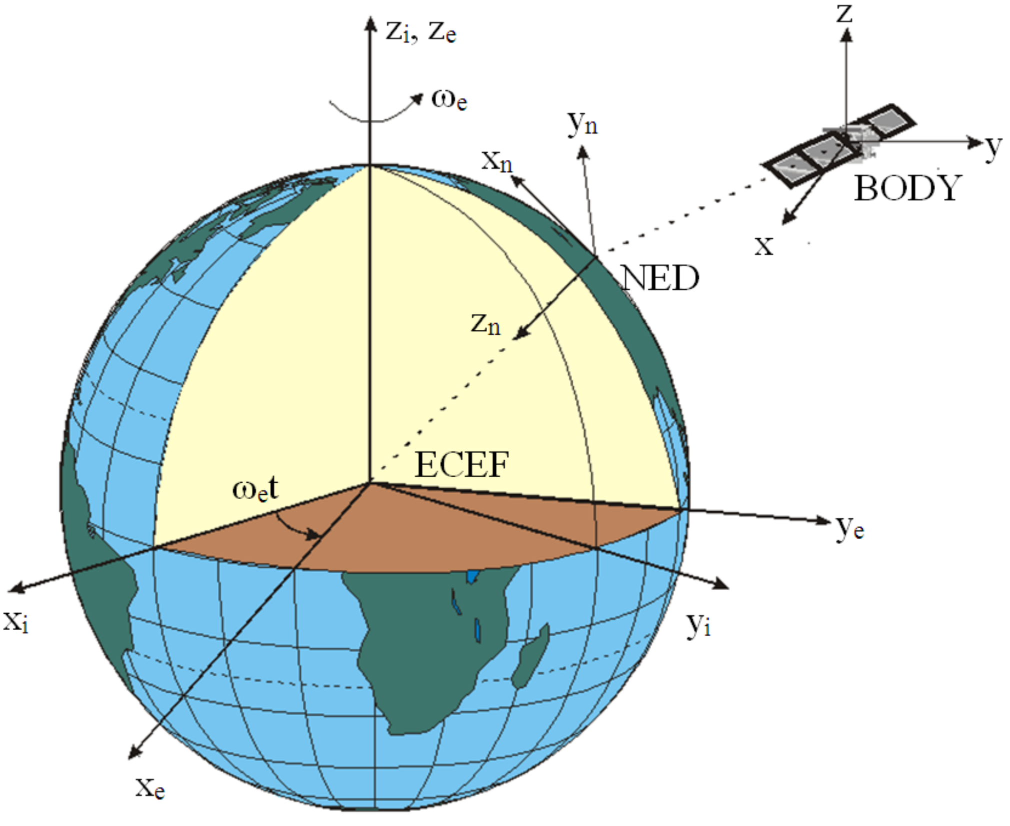


Figure 2 Reference frames (ECEF, NED, and BODY) for marine vehicles (Fossen, 2002)

The Earth-fixed reference frame and the body-fixed reference frame are used to describe kinematics and kinetics of a marine vehicle, respectively. The Earth-fixed reference frame is used to determine the position (kinematics) of the marine vehicle on the Earth while the body-fixed reference frame is used to determine forces and moments acting on the marine vehicle.

2.2 Notation

Vectors of dimension n in the Euclidean space are denoted as $\mathbf{x} \in \mathbb{R}^n$, matrices are denoted as $\mathbf{A} \in \mathbb{R}^{m\times n}$ and scalars are written as $a \in \mathbb{R}$.

A matrix $\mathbf{S} \in SS(n)$ that is the set of skew-symmetric matrices of order n, is said to be skew-symmetric if:

$$\mathbf{S} = -\mathbf{S}^T$$

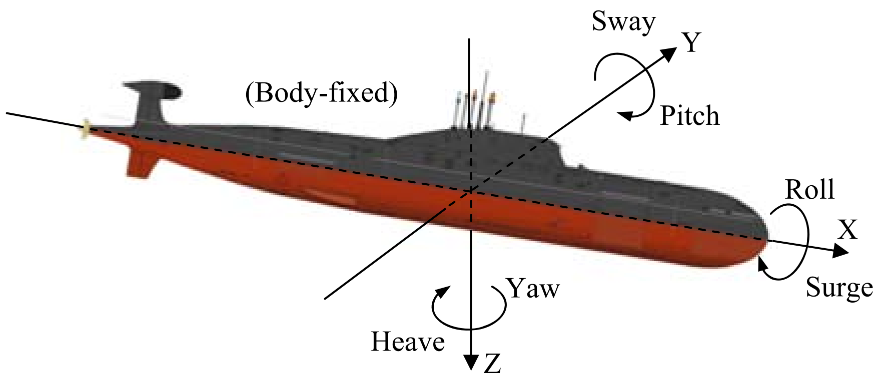


Figure 3 Body-fixed reference frame and 6-DOF motions

This implies that the off-diagonal elements of **S** satisfy $s_{ij} = -s_{ji}$ for $i \neq j$ while the diagonal elements are zero.

The vector cross product $\times$ is defined by

$$\lambda \times \mathbf{a} := \mathbf{S}(\lambda)\mathbf{a} \tag{1}$$

where $\mathbf{S} \in SS(3)$ is defined as

$$\mathbf{S}(\lambda) = -\mathbf{S}(\lambda) = \begin{bmatrix} 0 & -\lambda_3 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix}; \ \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \tag{2}$$

For underwater vehicles moving in six degrees of freedom, six independent coordinates are necessary to determine the position and orientation. The first three motion a long the x-, y- and z-axes, respectively, while the last three coordinates, and their time derivatives, are used to describe orientation and rotational motions. The six motion components are conveniently defined as surge, sway, heave, roll, pitch and yaw (Fossen, 2002, 2006).

The general motion of a marine vehicle in 6 DOF is modelled by using the notation as follows (Fossen, 2006)

$$\eta = [n, e, d, \phi, \theta, \psi]^T \text{ and } \nu = [u, v, w, p, q, r]^T \tag{3}$$

where n, e, d denote the North-East-Down (NED) positions in the Earth-fixed coordinates (n-frame), ϕ, θ and ψ are the Euler angles (orientation) and u, v, w, p, q, r are the six DOF generalised velocities in the body-fixed coordinates (b-frame).

2.3 Six DOF Equations of Kinematics

According to Fossen (2002, 2006), the six DOF kinematic equations are expressed in vector form below,

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta}) \tag{4}$$

where

$$\mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} \mathbf{R}_b^n(\boldsymbol{\Theta}) & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{T}_\Theta(\boldsymbol{\Theta}) \end{bmatrix} \tag{5}$$

with $\boldsymbol{\eta} \in \mathbb{R}^3 \times S^3$ and $\nu \in \mathbb{R}^3$. The angle rotation matrix $\mathbf{R}_b^n(\boldsymbol{\Theta}) \in \mathbb{R}^{3\times3}$ is defined in terms of the principal rotations,

$$\mathbf{R}_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & -s\phi \\ 0 & s\phi & c\phi \end{bmatrix},\ \mathbf{R}_{y,\theta} = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \text{ and } \mathbf{R}_{z,\psi} = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

where s $\cdot$ = sin(.), c $\cdot$ = cos(.) using the zyx-convention,

$$\mathbf{R}_b^n(\boldsymbol{\Theta}) := \mathbf{R}_{z,\psi}\mathbf{R}_{y,\theta}\mathbf{R}_{x,\phi} \tag{7}$$

or

$$\mathbf{R}_b^n(\boldsymbol{\Theta}) = \begin{bmatrix} c\psi c\theta & -s\psi c\theta + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{8}$$

The inverse transformation satisfies,

$$\mathbf{R}_b^n(\boldsymbol{\Theta})^{-1} = \mathbf{R}_n^b(\boldsymbol{\Theta}) = \mathbf{R}_{x,\phi}^T\mathbf{R}_{y,\theta}^T\mathbf{R}_{z,\psi}^T \tag{9}$$

The Euler angle attitude transformation matrix is,

$$\mathbf{T}_\Theta(\boldsymbol{\Theta}) = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi/c\theta & c\phi/c\theta \end{bmatrix} \Rightarrow \mathbf{T}_\Theta^{-1}(\boldsymbol{\Theta}) = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & c\theta s\phi \\ 0 & -s\phi & c\theta c\phi \end{bmatrix} \quad \theta \neq \pm 90^o \tag{10}$$

It should be noted that that $\mathbf{T}_\Theta(\boldsymbol{\Theta})$ is undefined for a pitch angle of $\theta \neq \pm 90^o$ and that $\mathbf{T}_\Theta^{-1}(\boldsymbol{\Theta}) \neq \mathbf{T}_\Theta^T(\boldsymbol{\Theta})$.

2.4 Six DOF Equations of Kinetics

In general for a deeply submerged vehicle the hydrodynamic forces and moments will be due to added mass and damping, while the hydrostatic forces and moments are due to weight and buoyancy. This suggests that

$$\underbrace{\mathbf{M}_{RB}\dot{\mathbf{v}} + \mathbf{C}_{RB}(\mathbf{v})\mathbf{v}}_{\text{rigid-body terms}} + \underbrace{\mathbf{M}_A\dot{\mathbf{v}} + \mathbf{C}_A(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v}}_{\text{hyrodynamic terms}} + \underbrace{\mathbf{g}(\boldsymbol{\eta})}_{\text{hydrostatic terms}} = \boldsymbol{\tau} \tag{11}$$

such that

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} \tag{12}$$

where $\mathbf{M} = \mathbf{M}_{RB} + \mathbf{M}_A(\mathbf{v})$, $\mathbf{C}(\mathbf{v}) = \mathbf{C}_{RB}(\mathbf{v}) + \mathbf{C}_A(\mathbf{v})$ and

- $\mathbf{M}$ system inertia matrix (including added mass)
- $\mathbf{C}(\mathbf{v})$ Coriolis-centripetal matrix (including added mass)
- $\mathbf{D}(\mathbf{v})$ damping matrix
- $\mathbf{g}(\boldsymbol{\eta})$ vector of gravitational/buoyancy forces and moments
- $\boldsymbol{\tau}$ vector of inputs (e.g. rudder, fin, propeller)

Equations (4) and (11) include marine vehicle system parameters and hydrodynamic coefficients. Equation (4) can be rewritten below:

$$\dot{n} = u\cos\psi\cos\theta + v(\cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi) + \omega(\sin\psi\sin\phi + \cos\psi\cos\phi\sin\theta) \tag{13}$$

$$\dot{e} = u\sin\psi\cos\theta + v(\cos\psi\cos\phi + \sin\phi\sin\theta\sin\psi) + \omega(\sin\theta\sin\psi\cos\phi - \cos\psi\sin\phi) \tag{14}$$

$$\dot{d} = -u\sin\theta + v\cos\theta\sin\phi + \omega\cos\theta\cos\phi \tag{15}$$

$$\dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \tag{16}$$

$$\dot{\theta} = p\cos\phi - r\sin\phi \tag{17}$$

$$\dot{\psi} = q\frac{\sin\phi}{\cos\theta} + r\frac{\cos\phi}{\cos\theta},\ \theta \neq \pm 90^{o} \tag{18}$$

Equation (11) has various forms depending on types of vessel. The following example is the linear model of Davidson Schiff (1946) for a surface vessel. For a surface vessel the equations for motion include the state variables v, r, ψ and the control input δ. The following assumptions are applied for equation (11):

(i) Homogeneous mass distribution and xz-plane symmetry ($I_{xy} = I_{yz} = 0$);
(ii) The heave, roll and pitch modes can be neglected ($w = p = q = \dot{w} = \dot{p} = \dot{q} = 0$);
(iii) The coordinate origin is set in the centre line of the ship $y_G = 0$.

Thus, a simplified version of equation (12) becomes

$$\text{Surge:}\quad m(\dot{u} - vr - x_G r) = X \tag{19}$$

$$\text{Sway:}\quad m(\dot{v} + ur + x_G\dot{r}) = Y \tag{20}$$

$$\text{Yaw:}\quad I_z\dot{r} + mx_G(\dot{v} + ur) = N \tag{21}$$

where X is forces in the x-axis, Y is forces in the y-axis and N is moments about the z-axis. X, Y and N are expressed as functions of state variables below:

$$X = X(u, v, r, \dot{u}, \delta, T) \tag{22a}$$

$$Y = Y(v, r, \dot{v}, \dot{r}, \delta) \tag{22b}$$

$$N = N(v, r, \dot{v}, \dot{r}, \delta) \tag{22c}$$

where T is the propeller thrust corresponding to one single-screw propeller.

Fossen (1994, 2002) suggested perturbed ship equations of motion by the following assumption:

(iv) The sway velocity v, the yaw rate r and the rudder angle δ are small.

This assumption implies that the surge mode can be decoupled from the sway and yaw modes by assuming that the mean forward speed u_0 is constant for constant thrust. We assume that the mean velocities in sway and yaw are $v_0 = r_0 = 0$, thus

$$u = u_0 + \Delta u\,;\; v = \Delta v\,;\; r = \Delta r \tag{23a}$$

$$X = X_0 + \Delta X\,;\; Y = \Delta Y\,;\; N = \Delta N \tag{23b}$$

where Δu, Δv and Δr are small perturbation from the nominal values u_0, v_0 and r_0, and ΔX, ΔY and Δz are small perturbation from the nominal values X_0, Y_0 and N_0.

Applying (23) into equations (19), (20) and (21) we have:

Speed equation: $$m(\dot{u} - vr - x_G r) = X \tag{24a}$$

Steering equations: $$m(\dot{v} + u_0 r + x_G \dot{r}) = Y \tag{24b}$$

$$I_z \dot{r} + m x_G (\dot{v} + u_0 r) = N \tag{24c}$$

Equations (24b) and (24c) are steering equation proposed by Davidson and Schiff (1946). Linear theory suggests that the hydrodynamic force and moment can be modelled as

$$Y = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + Y_r r + Y_\delta \delta_R \tag{25}$$

$$N = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v + N_r r + N_\delta \delta_R \tag{26}$$

Hence we can write the equations of motion according to

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{N}(u_0)\mathbf{v} = \mathbf{b}\delta_R \tag{27}$$

where $\mathbf{v} = [v \quad r]^T$ is the state vector, δ_R is the rudder angle and

$$\mathbf{M} = \begin{bmatrix} m - Y_{\dot{v}} & m x_G - Y_{\dot{r}} \\ m x_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix};\; \mathbf{N}(u_0) = \begin{bmatrix} -Y_v & m u_0 - Y_r \\ -N_v & m x_G u_0 - N_r \end{bmatrix} \text{ and } \mathbf{b} = \begin{bmatrix} Y_\delta \\ N_\delta \end{bmatrix}$$

2.5 Non-dimensional Equations – Normalisation Forms

According Fossen (1994), in designing and analysing ships' control systems it is often convenient to normalise the ship steering equations of motion such that the model parameters can be treated as constants with respect to the instantaneous speed U. The velocity components in surge and sway are defined as

$$u = u_0 + \Delta u\,;\; v = \Delta v \tag{23}$$

Hence, the total speed is:

$$U = \sqrt{u^2 + v^2} = \sqrt{(u_0 + \Delta u)^2 + \Delta v^2}\;; \tag{24}$$

For a ship moving at a constant speed on a constant both Δu and Δv are small, thus

$$U \approx u_0 \tag{25}$$

where u_0 is referred to as the *service speed*. However, during course changing manoeuvres the instantaneous speed will decrease due to increased resistance during the turn (Fossen, 1994).

The most commonly used normalisation form for ship steering equations of motion is the Prime-System of SNAME (1950). This system uses the ship's instantaneous speed U, the length $L = L_{pp}$ (the length between the fore and the aft perpendiculars), the time unit L/U and the mass unit $0.5\rho L^3$ or

$0.5\rho L^2 T$ as normalisation variables. The latter is inspired by wing theory where the reference area LT is used instead of L^2. An alternative system, the so-called Bis-system was proposed by Norrbin (1970). This system is based on the use of the time unit $\sqrt{L/g}$, the mass unit m and the body mass density ratio $\mu = m/\rho\nabla$ where ∇ is the hull contour displacement. For μ = 1, while for a heaving torpedo positive buoyant underwater vehicles $\mu < 1$, ships and neutrally buoyant underwater vehicles use μ = 1, while for a heavy torpedo μ will typically be in the range 1.3-1.5. The normalisation variables for the Prime- and Bis-systems are given in **Table 1**. The non-dimensional quantities in the Prime- and Bis-systems will be distinguished from those with dimension by applying (.)' for the Prime-system and (.)" for the Bis-system (Fossen, 1994).

Table 1 Normalisation variables used for the Prime-system and Bis-system (Fossen, 1994)

Unit	Prime-system I	Prime-system II	Bis-system
Length	L	L	L
Mass	$\frac{\rho}{2}L^3$	$\frac{\rho}{2}L^2T$	$\mu\rho\nabla$
Inertia moment	$\frac{\rho}{2}L^5$	$\frac{\rho}{2}L^4T$	$\mu\rho\nabla L^2$
Time	$\frac{L}{U}$	$\frac{L}{U}$	$\sqrt{L/g}$
Reference area	L^2	LT	$\mu\frac{2\nabla}{L}$
Position	L	L	L
Angle	1	1	1
Linear velocity	U	U	$\sqrt{Lg}$
Angular velocity	$\frac{U}{L}$	$\frac{U}{L}$	$\sqrt{\frac{g}{L}}$
Linear acceleration	$\frac{U^2}{L}$	$\frac{U^2}{L}$	g
Angular acceleration	$\frac{U^2}{L^2}$	$\frac{U^2}{L^2}$	$\frac{g}{L}$
Force	$\frac{\rho}{2}U^2L^2$	$\frac{\rho}{2}U^2LT$	$\mu\rho g\nabla$
Moment	$\frac{\rho}{2}U^2L^3$	$\frac{\rho}{2}U^2L^2T$	$\mu\rho g\nabla L$

The following example is to illustrate a non-dimensional equations for (20) and (21).

Normalisation of (27) according the Prime-system suggests

$$\mathbf{M}'\dot{\mathbf{v}}' + \mathbf{N}'(u_0')\mathbf{v}' = \mathbf{b}'\boldsymbol{\delta}_R' \tag{26}$$

where $\mathbf{v}' = [v', r']^T$ and

$$\mathbf{M}' = \begin{bmatrix} m' - Y_{\dot{v}}' & m'x_G' - Y_{\dot{r}}' \\ m'x_G' - N_{\dot{v}}' & I_z' - N_{\dot{r}}' \end{bmatrix};$$

$$\mathbf{N}'(u_0') = \begin{bmatrix} -Y_v' & m'u_0' - Y_r' \\ -N_v' & m'x_G'u_0' - N_r' \end{bmatrix} \text{ and } \mathbf{b}' = \begin{bmatrix} Y_\delta' \\ N_\delta' \end{bmatrix} \tag{27}$$

where

$$u_0' = \frac{u_0}{U} = \frac{u_0}{\sqrt{(u_0 + \Delta u)^2 + \Delta v^2}} \approx 1 \tag{28}$$

for small values of Δu and Δv. The non-dimensional system (26) can be related to () by simply applying the transformation:

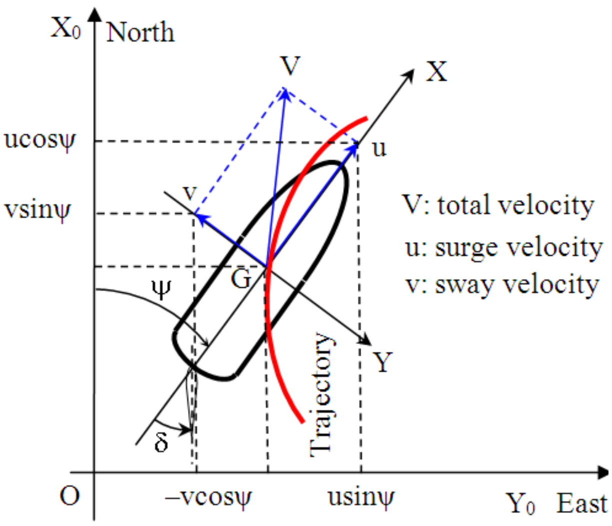
$$v = Uv'\,;\ r = \frac{U}{L}r'\,;\ \text{and}\ \ \delta_R = \delta'_R$$

The following sections deal with case study examples of ship manoeuvring models.

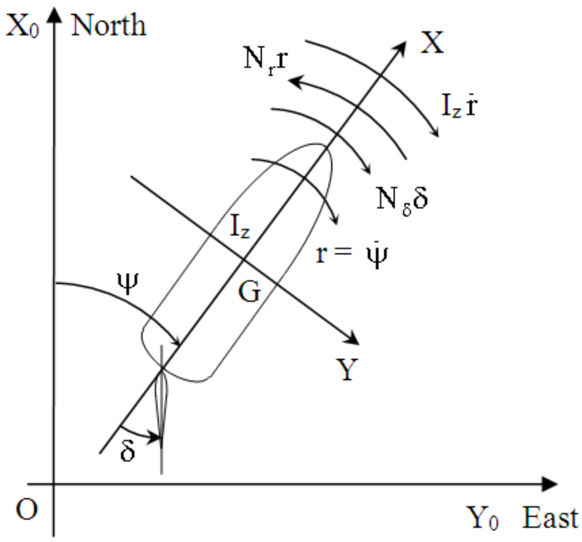
2.6 Nomoto's Steering Models and Simulation Scenarios

2.6.1 Ship's Hull Dynamics for Surface Vessel

For a surface vessel the motions on the horizontal are considered. They are surge, sway and yaw. In the case of designing a roll stabilization system roll motion is considered. **Fig. 4** shows a vessel in the horizontal plane.



(a) Trajectory



(b) Forces and moments

Figure 4 Motion of a vessel on the horizontal plane

List of variable and ship system parameters is below:

X_0OY_0: the Earth-fixed reference frame
XGY: the body-fixed reference frame
x, y: position of the vessel on the x-axis (longitude) and y-axis (latitude), respectively
u, v: surge and sway velocities
r: yaw rate
ψ : yaw angle (ship's course)
δ : rudder angle
I_z: moment of inertial of the vessel about the vertical z-axis
$N_\delta \delta$: turning moment caused by the rudder
$N_r r$: water resistance

The effect of a rudder handled by a hydraulic steering machine is illustrated in **Fig. 5**.

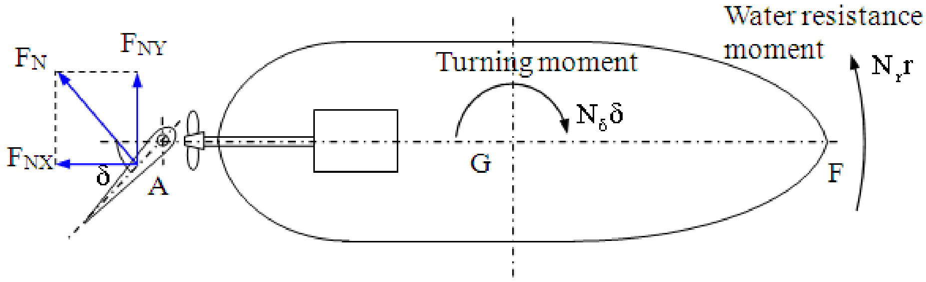


Figure 5 Effect of rudder on ship's turning motion (yaw)

From **Fig. 4**(b), according to the Newton's second law, we obtain

$$\sum T = I_z \dot{r} \tag{13}$$

$$I_z \dot{r} = \text{Turning moment} - \text{Water resistance moment} = N_\delta \delta - N_r r \tag{14}$$

$$I_z \dot{r} + N_r r = N_\delta \delta \;\Leftrightarrow\; \frac{I_z}{N_r}\dot{r} + r = \frac{N_\delta}{N_r}\delta \tag{15}$$

or

$$T\dot{r} + r = K\delta \tag{16}$$

where $T = \dfrac{I_z}{N_r}$ and $K = \dfrac{N_\delta}{N_r}$ are ship's manoeuvrability indices. The relation between the course angle and yaw rate is

$$\dot{\psi} = r \tag{17}$$

From **Fig. 4**(a) equations for the ship's position on the Earth's surface are

$$\dot{x} = u\cos\psi - v\sin\psi \tag{18}$$

$$\dot{y} = u\sin\psi + v\cos\psi \tag{19}$$

The ship's manoeuvring performance is understood by solutions of equations (16), (17), (18) and (19).

Use the following numerical values for simulation

A sea-going ship is steered by a rudder as shown in the figure below. The ship has the moment of inertia about the vertical axis (z) I_z of 15×10^9 kgm^2. The turning moment is proportional to the rudder angle (δ), ie $N_\delta \times \delta$ ($N_\delta = 22\times10^7$ Nm/rad). The water resistance moment (friction when the ship turns) is proportional to the yaw rate, i.e. $N_r r$ ($N_r = 2\times10^9$ Nms/rad).

2.6.2 Simulation of Open-loop Systems (Turning Circle and Zigzag Tests)

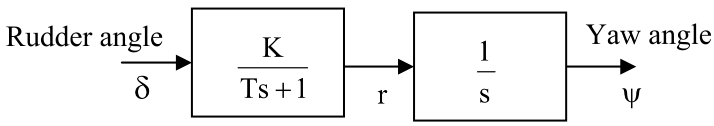


Figure 6 Ship hull's dynamics

Activity 1
Open-loop System without Trajectory (Turning Circle)
Equations (16), and (17)
(Sample Codes: M6Activity1.m)

Activity 2
Simulation of the Open-loop with Trajectory (Turning Circle)
Equations (16), (17), (18) and (19)
(Sample Codes: M6Activity2.m)

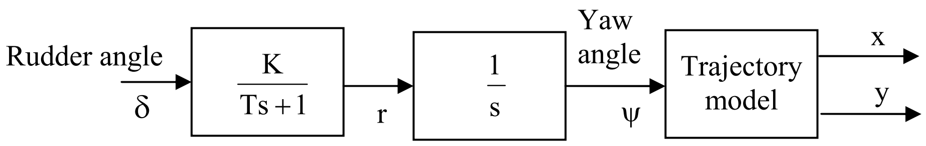


Figure 7s Ship hull's dynamics with trajectory model

Activity 3
Simulation of the Open-loop with Trajectory (Zigzag Test: 20-20 or 10-10 Z-test)
(Sample Codes: M6Activity3.m)

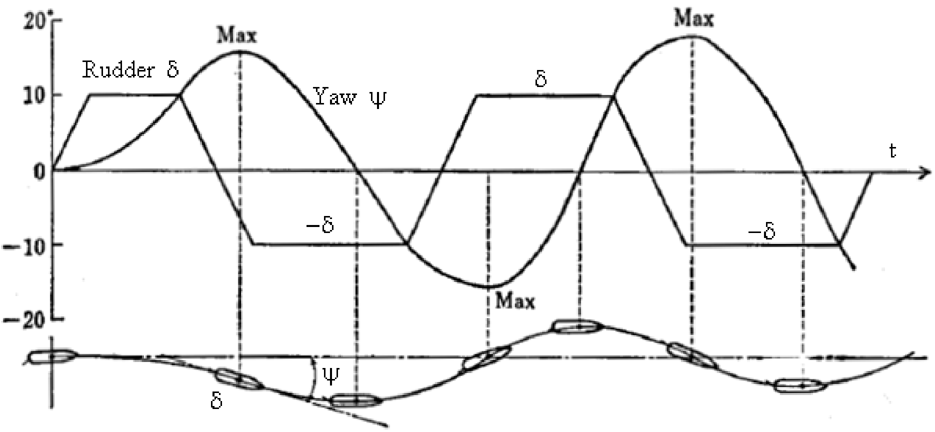


Figure 7b 10-10 Ztest

2.6.3 Mathematical Model of Hydraulic Steering Machine

Steering machine is an important component of a ship's control systems. Van Amerogen (1982) supposed a mathematical model of the steering machine as follows. The ship actuator or the steering machine is usually controlled by an on-off rudder control system. The on-off signals from the rudder controller are used to open and close the port and starboard valves of the telemotor system, see **Fig. 8**.

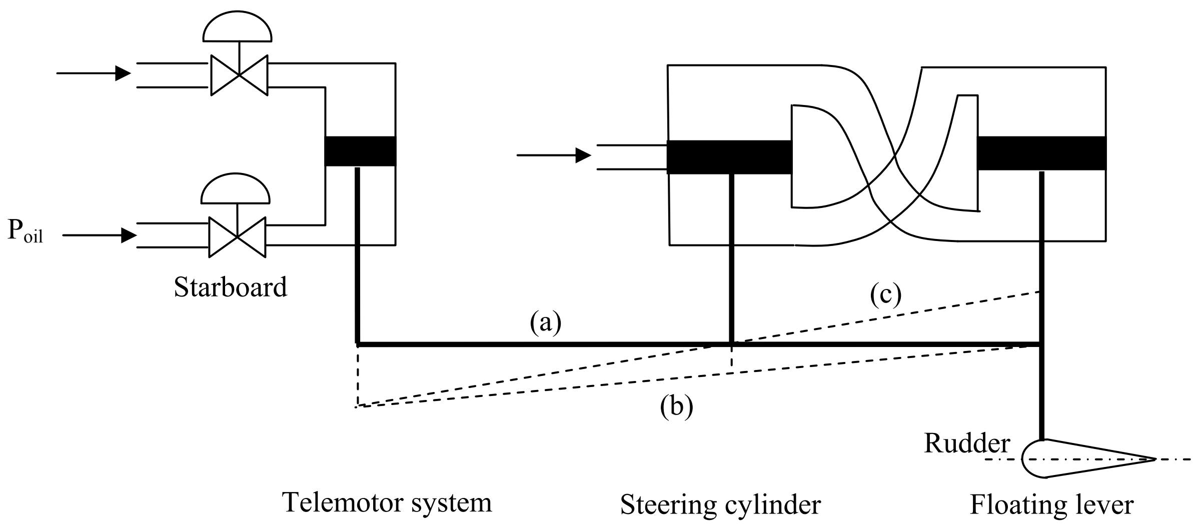


Figure 8 Simplified diagram of a two-stage hydraulic steering machine (Van Amerongen, 1982, Fossen, 1994)

Van Amerogen (1982) supposed the following model for steering machine:

$$\frac{\Delta}{\Delta_c} = \frac{K}{s(1+T_d s)} \tag{20}$$

By referring to **Fig. 8**, assume that the telemotor and floating level are initially at rest in position (a). The telemotor is moved to position (b) by opening the port valve. The rudder is still in its original position corresponding to position (b), that causes the steering cylinder valve to open. Consequently the floating lever will move to position (c) when the desired rudder angle has been reached. Thus the maximum opening of the steering cylinder valve with the pump capacity determines the maximum rudder speed (Fossen, 1994). **Fig. 9** shows the block diagram of the steering machines with the dynamics.

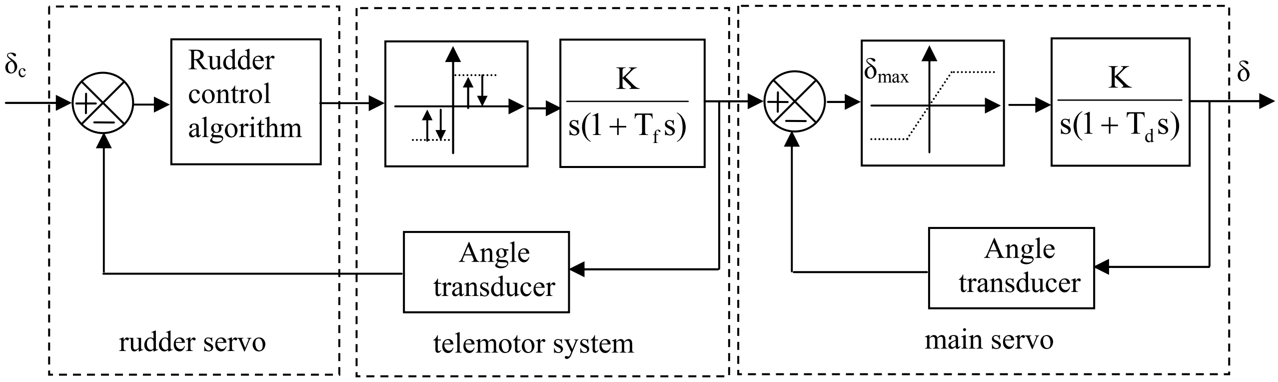


Figure 9 Block diagram of the rudder control system (Fossen, 1994, Van Amerongen, 1982)

A simplified model of the steering machine is shown in **Fig. 10**.

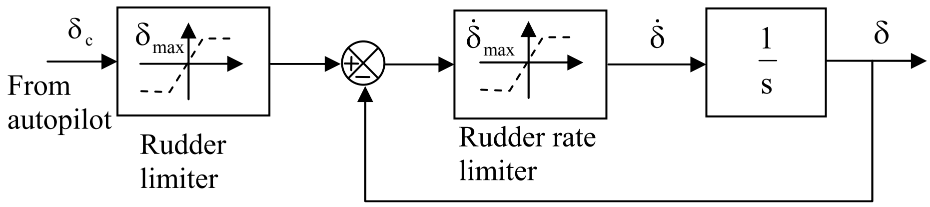


Figure 10 Simplified diagram of the rudder control loop (Fossen, 1994, Van Amerongen, 1990)

A group of researchers in Japan (namely MMG) supposed a mathematical model for steering machine as follows

$$\dot{\delta} = \frac{\delta_c - \delta}{|\delta_c - \delta| T_{rud} + a} \tag{21}$$

Activity 4
Simulation of Open-loop Systems with Steering Machine
(Sample Codes: M6Activity4.m)

2.6.4 Closed-loop System with PID Autopilot

Activity 5
Simulation of the Closed-loop system with PID autopilot
(Sample Codes: M6Activity5.m)

Activity 6
Make simulation programs for ship's control systems using GUI.
(Sample Codes: M6Activity6.m)

2.7 Mathematical Models of Surface Vessel (Container Vessel) with Roll Motion

A mathematical model for single screw high speed container ship in surge, sway, roll and yaw have been presented by Son and Nomoto (1981, 1982). The main results of this work are presented below as three mathematical models, all describing the couplings in sway, roll and yaw. The models are:

1. Nonlinear equations of motion in surge, sway, roll and yaw.
2. Nonlinear course-keeping equations of motion (sway, roll and yaw)
3. Linearised course-keeping equations of motion (sway, roll and yaw)

The container ship is given by the following set of data:

Container Ship		
Length (L)		175.00 (m)
Breadth (B)		25.40 (m)
Draft	fore (d_F)	8.00 (m)
	aft (d_A)	9.00 (m)
	mean (d)	8.50 (m)
Displacement volume (∇)		21,222.00 (m^3)
Height from keel to transverse metacentre (KM)		10.39 (m)
Height from keel to centre of buoyancy (KB)		4.6154 (m)
Block coefficient (C_B)		0.559 (-)
Rudder area (A_R)		33.0376 (m^2)
Aspect ratio (Λ)		1.8219 (-)
Propeller diameter		6.533 (m)

2.7.1 Nonlinear Equations of Motion (Surge, Sway, Roll and Yaw)

$$\left.\begin{aligned}
&(m' + m'_x)\dot{u}' - (m' + m'_y)v'r' = X' \\
&(m' + m'_y)\dot{v}' + (m' + m'_x)u'r' + m'_y\alpha'_y\dot{r}' - m'_y l'_y\dot{p}' = Y' \\
&(I'_x + J'_x)\dot{p}' - m'_y l'_y\dot{v}' - m'_x l'_x u'r' + W'\overline{G}\overline{M}'\phi' = K' \\
&(I'_z + J'_z)\dot{r}' - m'_y\alpha'_y\dot{v}' = N' - Y'x'_G
\end{aligned}\right\} \qquad (22)$$

Here m'_x, m'_y, J'_z and J'_x denote the added mass and added moment of inertia in the x and y directions and about the z and x axes, respectively. Furthermore, α'_y denotes the x-coordinates of the centre of m'_y, and I'_x and I'_y the z-coordinates of the centres of m'_x and m'_y, respectively. The hydrodynamic forces and moment are:

$$\left.\begin{aligned}
X' &= X'(u') + (1-t)T'(J) + X'_{vr}v'r' + X'_{vv}v'^2 \\
&\quad + X'_{rr}r'^2 + X''_{\phi\phi}\phi'^2 + c_{RX}F'_N \sin\delta' \\
K' &= K'_v v' + K'_r r' + K'_p p' + K'_\phi \phi' + K'_{vvv}v'^3 + K'_{rrr}r'^3 \\
&\quad + K'_{vvr}v'^2 r' + K'_{vrr}v'r'^2 + K'_{vv\phi}v'^2\phi' + K'_{v\phi\phi}v'\phi'^2 \\
&\quad + K'_{rr\phi}r'^2\phi' + K'_{r\phi\phi}r'\phi'^2 - (1+a_H)z'_R F'_N \cos\delta' \\
Y' &= Y'_v v' + Y'_r r' + Y'_p p' + Y'_\phi \phi' + Y'_{vvv}v'^3 + Y'_{rrr}r'^3 \\
&\quad + Y'_{vvr}v'^2 r' + Y'_{vrr}v'r'^2 + Y'_{vv\phi}v'^2\phi' + Y'_{v\phi\phi}v'\phi'^2 \\
&\quad + Y'_{rr\phi}r'^2\phi' + Y'_{r\phi\phi}r'\phi'^2 + (1+a_H)F'_N \cos\delta' \\
N' &= N'_v v' + N'_r r' + N'_p p' + N'_\phi \phi' + N'_{vvv}v'^3 + N'_{rrr}r'^3 \\
&\quad + N'_{vvr}v'^2 r' + N'_{vrr}v'r'^2 + N'_{vv\phi}v'^2\phi' + N'_{v\phi\phi}v'\phi'^2 \\
&\quad + N'_{rr\phi}r'^2\phi' + N'_{r\phi\phi}r'\phi'^2 + (x'_R + a_H x'_H)F'_N \cos\delta'
\end{aligned}\right\} \tag{23}$$

where $X'(u)$ is a velocity dependent damping function, e.g. $X'(u) = X'_{|u|u}|u|u$. The rudder force F'_N can be resolved as

$$\left.\begin{aligned}
F'_N &= -\frac{6.13\Lambda}{\Lambda + 2.25}\frac{A_R}{L^2}\left(u'^2_R + v'^2_R\right)\sin\alpha_R \\
\alpha_R &= \delta + \tan^{-1}\left(\frac{v'_R}{u'_R}\right) \\
u'_R &= u'_P \varepsilon\sqrt{1 + \frac{8kK_T}{(\pi J)^2}} \\
v'_R &= \gamma v' + c_{Rr}r' + c_{Rrrr}r'^3 + c_{Rrrv}r'^2 v'
\end{aligned}\right\} \tag{24}$$

where

$$\left.\begin{aligned}
J &= u'_P \frac{U}{nD} \\
u'_P &= \cos v'\left[(1-w_p) + \tau\left\{(v' + x'_p r')^2 + c_{pv}v' + c_{pr}r'\right\}\right]
\end{aligned}\right\} \tag{25}$$

The different parameters in the model are given below.

Model Parameters

(a) Hull only

m'	0.00792	Y'_p	0.0	$N'_{vv\phi}$	–0.019058
m'_x	0.000238	Y'_ϕ	–0.000063	$N'_{v\phi\phi}$	–0.0053766
m'_y	0.007049	Y'_{vvv}	–0.109	$N'_{rr\phi}$	–0.0038592
I'_x	0.0000176	Y'_{rrr}	0.00177	$N'_{r\phi\phi}$	0.0024195
J'_x	0.0000034	Y'_{rvv}	0.0214	K'_v	0.0003026
I'_z	0.000456	Y'_{rrv}	–0.0405	K'_r	–0.0003026
J'_z	0.000419	$Y'_{vv\phi}$	0.04605	κ_ϕ	0.1 ($F_n \le 1$)
α'_y	0.05	$Y'_{v\phi\phi}$	0.00304		0.2 ($F_n \ge 0.2$)

l'_x	0.0313	$Y'_{rr\phi}$	0.009325		F_n $(0.1 < F_n < 0.2)$
l'_y	0.0313	$Y'_{r\phi\phi}$	–0.001368	K'_ϕ	–0.000021
K_T	0.527 – 0.455J	N'_v	–0.0038545	K'_p	–0.0000075
X'_{uu}	–0.0004226	N'_r	–0.00222	K'_{vvv}	0.002843
X'_{vr}	–0.00311	N'_p	0.000213	K'_{rrr}	–0.0000462
X'_{vv}	–0.00386	N'_ϕ	–0.0001424	K'_{rvv}	–0.000558
X'_{rr}	0.00020	N'_{vvv}	0.00192	K'_{rrv}	0.0010565
$X'_{\phi\phi}$	–0.00020	N'_{rrr}	–0.00229	$K'_{vv\phi}$	–0.0012012
Y'_v	–0.0116	N'_{rvv}	–0.0424	$K'_{v\phi\phi}$	–0.0000793
Y'_r	0.00242	N'_{rrv}	0.00156	$K'_{rr\phi}$	–0.000243
				$K'_{r\phi\phi}$	0.00003569

(b) Propeller and rudder

N_p (rpm)	79.10 (F_n 0.2) 118.64 (F_n 0.3) 158.19 (F_n 0.4)	a_H x'_H c_{RX}	0.237 –0.48 0.71	ε k γ	0.921 0.631 0.088 ($v' > 0$)
(1 – t)	0.825	z'_R	0.033		0.193 ($v' \le 0$)
(1 – w_p)	0.816	c_{pv}	0.0	c_{Rr}	–0.156
x'_R	–0.5	c_{pr}	0.0	c_{Rrrr}	–0.275
x'_p	–0.526	τ	1.09	c_{Rrrv}	1.96

2.7.2 Nonlinear Course-keeping Equations of Motion (Sway, Roll and Yaw)

Consider a ship sailing nearly straight with an automatic course-keeping device in operation. Hence, we can assume constant forward speed (u' = 1) which implies that the above equations of motion can be approximated by:

$$\begin{bmatrix} (m'+m'_y) & -m'_y l'_y & 0 \\ -m'_y l'_y & I'_x + J'_x & 0 \\ 0 & 0 & I'_z + J'_z \end{bmatrix} \begin{bmatrix} \dot{v}' \\ \dot{p}' \\ \dot{r}' \end{bmatrix} = \begin{bmatrix} Y' \\ K' \\ N' \end{bmatrix} \tag{26}$$

where

$$\left.\begin{aligned} Y' &= Y'_v v' - (m' + m'_x - Y'_r) r' + Y'_p p' + Y'_\phi \phi' + Y'_{vv\phi} v'^2 \phi' + Y'_{v\phi\phi} v' \phi'^2 \\ &\quad + Y'_{rr\phi} r'^2 \phi' + Y'_{r\phi\phi} r' \phi'^2 + Y'_\delta \delta' \\ K' &= K'_p p' - (W'\overline{GM}' - K'_\phi)\phi' + K'_v v' + (m'_x l'_x + K'_r) r' + K'_{vv\phi} v'^2 \phi' \\ &\quad + K'_{v\phi\phi} v' \phi'^2 + K'_{rr\phi} r'^2 \phi' + K'_{r\phi\phi} r' \phi'^2 + K'_\delta \delta' \\ N' &= N'_r r' + N'_v v' + N'_p p' + N'_\phi \phi' + N'_{vv\phi} v'^2 \phi' + N'_{v\phi\phi} v' \phi'^2 + N'_{rr\phi} r'^2 \phi' \\ &\quad + N'_{r\phi\phi} r' \phi'^2 + N'_\delta \delta' \end{aligned}\right\} \tag{27}$$

with $p' = \dot{\phi}' = \dot{\phi}(L/U)$. The non-dimensional hydrodynamic derivatives for the course-keeping model with $\overline{KG}$ = 10.99 m and $\overline{GM}$ = 0.3 m are given below:

$(m' + m'_y)$	0.01497	N'_p	0.000213
$(I'_z + J'_z)$	0.000875	N'_ϕ	–0.0001468
$(I'_x + J'_x)$	0.000021	$N'_{vv\phi}$	–0.018191
$m'_y \alpha'_y$	0.0003525	$N'_{v\phi\phi}$	–0.005299
$m'_y l'_y$	0.0002205	$N'_{rr\phi}$	–0.003684
Y'_y	–0.012035	$N'_{r\phi\phi}$	0.0023843
$(m' + m'_x - Y'_r)$	0.00522	N'_δ	0.00126
Y'_p	0.0	κ_ϕ	0.2
Y'_ϕ	–0.000074	K'_ϕ	–0.000021
$Y'_{vv\phi}$	0.046364	K'_v	0.000314
$Y'_{v\phi\phi}$	0.003005	$(m'_x l'_x + K'_r)$	–0.0000692
$Y'_{rr\phi}$	0.0093887	$K'_{vv\phi}$	–0.0012094
$Y'_{r\phi\phi}$	–0.0013523	$K'_{v\phi\phi}$	–0.0000784
Y'_δ	–0.002578	$K'_{rr\phi}$	–0.0002449
N'_r	–0.00243	$K'_{r\phi\phi}$	0.00003528
N'_v	–0.0038436	K'_δ	0.0000855

2.7.3 Linearised Course-Keeping Equations of Motion (Sway, Roll and Yaw)

The linearised course-keeping equations of motion are:

$$\begin{bmatrix} m'_{11} & m'_{12} & 0 & 0 \\ m'_{21} & m'_{22} & 0 & 0 \\ 0 & 0 & m'_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\dot{v}' \\ \Delta\dot{p}' \\ \Delta\dot{r}' \\ \Delta\dot{\phi}' \end{bmatrix} + \begin{bmatrix} d'_{11} & d'_{12} & d'_{13} & d'_{14} \\ d'_{21} & d'_{22} & d'_{23} & d'_{24} \\ d'_{31} & d'_{32} & d'_{33} & d'_{34} \\ 0 & -\frac{U}{L} & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta v' \\ \Delta p' \\ \Delta r' \\ \Delta\phi' \end{bmatrix} = \begin{bmatrix} b'_1 \\ b'_2 \\ b'_3 \\ 0 \end{bmatrix} \Delta\delta \qquad (28)$$

where

$$m'_{11} = m' + m'_y$$
$$m'_{12} = -m'_y l'_y$$
$$m'_{21} = m_{12}$$
$$m'_{22} = I'_x + J'_x$$
$$m'_{33} = I'_z + J'_z$$
$$d'_{11} = -Y'_v - 2Y'_{vv\phi} v'_0 \phi'_0 - Y'_{v\phi\phi} \phi'^2_0$$
$$d'_{12} = -Y'_p$$
$$d'_{13} = (m' + m'_x - Y'_r) - 2Y'_{rr\phi} r'_0 \phi'_0 - Y'_{r\phi\phi} \phi'^2_0$$
$$d'_{14} = -Y'_\phi - Y'_{vv\phi} v'^2_0 - 2Y'_{v\phi\phi} v'_0 \phi'_0 - Y'_{rr\phi} r'^2 - 2Y'_{r\phi\phi} r'_0 \phi'_0$$
$$d'_{21} = -K'_v - 2K'_{vv\phi} v'_0 \phi'_0 - K'_{v\phi\phi} \phi'^2_0$$

$$d'_{22} = -K'_p$$
$$d'_{23} = -\left(m'_x l'_x + K'_r\right) - 2K'_{rr\phi} r'_0 \phi'_0 - K'_{r\phi\phi} \phi'^2_0$$
$$d'_{24} = \left(W'\overline{G}\overline{M}' - K'_\phi\right) - K'_{vv\phi} v'^2_0 - 2K'_{v\phi\phi} v'_0 \phi'_0 - K'_{rr\phi} r'^2_0 - 2K'_{r\phi\phi} r'_0 \phi'_0$$
$$d'_{31} = -N'_v - 2N'_{vv\phi} v'_0 \phi'_0 - N'_{v\phi\phi} \phi'^2_0$$
$$d'_{32} = -N'_p$$
$$d'_{33} = N'_r - 2N'_{rr\phi} r'_0 \phi'_0 - N'_{r\phi\phi} \phi'^2_0$$
$$d'_{34} = -N'_\phi - N'_{vv\phi} v'^2_0 - 2N'_{v\phi\phi} v'_0 \phi'_0 - N'_{rr\phi} r'^2_0 - 2N'_{r\phi\phi} r'_0 \phi'_0$$
$$b'_1 = Y'_\delta$$
$$b'_2 = K'_\delta$$
$$b'_3 = N'_\delta$$

MATLAB M-File for Nonlinear Model of Container Ship (Fossen, 1994 and 2002)

```
function [xdot,U] = container(x,ui)
% [xdot,U] = container(x,ui) returns the speed U in m/s (optionally) and the
% time derivative of the state vector: x = [ u v r x y psi p phi delta n ]'  for
% a container ship L = 175 m, where
%
% u     = surge velocity          (m/s)
% v     = sway velocity           (m/s)
% r     = yaw velocity            (rad/s)
% x     = position in x-direction (m)
% y     = position in y-direction (m)
% psi   = yaw angle               (rad)
% p     = roll velocity           (rad/s)
% phi   = roll angle              (rad)
% delta = actual rudder angle     (rad)
% n     = actual shaft velocity   (rpm)
%
% The input vector is :
%
% ui      = [ delta_c n_c ]'  where
%
% delta_c = commanded rudder angle   (rad)
% n_c     = commanded shaft velocity (rpm)
%
% Reference:  Son og Nomoto (1982). On the Coupled Motion of Steering and
%             Rolling of a High Speed Container Ship, Naval Architect of Ocean
Engineering,
%             20: 73-83. From J.S.N.A. , Japan, Vol. 150, 1981.
%
% Author:    Trygve Lauvdal
% Date:      12th May 1994
% Revisions: 18th July 2001 (Thor I. Fossen): added output U, changed order of x-
vector
%            20th July 2001 (Thor I. Fossen): changed my = 0.000238 to my = 0.007049

% Check of input and state dimensions

if (length(x) ~= 10),error('x-vector must have dimension 10 !');end
if (length(ui) ~= 2),error('u-vector must have dimension  2 !');end

% Normalization variables
L = 175;                      % length of ship (m)
U = sqrt(x(1)^2 + x(2)^2);    % service speed (m/s)

% Check service speed
if U <= 0,error('The ship must have speed greater than zero');end
```

```
if x(10) <= 0,error('The propeller rpm must be greater than zero');end

delta_max  = 10;             % max rudder angle (deg)
Ddelta_max = 5;              % max rudder rate (deg/s)
n_max      = 160;            % max shaft velocity (rpm)

% Non-dimensional states and inputs
delta_c = ui(1);
n_c     = ui(2)/60*L/U;

u     = x(1)/U;   v   = x(2)/U;
p     = x(7)*L/U; r   = x(3)*L/U;
phi   = x(8);     psi = x(6);
delta = x(9);     n   = x(10)/60*L/U;

% Parameters, hydrodynamic derivatives and main dimensions
m  = 0.00792;    mx     = 0.000238;   my = 0.007049;
Ix = 0.0000176;  alphay = 0.05;       lx = 0.0313;
ly = 0.0313;     Ix     = 0.0000176;  Iz = 0.000456;
Jx = 0.0000034;  Jz     = 0.000419;   xG = 0;

B     = 25.40;   dF = 8.00;    g     = 9.81;
dA    = 9.00;    d  = 8.50;    nabla = 21222;
KM    = 10.39;   KB = 4.6154;  AR    = 33.0376;
Delta = 1.8219;  D  = 6.533;   GM    = 0.3/L;
rho   = 1025;    t  = 0.175;   T     = 0.0005;

W     = rho*g*nabla/(rho*L^2*U^2/2);

Xuu      = -0.0004226;  Xvr    = -0.00311;    Xrr      = 0.00020;
Xphiphi  = -0.00020;    Xvv    = -0.00386;

Kv       =  0.0003026;  Kr     = -0.000063;   Kp       = -0.0000075;
Kphi     = -0.000021;   Kvvv   =  0.002843;   Krrr     = -0.0000462;
Kvvr     = -0.000588;   Kvrr   =  0.0010565;  Kvvphi   = -0.0012012;
Kvphiphi = -0.0000793;  Krrphi = -0.000243;   Krphiphi =  0.00003569;

Yv       = -0.0116;     Yr     =  0.00242;    Yp       =  0;
Yphi     = -0.000063;   Yvvv   = -0.109;      Yrrr     =  0.00177;
Yvvr     =  0.0214;     Yvrr   = -0.0405;     Yvvphi   =  0.04605;
Yvphiphi =  0.00304;    Yrrphi =  0.009325;   Yrphiphi = -0.001368;

Nv       = -0.0038545;  Nr     = -0.00222;    Np       =  0.000213;
Nphi     = -0.0001424;  Nvvv   =  0.001492;   Nrrr     = -0.00229;
Nvvr     = -0.0424;     Nvrr   =  0.00156;    Nvvphi   = -0.019058;
Nvphiphi = -0.0053766;  Nrrphi = -0.0038592;  Nrphiphi =  0.0024195;

kk     =  0.631;  epsilon =  0.921;  xR    = -0.5;
wp     =  0.184;  tau     =  1.09;   xp    = -0.526;
cpv    =  0.0;    cpr     =  0.0;    ga    =  0.088;
cRr    = -0.156;  cRrrr   = -0.275;  cRrrv =  1.96;
cRX    =  0.71;   aH      =  0.237;  zR    =  0.033;
xH     = -0.48;

% Masses and moments of inertia
m11 = (m+mx);
m22 = (m+my);
m32 = -my*ly;
m42 = my*alphay;
m33 = (Ix+Jx);
m44 = (Iz+Jz);

% Rudder saturation and dynamics
if abs(delta_c) >= delta_max*pi/180,
   delta_c = sign(delta_c)*delta_max*pi/180;
end

delta_dot = delta_c - delta;
```

```
if abs(delta_dot) >= Ddelta_max*pi/180,
   delta_dot = sign(delta_dot)*Ddelta_max*pi/180;
end

% Shaft velocity saturation and dynamics
n_c = n_c*U/L;
n   = n*U/L;
if abs(n_c) >= n_max/60,
   n_c = sign(n_c)*n_max/60;
end

if n > 0.3,Tm=5.65/n;else,Tm=18.83;end
n_dot = 1/Tm*(n_c-n)*60;

% Calculation of state derivatives
  vR     = ga*v + cRr*r + cRrrr*r^3 + cRrrv*r^2*v;
  uP     = cos(v)*((1 - wp) + tau*((v + xp*r)^2 + cpv*v + cpr*r));
   J     = uP*U/(n*D);
  KT     = 0.527 - 0.455*J;
  uR     = uP*epsilon*sqrt(1 + 8*kk*KT/(pi*J^2));
  alphaR = delta + atan(vR/uR);
  FN     = - ((6.13*Delta)/(Delta + 2.25))*(AR/L^2)*(uR^2 + vR^2)*sin(alphaR);
  T      = 2*rho*D^4/(U^2*L^2*rho)*KT*n*abs(n);

% Forces and moments
  X    = Xuu*u^2 + (1-t)*T + Xvr*v*r + Xvv*v^2 + Xrr*r^2 + Xphiphi*phi^2 + ...
         cRX*FN*sin(delta) + (m + my)*v*r;

  Y    = Yv*v + Yr*r + Yp*p + Yphi*phi + Yvvv*v^3 + Yrrr*r^3 + Yvvr*v^2*r + ...
         Yvrr*v*r^2 + Yvvphi*v^2*phi + Yvphiphi*v*phi^2 + Yrrphi*r^2*phi + ...
         Yrphiphi*r*phi^2 + (1 + aH)*FN*cos(delta) - (m + mx)*u*r;

  K    = Kv*v + Kr*r + Kp*p + Kphi*phi + Kvvv*v^3 + Krrr*r^3 + Kvvr*v^2*r + ...
         Kvrr*v*r^2 + Kvvphi*v^2*phi + Kvphiphi*v*phi^2 + Krrphi*r^2*phi + ...
         Krphiphi*r*phi^2 - (1 + aH)*zR*FN*cos(delta) + mx*lx*u*r - W*GM*phi;

  N    = Nv*v + Nr*r + Np*p + Nphi*phi + Nvvv*v^3 + Nrrr*r^3 + Nvvr*v^2*r + ...
         Nvrr*v*r^2 + Nvvphi*v^2*phi + Nvphiphi*v*phi^2 + Nrrphi*r^2*phi + ...
         Nrphiphi*r*phi^2 + (xR + aH*xH)*FN*cos(delta);

% Dimensional state derivatives  xdot = [ u v r x y psi p phi delta n ]'
detM = m22*m33*m44-m32^2*m44-m42^2*m33;

xdot =[                      X*(U^2/L)/m11
          -((-m33*m44*Y+m32*m44*K+m42*m33*N)/detM)*(U^2/L)
           ((-m42*m33*Y+m32*m42*K+N*m22*m33-N*m32^2)/detM)*(U^2/L^2)
                   (cos(psi)*u-sin(psi)*cos(phi)*v)*U
                   (sin(psi)*u+cos(psi)*cos(phi)*v)*U
                              cos(phi)*r*(U/L)
           ((-m32*m44*Y+K*m22*m44-K*m42^2+m32*m42*N)/detM)*(U^2/L^2)
                                p*(U/L)
                              delta_dot
                                n_dot                  ];
```

Activity 7 (Simulation for Container Vessel)

1. Simulation of Open-loop System

(Sample Codes:M6Activity71.m)

2. Simulation of Closed-loop with PID Autopilot

(Sample Codes: Codes:M6Activity72.m)

3. Simulation of Closed-loop with PID Autopilot and Rudder-Roll Stabilization/Damping

(Sample Codes: M6Activity73.m)

3. Diesel Electric Propulsion Systems and Marine Electric/Electronic Systems/Power Electronics

Marine systems are isolated from the shore and there are many subsystems on a marine system. For ocean going vehicles the propulsion systems play an very important role in their operation. There are two arrangements of propulsion systems (conventional and diesel electric) as shown in **Fig. 11**.

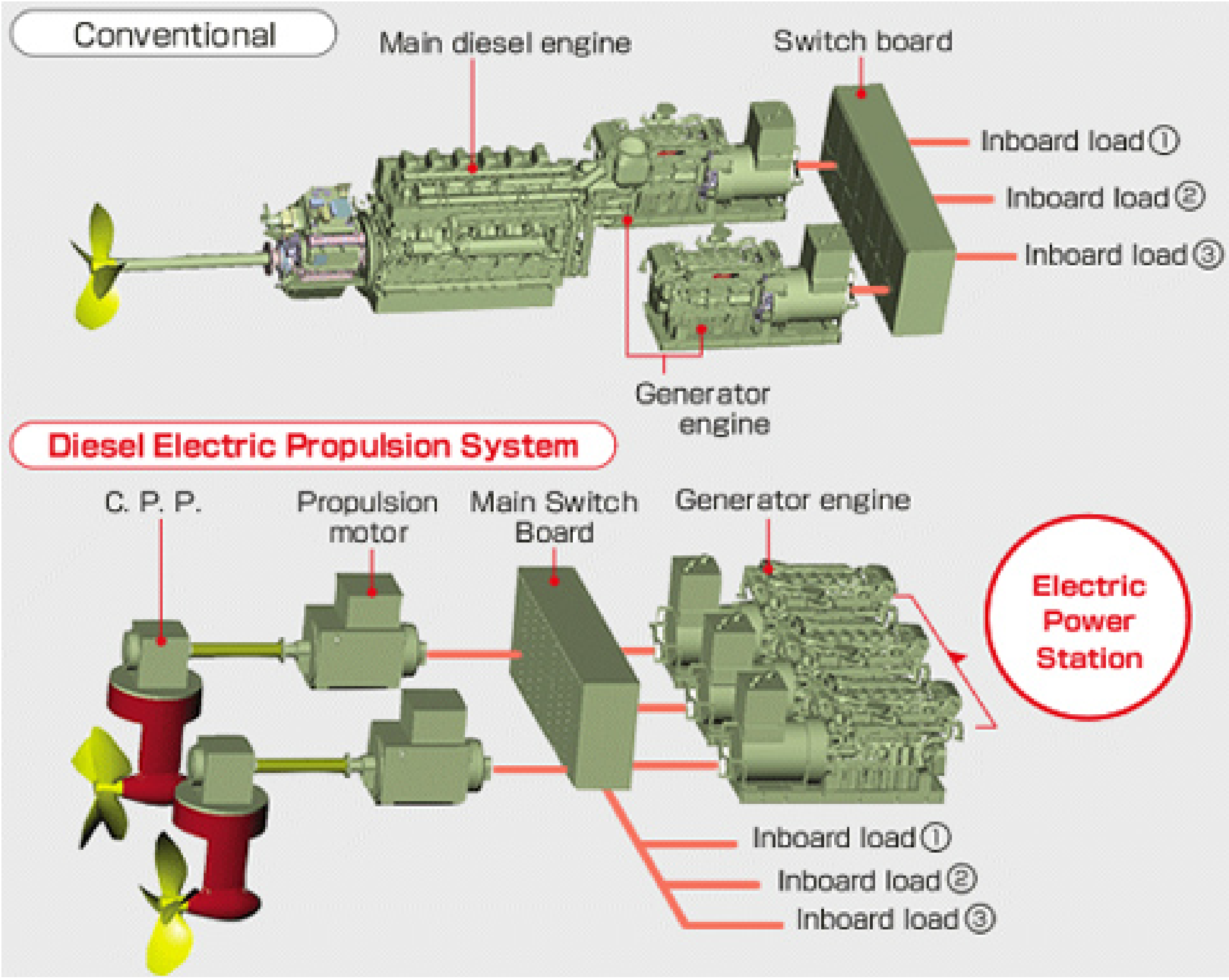


Figure 11 Diesel electrical propulsion system
(http://www.yanmar.co.jp/en/marine/products/electricPropulsion/detail/image/picIndex03.jpg)

Fig. 12 shows an arrangement of a diesel electric propulsion system using Wartsila 8L32 generator and VSD (variable speed drive). As shown in **Fig. 12** a diesel electric propulsion system consists of a generators, switch boards, control units (VSD, variable speed drives), LLC (Low Loss Concept) units and thrusters driven by motors.

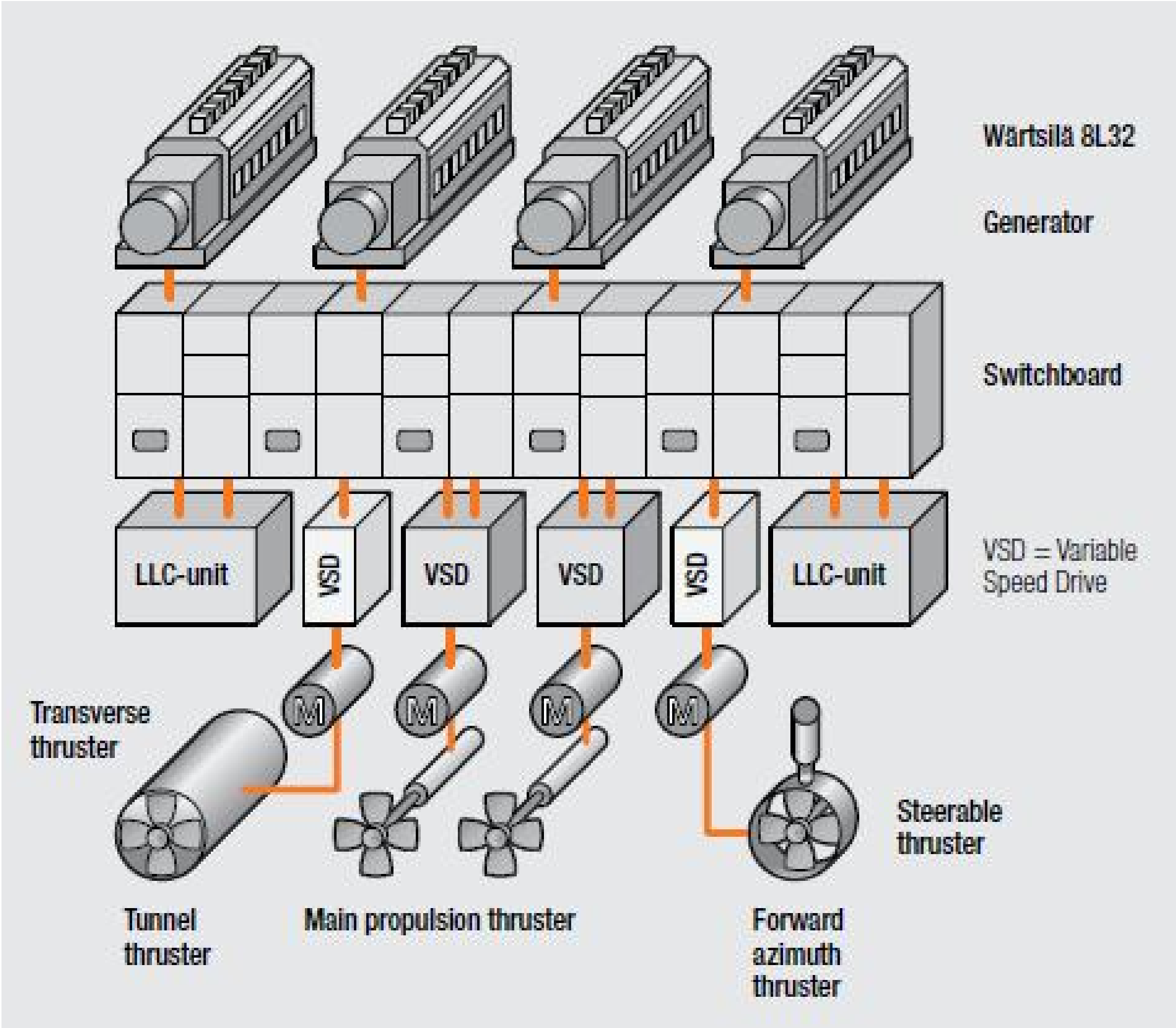


Figure 12 Example of a diesel electrical propulsion system (Courtesy of Wartsila)

In this section we take some case study examples of marine systems.

3.1 Marine Electrical Machines

The following machines are used in maritime industry:

- DC machines
    - DC motors (brushed, brushless and stepper motors)
    - DC generators (
- Induction (Asynchronous) machines
- Synchronous machines
- Other electrical machines: transformers, automatic voltage regulators,

3.1.1 DC Motors

Activity 8
(Armature-controlled dc motor & field-controlled dc motor)
Make simulation programs for the dc motor in Case Study 5, Module 1. Use the following numerical values:

$J_m = 3\times 10^{-5}$ kgm^2

$J_d = 0.001$ kgm^2 (moment of inertia of a load disk attached to the motor shaft)

R_a = 5.5 Ohms
$L_a = 11.98\times10^{-2}$ (H)
$B = 1.5\times10^{-6}$ Ns/m
T_L = 0 (the bearing friction is neglected)
K_t = 0.00275 V/rpm
K_a = 7.0 V/V
K_m = 0.058 Nm/A
K_b = 0.058 V/rad/s

(Sample Code: M6Activity8.m)

3.1.2 DC Generators

Activity 9 (separately-excited dc generator): A separately excited dc generator has the following system parameters:

Rated output voltage of armature: V_a = 115 DCV
Armature resistance R_a = 0.9 Ω
Armature inductance L_a = 0.01 H
Field resistance R_f = 75 Ω
Field inductance L_f = 50 H
Number of parallel paths (yokes) between brushes of opposite polarity a = 2
Number of poles pairs p = 2
Number of effective conductors N = 300 ($N = 2an_sn_c$ where n_c = number of turns per coil and n_s = number of identical coils, an_s = total number of coils)
Moment of inertial of rotor J = 0.0215 kgm^2
Rated power P = 2.5 kW
Viscous friction coefficient B = 0.1836 N.m.s
Rated angular velocity of rotor n = 1300 rpm

The following shows an equivalent circuit of a separately excited dc generator.

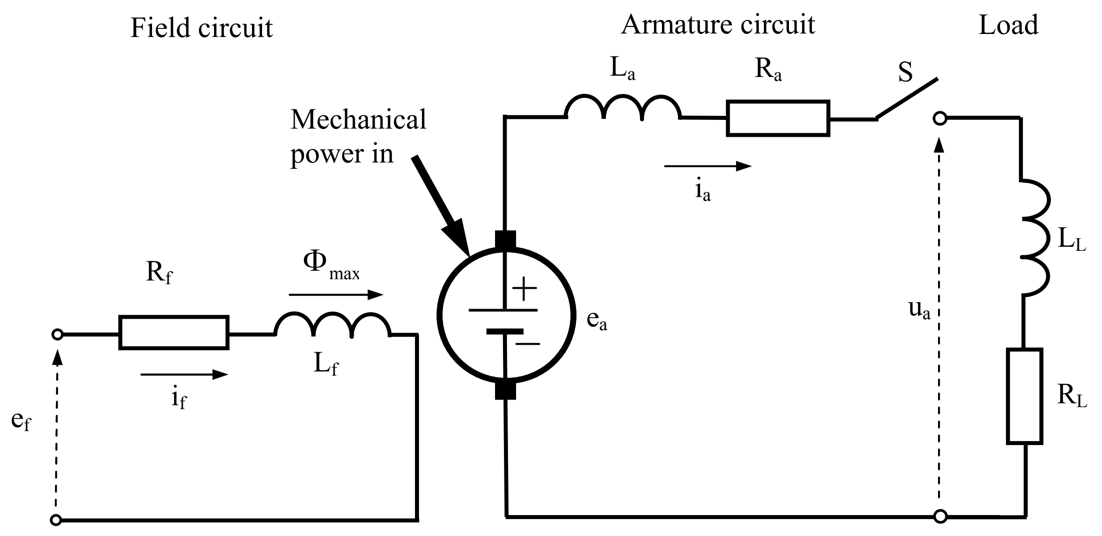


Figure 13 Equivalent circuit of a separately excited DC generator

Develop equations to relate the output voltage and exciting voltage and make simulation programs for various scenarios. Design a controller to regulate the output voltage (an AVR: automatic voltage regulator).

Solution

Equations in unloaded armature circuit:

Flux per pole constant in armature

$$K_i = \frac{pN}{60a} = \frac{2 \times 300}{2 \times 60} = 5 \quad (29)$$

Define the nominal coefficient:

$$K_f = \frac{K_i}{R_f} \text{ (where } R_f \text{ is the field resistance)} \quad (30)$$

The excitation voltage in the field circuit is:

$$e_f = R_f i_f + L_f \frac{di_f}{dt} \text{ (where } i_f \text{ is the field winding current)} \quad (31)$$

or transfer function

$$\frac{I_f}{E_f} = \frac{1}{R_f\left(1 + T_f s\right)} \quad (32)$$

where $T_f = \dfrac{L_f}{R_f}$ is the field time constant (seconds).

The induced emf of the armature (with ignoring flux saturation and assumption that the relationship between the flux per pole and field mmf (magnetomotive force) is linear):

$$e_a = \omega_m K_f i_f = \frac{2\pi n}{60} K_f i_f = K_e n i_f \quad (33)$$

where $K_e = \dfrac{2\pi K_f}{60}$

or transfer function

$$\frac{E_a}{I_f} = K_e n \quad (34)$$

Equations in loaded armature

$$e_a = R_c i_a + L_c \frac{di_a}{dt} \quad (35)$$

where $R_c = R_a + R_L$ and $L_c = L_a + L_L$.

or transfer function

$$\frac{I_a}{E_a} = \frac{1}{R_c\left(1 + T_a s\right)} \quad (36)$$

where $T_a = \dfrac{L_c}{R_c}$ is the armature time constant (seconds).

The output voltage is

$$v_a = R_c i_a = e_a - R_a i_a \tag{37}$$

Hence, we have the following block diagram for the generator (with constant speed of rotor):

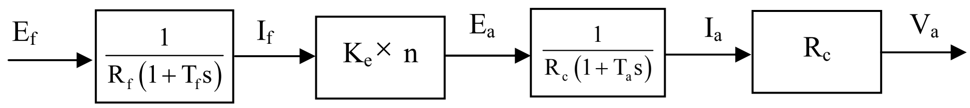


Figure 14 Block diagram of separately excited dc generator

When considering speed variation the equation of motion of the rotor is:

$$J\frac{d\omega_m}{dt} + \sin(\omega_m)T_L + B\omega_m + T_f = T_e = K_m i_a \tag{38}$$

where J = inertia, B_m = viscous friction coefficient, and T_f = Coulomb friction torque. For a DC generator, assuming that $T_L = 0$ and $T_f = 0$, the following equation is obtained:

$$J\frac{d\omega_m}{dt} + B\omega_m = T_{mech} - T_{em} = T \tag{39}$$

where T_{mech} is torque caused by the prime mover and $T_{em} = K_g i_a$ ($K_g = E_{ao}/\omega_{mo}$), electromagnetic torque (N.m), or transfer function

$$\frac{\Omega_m(s)}{T(s)} = \frac{1}{Js+B} \quad \text{or} \quad \frac{N(s)}{T(s)} = \frac{1}{Js+B}\frac{60}{2\pi} \tag{40}$$

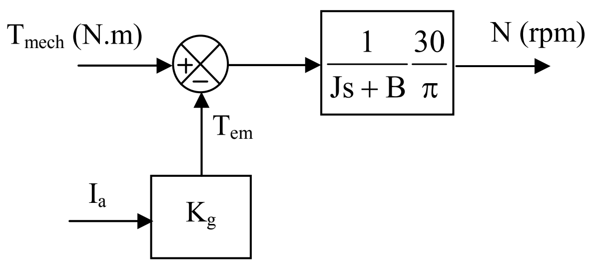


Figure 15 Block diagram for mechanical part of a separately excited dc generator

Control of Output Voltage

The output voltage of the DC generator can be regulated by a PID controller that adjusts the field voltage. **Fig. 16** shows a block diagram for the control system of DC generator.

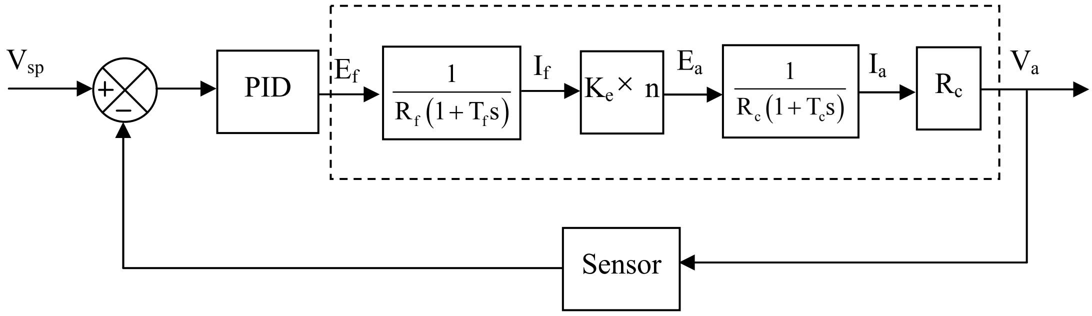


Figure 16 Block diagram of separately excited dc generator

3.3 Marine Diesel Propulsion Systems

3.3. 1 Governor System

Activity 10 Marine governor

Let's consider a speed control system (governor) for a marine diesel engine that drives a fixed pitch propeller as shown in the following figure. Assume the relation between the fuel flowrate and the engine shaft speed is

$$G(s) = \frac{\Omega(s)}{U(s)} = \frac{1}{s(s+5)} \tag{41}$$

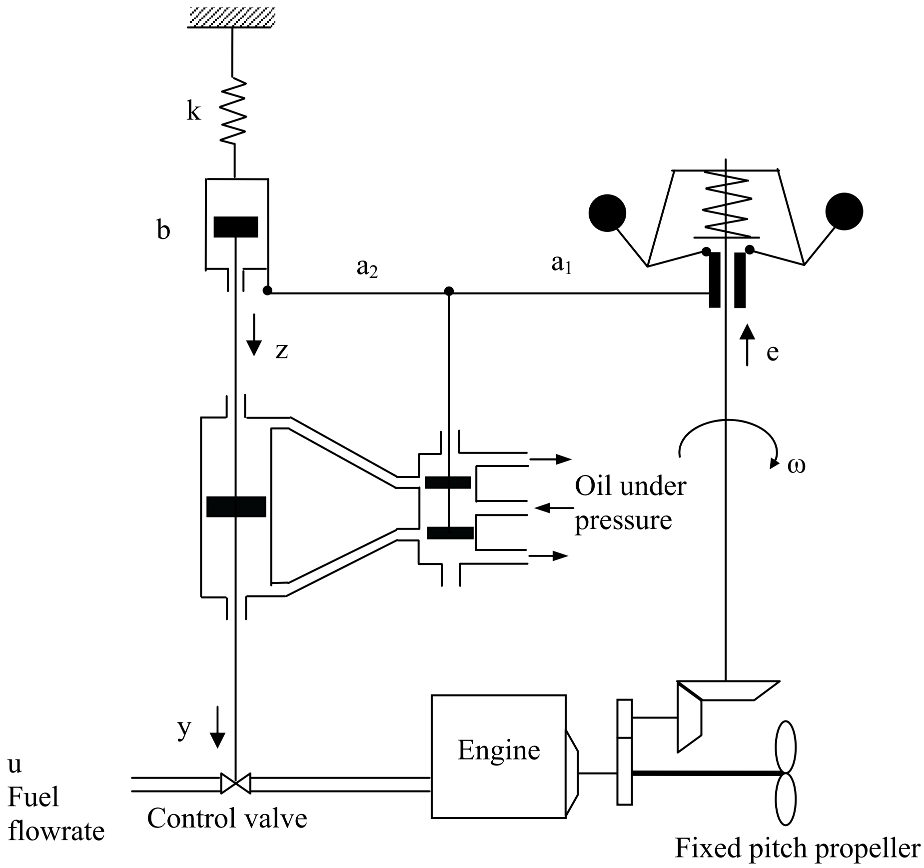


Figure 17 Speed control system (governor)

Solution

Block diagram for the hydraulic controller

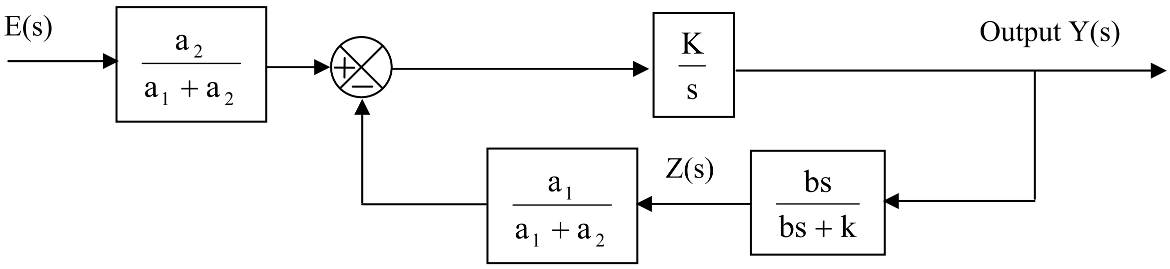


Figure 18 Block diagram for the speed control system

Suggest numerical values for the hydraulic control and make simulation program/s.

3.3.2 Case Study 1: Diesel Electric Propulsion Systems for Marine Vehicles

(See Jan F. Hansen, Alf K. Adnanes and Thor I. Fossen, 2001)
Hansen, J.F., Adnanes, A.K. and Fossen, T.I. (2001). Mathematical Modelling of Deisel-Electric Propulsion Systems for Marine Vehicles. *Mathematical and Computer Modelling of Dynamic Systems*, Vol. 7, No. 1, pp. 1-33. Swets and Zeitlinger.

3.3.3 Case Study 2: Electrically Driven Marine Propulsion

(See Kaushik, Chandan and Thotakura, 2012)
Kaushik, S., Chandan, K.S. and Thotakura, S. (2012). Electrically Driven Marine Propulsion. *The Internationl Journal of Engineering Research and Application*. Vol. 2, No. 1, pp. 446-451. www.ijera.com.

4. Other Marine Systems

The following are examples of control systems in maritime industry.

- Electrically operated pumps
- Temperature control system
- HVAC systems
- Heated tank systems
- Air-conditioning system (heat exchanger in fridge)
- Steam pressure control system
- Boiler level control system

4.1 Level Control System

Activity 11

1. Let's recall the tank level system with motor-driven valve in Module 1. Make MATLAB programs to simulate this tank level control system with a PID controller;

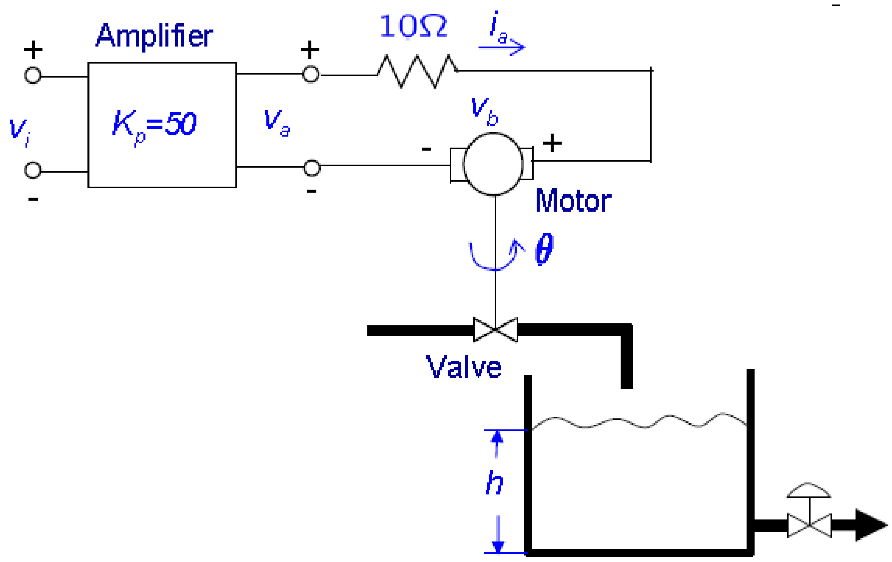


Figure 19 Level control system (as in marine boiler)

Use the following numerical values: $K_m = 10$, $J = 6E\text{-}3\ kgm^2$, and equations in Module 1.
2. Modify the above program/s for the tank below. Suggest a differential pressure level transmitter.

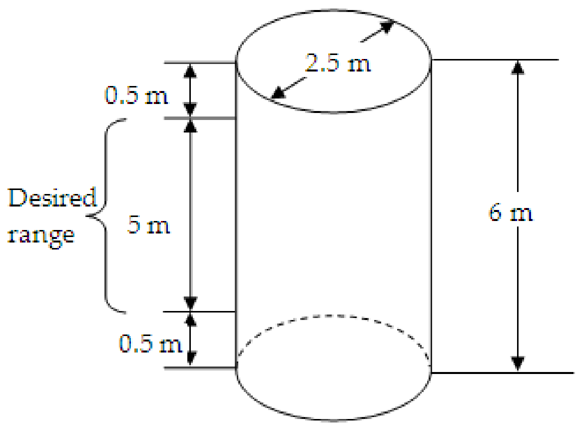


Figure 20 Dimensions of an experimental tank

4.2 Temperature Control System

Activity 12 Temperature control system
Temperature control is required on many marine and offshore systems, for examples, temperature control in the engine room, temperature control in the cooling system, in a refrigeration. In this activity we will model and simulate a room temperature control system. A temperature control system is shown in the following figure.

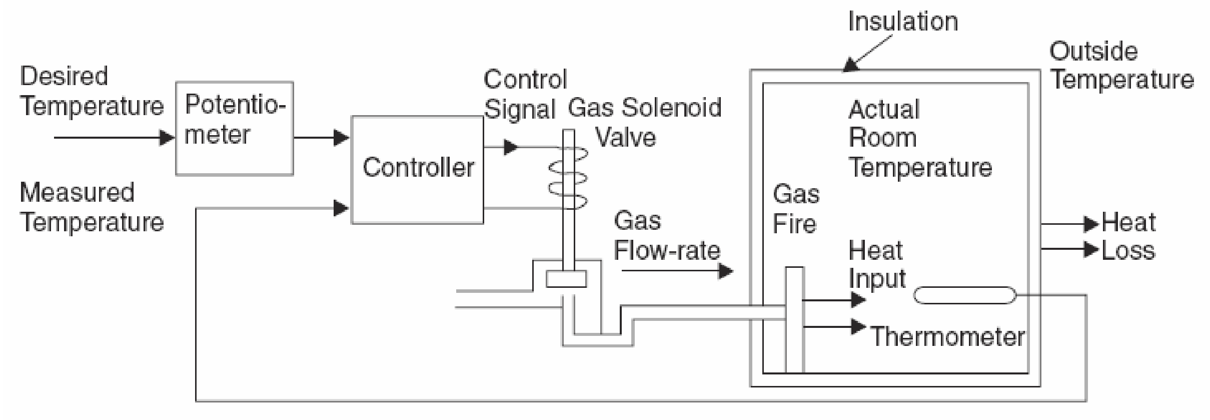


Figure 21 Room temperature control system

The system variables are:

$\theta_d(t)$ = Desired temperature (°C)

$\theta_m(t)$ = Measured temperature (V)

$\theta_o(t)$ = Actual temperature (°C)

$\theta_s(t)$ = Temperature of surroundings (°C)

$u(t)$ = Control signal (v)

$\dot{v}(t)$ = Gas flow-rate (m^3/s)

$Q_i(t)$ = Heat flow into room (J/s = W)

$Q_o(t)$ = Heat flow though walls (W)

System parameters:

$K_2K_3 = 5$ W/V $R_T = 0.1$ °Cs/J

$C_T = 80$ J/°C $H_1 = 1.0$ V/°C

$T_1 = 4$ seconds

Make simulation program/s for the temperature control system.

Summary of Module 6

Module 6 is summarised as follows:

- Marine vehicles;
- Marine electrical systems;
- Marine propulsion system; and
- Other marine systems.

References and Further Reading

Antonelli, G. (2006). *Underwater Robots – Motion and Force Control of Vehicle-Manipulated Systems*, 2nd Edition. Springer.

Bose, N., Lewis, R., Adams, S., 2009, Use of an Explorer class autonomous underwater vehicle for missions under sea ice, 3rd International Conference in Ocean Engineering, ICOE 2009, IIT Madras, Chennai, India. Keynote presentation.

Burcher, R. and L. Rydill (1994). *Concepts in Submarine Design*. Cambridge University Press
Chapman, S.J. (2004). Electric Machinery Fundamentals, Fourth Edition. McGraw-Hill, Inc.
Christ, R.D. and R.L. Wernli Sr (2007). *The ROV Manual – A User Guide for Observation Class Remotely Operated Vehicles*. Butter-Heinemann (Elsevier). Oxford.
Fossen, T.I. (2002). *Marine Control Systems – Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles*. Marine Cybernetics. Trondheim.
Fossen, T.I. (1994). *Guidance and Control of Ocean Vehicles*. John Wiley and Sons, London.
Griffiths, G. (Editor) (2003). *Technology and Applications of Autonomous Underwater Vehicles*. Taylor and Francis.
Groves, P.D. (2008). *GNSS, Inertial, and Multisensor Integrated Navigation Systems*. Artech House.
Hansen, J.F., Adnanes, A.K. and Fossen, T.I. (2001). Mathematical Modelling of Deisel-Electric Propulsion Systems for Marine Vehicles. *Mathematical and Computer Modelling of Dynamic Systems*, Vol. 7, No. 1, pp. 1-33. Swets and Zeitlinger.
Kaushik, S., Chandan, K.S. and Thotakura, S. (2012). Electrically Driven Marine Propulsion. *The Internationl Journal of Engineering Research and Application*. Vol. 2, No. 1, pp. 446-451. www.ijera.com.
Niyomka, P and Binns, JR and Bose, N and Nguyen, HD, 'Modeling, Simulation and Control of a Cyclic and Collective Pitch Propeller for Underwater Vehicles', *Proceedings The 1st Vietnam Conference on Control and Automation*, 25-26 November 2011, Hanoi, Vietnam, pp. 125-132. ISBN 978-604-911-020-7 (2011)
Roberts, G. and R. Sutton (Editors) (2006). *Advances in Unmanned Marine Vehicles*. The Institute of Electrical Engineers.
Sørensen, A.J. (2012). *Marine Control Systems - Propulsion and Motion Control of Ships and Ocean Structures*, Lecture Notes. Department of Marine Technology, Norwegian University of Science and Technology. Trondheim.
Van Amerongen, J. (1982). *Adaptive Steering of Ships – A Model Reference Approach to Improved Manoeuvring and Economical Course Keeping*, PhD Thesis, Delft University of Technology , The Netherlands.
Van Amerongen, J. (1990). Rudder Roll Stabilisation for Ships. *Automatica*, Vol. 26, No. 4, pp. 679-690. Pergamon Press, GB.
http://afscheid.vanamerongen.org/publicaties/. Accessed on 28 August, 2012.
Marine System Simulators website: http://www.marinecontrol.org/

Modelling and Simulation Tools
MATLAB/Simulink: SimHydraulics, SimPowerSystems and SimMechanics
National Instruments LabVIEW and Modules

Appendix Structure of Simulation Program

One simulator may have many M-files among which one file is the main program that should have the following structure:

- Initial values
- System parameters
- Simulation parameters (step size, start time, final time)
- Numerical integration method/s
- Storage of simulated data (solutions)
- Visualisation of simulated data (plotting)