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Mathematical Models of Ships and Underwater Vehicles

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Abstract

This entry describes the equations of motion of ships and underwater vehicles. Standard hydrodynamic models in the literature are reviewed and presented using the nonlinear robot-like vectorial notation of Fossen (Nonlinear Modelling and Control of Underwater Vehicles. PhD Thesis, Dept. of Eng. Cybernetics, Norwegian Univ. of Sci. and Techn, 1991; 1994, Guidance and control of ocean vehicles. Wiley, Chichester; 2011). The matrix-vector notation is highly advantageous when designing control systems since well-known system properties such as symmetry, skew-symmetry, and positiveness can be exploited in the design.

Keywords

Kinematics; Kinetics; Degrees of freedom; Euler angles; Ship; Underwater vehicles; AUV, ROV; Hydrodynamics; Seakeeping; Maneuvering

Introduction

The subject of this entry is mathematical modeling of ships and underwater vehicles. With *ship* we mean "any large floating vessel capable of crossing open waters," as opposed to a boat, which is generally a smaller craft. An *underwater vehicle* is a "small vehicle that is capable of propelling itself beneath the water surface as well as on the water's surface." This includes unmanned underwater vehicles (UUV), remotely operated vehicles (ROV), autonomous underwater vehicles (AUV) and underwater robotic vehicles (URV).

This entry is based on Fossen (1994, 2011), which contains a large number of standard models for ships, rigs, and underwater vehicles. There exist a large number of textbooks on mathematical modeling of ships; see Rawson and Tupper (1994), Lewanddowski (2004), and Perez (2005). For underwater vehicles, see Allmendinger (1990), Sutton and Roberts (2006), Inzartsev (2009), Anotonelli (2010), andWadoo and Kachroo (2010). Some useful references on ship hydrodynamics are Newman (1977), Faltinsen (1991), Bertram (2012).

Degrees of Freedom

A mathematical model of marine craft is usually represented by a set of ordinary differential equations (ODEs) describing the motions in six degrees of freedom (DOF): *surge, sway, heave, roll, pitch*, and *yaw*.

Hydrodynamics

In hydrodynamics it is common to distinguish between two theories:

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- **Seakeeping theory**: The motions of ships at zero or constant speed in waves are analyzed using hydrodynamic coefficients and wave forces, which depends of the wave excitation frequency and thus the hull geometry and mass distribution. For underwater vehicles operating below the wave-affected zone, the wave excitation frequency will not influence the hydrodynamic coefficients.
- **Maneuvering theory**: The ship is moving in restricted calm water – that is, in sheltered waters or in a harbor. Hence, the maneuvering model is derived for a ship moving at positive speed under a zero-frequency wave excitation assumption such that added mass and damping can be represented by constant parameters.

Seakeeping models are typically used for ocean structures and dynamically positioned vessels. Several hundred ODEs are needed to effectively represent a seakeeping model; see Fossen (2011), and Perez and Fossen (2011a, b).

The remaining of this entry assumes *maneuvering theory*, since this gives Lower-order models typically suited for controller-observer design. Six ODEs are needed to describe the *kinematics*, that is, the geometrical aspects of motion while Newton-Euler's equations represent additional six ODEs describing the forces and moments causing the motion (*kinetics*).

Notation

The equations of motion are usually represented using generalized position, velocity and forces (Fossen 1991, 1994, 2011) defined by the state vectors:

$$\boldsymbol{\eta} := [x, y, z, \phi, \theta, \psi]^{\mathrm{T}} \tag{1}$$

$$\boldsymbol{\nu} := [u, v, w, p, q, r]^{\mathrm{T}} \tag{2}$$

$$\boldsymbol{\tau} := [X, Y, Z, K, M, N]^{\mathrm{T}} \tag{3}$$

where $\boldsymbol{\eta}$ is the generalized position expressed in the North-East-Down (NED) reference frame $\{n\}$. A body-fixed reference frame $\{b\}$ with axes:

x_b – longitudinal axis (from aft to fore)
y_b – transversal axis (to starboard)
z_b – normal axis (directed downward)

is rotating about the NED reference frame $\{n\}$ with angular velocity $\boldsymbol{\omega} = [p,q,r]^{\mathrm{T}}$. The generalized velocity vector $\boldsymbol{\nu}$ and forces $\boldsymbol{\tau}$ are both expressed in $\{b\}$, and the 6-DOF states are defined according to (SNAME 1950):

- **Surge** position x, linear velocity u, force X
- **Sway** position y, linear velocity v, force Y
- **Heave** position z, linear velocity w, force Z
- **Roll** angle ϕ, angular velocity p, moment K
- **Pitch** angle θ, angular velocity q, moment M
- **Yaw** angle ψ, angular velocity r, moment N

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Kinematics

The generalized velocities $\dot{\boldsymbol{\eta}}$ and $\boldsymbol{\nu}$ in $\{b\}$ and $\{n\}$, respectively satisfy the following kinematic transformation (Fossen 1994, 2011):

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

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

where $\boldsymbol{\Theta} = [\phi,\theta,\psi]^{\mathrm{T}}$ is the *Euler angles* and

$$\mathbf{R}(\boldsymbol{\Theta}) = \begin{bmatrix} \mathrm{c}\psi\mathrm{c}\theta & -\mathrm{s}\psi\mathrm{c}\phi + \mathrm{c}\psi\mathrm{s}\theta\mathrm{s}\phi & \mathrm{s}\psi\mathrm{s}\phi + \mathrm{c}\psi\mathrm{c}\phi\mathrm{s}\theta \\ \mathrm{s}\psi\mathrm{c}\theta & \mathrm{c}\psi\mathrm{c}\phi + \mathrm{s}\phi\mathrm{s}\theta\mathrm{s}\psi & -\mathrm{c}\psi\mathrm{s}\phi + \mathrm{s}\theta\mathrm{s}\psi\mathrm{c}\phi \\ -\mathrm{s}\theta & \mathrm{c}\theta\mathrm{s}\phi & \mathrm{c}\theta\mathrm{c}\phi \end{bmatrix} \tag{6}$$

with $\mathrm{s}\cdot = \sin(\cdot)$, $\mathrm{c}\cdot = \cos(\cdot)$ and $\mathrm{t}\cdot = \tan(\cdot)$.

The matrix $\mathbf{R}$ is recognized as the Euler angle rotation matrix $\mathbf{R} \in SO(3)$ satisfying $\mathbf{R}\mathbf{R}^{\mathrm{T}} = \mathbf{R}^{\mathrm{T}}\mathbf{R} = \mathbf{I}$, and $\det(\mathbf{R}) = 1$, which implies that $\mathbf{R}$ is orthogonal. Consequently, the inverse rotation matrix is given by: $\mathbf{R}^{-1} = \mathbf{R}^{\mathrm{T}}$. The Euler rates $\dot{\boldsymbol{\Theta}} = \mathbf{T}(\boldsymbol{\Theta})\boldsymbol{\omega}$ are singular for $\theta \neq \pm\pi/2$ since:

$$\mathbf{T}(\boldsymbol{\Theta}) = \begin{bmatrix} 1 & \mathrm{s}\phi\mathrm{t}\theta & \mathrm{c}\phi\mathrm{t}\theta \\ 0 & \mathrm{c}\phi & -\mathrm{s}\phi \\ 0 & \mathrm{s}\phi/\mathrm{c}\theta & \mathrm{c}\phi/\mathrm{c}\theta \end{bmatrix}, \theta \neq \pm\frac{\pi}{2} \tag{7}$$

Singularities can be avoided by using unit quaternions instead (Fossen 1994, 2011).

Kinetics

The rigid-body kinetics can be derived using the *Newton-Euler formulation*, which is based on *Newton's second law*. Following Fossen (1994, 2011) this gives:

$$\mathbf{M}_{RB}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau}_{RB} \tag{8}$$

where $\mathbf{M}_{RB}$ is the rigid-body mass matrix, $\mathbf{C}_{RB}$ is the rigid-body Coriolis and centripetal matrix due to the rotation of $\{b\}$ about the geographical frame $\{n\}$. The generalized force vector $\boldsymbol{\tau}_{RB}$ represents external forces and moments expressed in $\{b\}$. In the nonlinear case:

$$\boldsymbol{\tau}_{RB} = -\boldsymbol{M}_A\dot{\boldsymbol{\nu}} - \mathbf{C}_A(\boldsymbol{\nu})\boldsymbol{\nu} - \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} - \mathbf{g}(\boldsymbol{\eta}) + \boldsymbol{\tau} \tag{9}$$

where the matrices $\mathbf{M}_A$ and $\mathbf{C}_A(\boldsymbol{\nu})$ represent hydrodynamic added mass due to acceleration $\dot{\boldsymbol{\nu}}$ and Coriolis acceleration due to the rotation of $\{b\}$ about the geographical frame $\{n\}$. The potential and viscous damping terms are lumped together into a nonlinear matrix $\mathbf{D}(\boldsymbol{\nu})$ while $\mathbf{g}(\boldsymbol{\eta})$ is a vector of generalized restoring forces. The control inputs are generalized forces given by $\boldsymbol{\tau}$.

Formulae (8) and (9) together with (4) are the fundamental equations when deriving the ship and underwater vehicle models. This is the topic for the next sections.

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Ship Model

The ship equations of motion are usually represented in three DOFs by neglecting *heave, roll* and *pitch*. Combining (4), (8), and (9) we get:

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \tag{10}$$

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau} + \boldsymbol{\tau}_{\text{wind}} + \boldsymbol{\tau}_{\text{wave}} \tag{11}$$

where $\dot{\boldsymbol{\eta}} := [x, y, \psi]^{\mathrm{T}}$, $\boldsymbol{\nu} := [u, v, r]^{\mathrm{T}}$ and

$$\mathbf{R}(\psi) = \begin{bmatrix} \mathrm{c}\psi & -\mathrm{s}\psi & 0 \\ \mathrm{s}\psi & \mathrm{c}\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12}$$

is the rotation matrix in yaw. It is assumed that wind and wave-induced forces $\boldsymbol{\tau}_{\text{wind}}$ and $\boldsymbol{\tau}_{\text{wave}}$ can be linearly superpositioned. The system matrices $\mathbf{M} = \mathbf{M}_{RB} + \mathbf{M}_A$ and $\mathbf{C}(\boldsymbol{\nu}) = \mathbf{C}_{RB}(\boldsymbol{\nu}) + \mathbf{C}_A(\boldsymbol{\nu})$ are usually derived under the assumption of port-starboard symmetry and that surge can be decoupled from sway and yaw (Fossen 2011). Moreover,

$$\mathbf{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{13}$$

$$\mathbf{C}_{RB}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & -mr & -mx_g r \\ mr & 0 & 0 \\ mx_g r & 0 & 0 \end{bmatrix} \tag{14}$$

$$\mathbf{C}_A(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & Y_{\dot{v}}v + Y_{\dot{r}}r \\ 0 & 0 & -X_{\dot{u}}u \\ -Y_{\dot{v}}v + Y_{\dot{r}}r & X_{\dot{u}}u & 0 \end{bmatrix} \tag{15}$$

Hydrodynamic damping will, in its simplest form, be linear:

$$\mathbf{D} = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_u & -Y_r \\ 0 & -N_r & -N_r \end{bmatrix} \tag{16}$$

while a nonlinear expression based on second-order modulus functions describing quadratic drag and cross-flow drag is:

$$\mathbf{D}(\boldsymbol{\nu}) = \begin{bmatrix} -X_{|u|u}|u| & 0 & 0 \\ 0 & -Y_{|v|v}|u| - Y_{|r|v}|r| & -Y_{|v|r}|u| - Y_{|r|r}|r| \\ 0 & -N_{|v|v}|u| - N_{|r|v}|r| & -N_{|v|r}|u| - N_{|r|r}|r| \end{bmatrix} \tag{17}$$

Other nonlinear representations are found in Fossen (1994, 2011).

In the case of *irrotational ocean currents*, we introduce the relative velocity vector:

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$$\boldsymbol{\nu}_r = \boldsymbol{\nu} - \boldsymbol{\nu}_c$$

where $\boldsymbol{\nu}_c = [u_c^b, v_c^b, 0]^{\mathrm{T}}$ is a vector of current velocities in $\{b\}$. Hence, the kinetic model takes the form:

$$\underbrace{\mathbf{M}_{RB}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu}}_{\text{rigid-body forces}} + \underbrace{\mathbf{M}_A\dot{\boldsymbol{\nu}}_r + \mathbf{C}_A(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathrm{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r}_{\text{hydrodynamic forces}} = \boldsymbol{\tau} + \boldsymbol{\tau}_{\text{wind}} + \boldsymbol{\tau}_{\text{wave}}$$

This model can be simplified if the *ocean currents* are assumed to be *constant* and *irrotational* in $\{n\}$. According to (Fossen 2011, Property 8.1), $\mathbf{M}_{RB}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} \equiv \mathbf{M}_{RB}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r$ if the rigid-body Coriolis and centripetal matrix satisfies $\mathbf{C}_{RB}(\boldsymbol{\nu}_r) = \mathbf{C}_{RB}(\boldsymbol{\nu})$. One parameterization satisfying this is (14). Hence, the Coriolis and centripetal matrix satisfies $\mathbf{C}(\boldsymbol{\nu}_r) = \mathbf{C}_{RB}(\boldsymbol{\nu}_r) + \mathbf{C}_A(\boldsymbol{\nu}_r)$ and it follows that:

$$\mathbf{M}\dot{\boldsymbol{\nu}}_r + \mathbf{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathrm{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r = \boldsymbol{\tau} + \boldsymbol{\tau}_{\text{wind}} + \boldsymbol{\tau}_{\text{wave}} \tag{18}$$

The kinematic equation (10) can be modified to include the relative velocity $\boldsymbol{\nu}_r$ according to:

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu}_r + \left[u_c^n, v_c^n, 0\right]^{\mathrm{T}} \tag{19}$$

where the ocean current velocities $u_c^n = constant$ and $u_c^n = constant$ in $\{n\}$. Notice that the body-fixed velocities $\boldsymbol{\nu}_c = \mathbf{R}(\psi)^{\mathrm{T}}[u_c^n, v_c^n, 0]^{\mathrm{T}}$ will vary with the heading angle ψ.

The maneuvering model presented in this entry is intended for controller-observer design, prediction, and computer simulations, as well as system identification and parameter estimation. A large number of application-specific models for marine craft are found in Fossen (2011, Chapter 7).

Hydrodynamic programs compute mass, inertia, potential damping and restoring forces while a more detailed treatment of viscous dissipative forces (damping) and sealoads are found in the extensive literature on hydrodynamics – see Faltinsen (1990) and Newman (1977).

Underwater Vehicle Model

The 6-DOF underwater vehicle equations of motion follow from (4), (8), and (9) under the assumption that wave-induced motions can be neglected:

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{20}$$

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} \tag{21}$$

with generalized position $\boldsymbol{\eta} := \left[x, y, z, \phi, \theta, \psi\right]^{\mathrm{T}}$ and velocity $\boldsymbol{\nu} := [u, v, w, p, q, r]^{\mathrm{T}}$. Assume that the gravitational force acts through the center of gravity (CG) defined by the vector $\mathbf{r}_g := [x_g, y_g, z_g]^{\mathrm{T}}$ with respect to the coordinate origin $\{b\}$. Similarly, the buoyancy force acts through the center of buoyancy (CB) defined by the vector $\mathbf{r}_b := [x_b, y_b, z_b]^{\mathrm{T}}$. For most vehicles $y_g = y_b = 0$.

For a port-starboard symmetrical vehicle with homogenous mass distribution, CG satisfying $y_g = 0$ and products of inertia $I_{xy} = I_{yz} = 0$, the system inertia matrix becomes:

$$\mathbf{M} := \begin{bmatrix} m - X_{\dot{u}} & 0 & -X_{\dot{w}} & 0 & mz_g - X_{\dot{q}} & 0 \\ 0 & m - Y_{\dot{v}} & 0 & -mz_g - Y_{\dot{p}} & 0 & mx_g - Y_{\dot{r}} \\ -X_{\dot{w}} & 0 & m - Z_{\dot{w}} & 0 & -mx_g - Z_{\dot{q}} & 0 \\ 0 & -mz_g - Y_{\dot{p}} & 0 & I_x - K_{\dot{p}} & 0 & -I_{zx} - K_{\dot{r}} \\ mz_g - X_{\dot{q}} & 0 & -mx_g - Z_{\dot{q}} & 0 & I_y - M_{\dot{q}} & 0 \\ 0 & mx_g - X_{\dot{r}} & 0 & -I_{zx} - K_{\dot{r}} & 0 & I_z - N_{\dot{r}} \end{bmatrix} \tag{22}$$

where the hydrodynamic derivatives are defined according to SNAME (1950). The Coriolis and centripetal matrices are:

$$\mathbf{C}_A(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & 0 & 0 & -a_3 & a_2 \\ 0 & 0 & 0 & a_3 & 0 & -a_1 \\ 0 & 0 & 0 & -a_2 & a_1 & 0 \\ 0 & -a_3 & a_2 & 0 & -b_3 & b_2 \\ a_3 & 0 & -a_1 & b_3 & 0 & -b_1 \\ -a_2 & a_1 & 0 & -b_2 & b_1 & 0 \end{bmatrix} \tag{23}$$

where

$$\begin{aligned} a_1 &= X_{\dot{u}}u + X_{\dot{w}}w + X_{\dot{q}}q \\ a_2 &= Y_{\dot{v}}v + Y_{\dot{p}}p + Y_{\dot{r}}r \\ a_3 &= Z_{\dot{u}}u + Z_{\dot{w}}w + Z_{\dot{q}}q \\ b_1 &= K_{\dot{v}}v + K_{\dot{p}}p + K_{\dot{r}}r \\ b_2 &= M_{\dot{u}}u + M_{\dot{w}}w + M_{\dot{q}}q \\ b_3 &= N_{\dot{v}}v + N_{\dot{p}}p + N_{\dot{r}}r \end{aligned} \tag{24}$$

and

$$\mathbf{C}_{RB}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & -mr & mq & mz_gr & -mx_gq & -mx_gr \\ mr & 0 & -mp & 0 & m(z_gr + x_gp) & 0 \\ -mq & mp & 0 & -mz_gp & -mz_gq & mx_gp \\ -mz_gr & 0 & mz_gp & 0 & -I_{xz}p + I_zr & -I_yq \\ mx_gq & -m(z_gr + x_gp) & mz_gq & I_{xz}p - I_zr & 0 & -I_{xz}r + I_zp \\ mx_gr & 0 & -mx_gp & I_yq & I_{xz}r - I_xp & 0 \end{bmatrix} \tag{25}$$

Notice that this representation of $\mathbf{C}_{RB}(\boldsymbol{\nu})$ only depends on the angular velocities p, q, and r, and not the linear velocities u,v, and r. This property will be exploited when including drift due to ocean currents.

Linear damping for a port-starboard symmetrical vehicle takes the following form:

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$$\mathbf{D} = -\begin{bmatrix} X_u & 0 & X_w & 0 & X_q & 0 \\ 0 & Y_u & 0 & Y_p & 0 & Y_r \\ Z_u & 0 & Z_w & 0 & Z_q & 0 \\ 0 & K_u & 0 & K_p & 0 & K_r \\ M_u & 0 & M_w & 0 & M_q & 0 \\ 0 & N_v & 0 & N_p & 0 & N_r \end{bmatrix} \tag{26}$$

Let $W = mg$ and $B = \rho g \nabla$ denote the weight and buoyance where m is the mass of the vehicle including water in free floating space, ∇ the volume of fluid displaced by the vehicle, g the acceleration of gravity (positive downward), and ρ the water density. Hence, the generalized restoring forces for a vehicle satisfying $y_g = y_b = 0$ becomes (Fossen 1994, 2011):

$$\mathbf{g}(\boldsymbol{\eta}) = \begin{bmatrix} (W - B)s\theta \\ -(W - B)c\theta s\phi \\ -(W - B)c\theta c\phi \\ \left(z_g W - z_b B\right)c\theta s\phi \\ \left(z_g W - z_b B\right)s\theta + \left(x_g W - x_b B\right)c\theta c\phi \\ -\left(x_g W - x_b B\right)c\theta s\phi \end{bmatrix} \tag{27}$$

The expression for $\mathbf{D}$ can be extended to include nonlinear damping terms if necessary. Quadratic damping is important at higher speeds since the Coriolis and centripetal terms $\mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu}$ can destabilize the system if only linear damping is used.

In the presence of irrotational ocean currents, we can rewrite (20) and (21) in terms of relative velocity $\boldsymbol{\nu}_r = \boldsymbol{\nu} - \boldsymbol{\nu}_c$ according to:

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\nu}_r + \left[u_c^n, v_c^n, w_c^n, 0, 0, 0\right]^{\mathrm{T}} \tag{28}$$

$$\mathbf{M}\dot{\boldsymbol{\nu}}_r + \mathbf{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathbf{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} \tag{29}$$

where it is assumed that $\mathbf{C}_{RB}(\boldsymbol{\nu}_r) = \mathbf{C}_{RB}(\boldsymbol{\nu})$, which clearly is satisfied for (25). In addition, it is assumed that u_c^n, v_c^n, and w_c^n are constant. For more details see Fossen (2011).

Programs and Data

The Marine Systems Simulator (MSS) is a MATLAB/Simulink library and simulator for marine craft (http://www.marinecontrol.org). It includes models for ships, underwater vehicles, and floating structures.

Summary and Future Directions

This entry has presented standard models for simulation of ships and underwater vehicles. It is recommended to consult Fossen (1994, 2011) for a more detailed description of marine craft hydrodynamics.

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Cross-References

- ► Control of Ship Roll Motion
- ► Cooperative Control of Autonomous Surface and Underwater Vehicles
- ► DP (Dynamic Positioning) Control Systems for Ships and AUVs
- ► Underactuated Marine Control Systems

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