Submarine Hydrodynamics

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This book is dedicated to my wonderful wife, Susan, who has looked after me when I have been ill. She has also been a great support and has assisted with the arrangement of the manuscript. I would not have managed to have completed this without her.

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Martin Renilson

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About the Author

Martin Renilson (Prof.) has been working in the field of Ship Hydrodynamics for over 35 years. He established the Ship Hydrodynamics Centre at the Australian Maritime College (AMC) in 1983 and was Director of the Australian Maritime Engineering Cooperative Research Centre in 1992. He started the Department of Naval Architecture & Ocean Engineering at AMC in 1996, which he ran until 2001 when he was appointed Technical Manager, Maritime Platforms & Equipment for DERA/QinetiQ in the UK.

In 2007, he returned to Australia and set up his own company, conducting maritime-related consulting. He also held a part-time chair in hydrodynamics at AMC, now an institute of the University of Tasmania.

In 2012, he was appointed inaugural Dean of Maritime Programs at the Higher Colleges of Technology, United Arab Emirates, to start maritime education for the country. He retired from this position in November 2015 and returned to Tasmania.

He holds the position of Adjunct Professor in Hydrodynamics at the University of Tasmania, Australia and is President of the Australian Division of the Royal Institution of Naval Architects.

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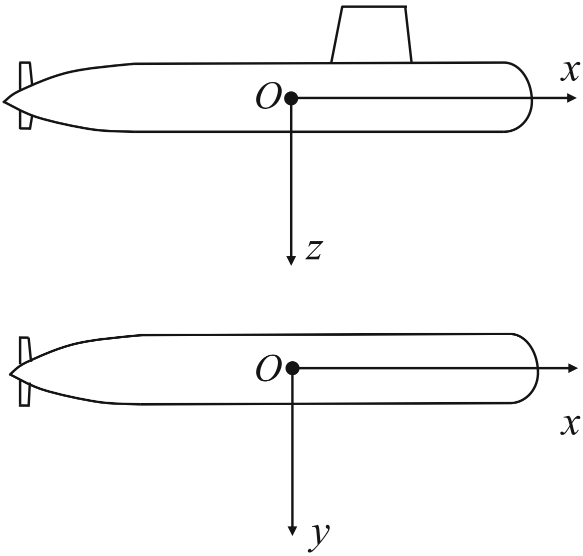
Nomenclature and Abbreviations

Notes

1. Where possible, the notation used for manoeuvring is the same as that given by Gertler and Hagen (1967), however much of that is repeated here for completeness.
2. The body-fixed axis system is given in the figure below. The origin, *O*, is taken on the centreline at the position of the longitudinal centre of gravity of the submarine. The positive linear distances, velocities, accelerations and forces are all in the positive direction of the relevant axes, and the positive rotational values are all in the clockwise direction looking along the positive direction of the axes from the origin.
3. The prime notation is used for non-dimensionalisation, where non-dimensional quantities are denoted by a dash, as with: X', indicating the non-dimensional form of the force in the longitudinal axis, *X*. Unless otherwise stated, non-dimensionalisation is achieved by dividing the quantity by ½ density of water times length and velocity to the required powers.
4. Coefficients of forces and moments when manoeuvring are denoted by subscripts referring to the velocities and accelerations which the relevant force, or moment, is a function of. For example, Y_v denotes the first-order coefficient used in representing the sway force, *Y*, as a function of sway velocity, *v*. This is the partial derivative of the sway force, *Y*, with respect to sway velocity, *v*.
5. Differentiation with respect to time is denoted by a dot above the variable. For example, $\dot{v}$ is the derivative of sway velocity with respect to time—the sway acceleration.
6. Nonlinear coefficients of forces and moments, and those due to coupling, are represented by the relevant subscripts. For example, the nonlinear coefficient of sway force, *Y*, as a function of sway velocity, *v*, is represented by: $Y_{v|v|}$. Note that in this case the modulus of the sway velocity is used because the function is an odd function.

7. Where possible, the notation used is that commonly used for the topic being discussed. Thus, in some cases, the same quantity is defined by different symbols in different chapters.
8. For brevity, where symbols are only used in one location in the text and are clearly defined there, then these are not always defined in the notation.



Axis system

Symbols

$A_{frontal}$	Sail frontal area
A_F	Fore body frontal area
A_m	Submarine midships cross-sectional area
A_{plan}	Plan area of appendage
A_{wind}	Profile windage area above the waterline
a	Chord of flat plate
a_i, b_i, c_i	Coefficients used to represent the resistance of the submarine in the x-axis
B	Upward force due to the buoyancy = $\nabla \rho g$
B	Position of centre of buoyancy
B_F	Position of centre of buoyancy of form displacement

BG	Distance between the centre of buoyancy and the centre of gravity
BG_F	Distance between the centre of buoyancy and the centre of gravity corrected for free surface
B_H	Position of centre of buoyancy of hydrostatic displacement
BM	Distance between the centre of buoyancy and the metacentre
B_p	Propulsor loading coefficient
b	Span of flat plate
bg	Vertical upward force through the centre of buoyancy
C_A	Correlation allowance
C_D	Non-dimensional drag coefficient at zero angle of attack
C_{D_α}	Non-dimensional slope of drag as a function of angle of attack
C_F	Non-dimensional friction resistance coefficient = $R_F/\left(\frac{1}{2}\rho SV^2\right)$
$C_{F_{flat}}$	Non-dimensional flat plate frictional resistance = $R_{F_{flat}}/\left(\frac{1}{2}\rho SV^2\right)$
$C_{F_{form}}$	Non-dimensional frictional resistance including frictional-form resistance = $R_{F_{form}}/\left(\frac{1}{2}\rho SV^2\right)$
C_{L_α}	Non-dimensional slope of lift as a function of angle of attack
$C_{L_{\delta B}}$, $C_{L_{\delta R}}$, $C_{L_{\delta S}}$	Non-dimensional slope of the lift as a function of deflection angle for the bow plane, the rudder and the stern plane, respectively
$\mathrm{C_p}$	Prismatic coefficient = $\nabla\ /\mathrm{A_m}L$
C_p	Non-dimensional pressure drag = $R_P/\left(\frac{1}{2}\rho SV^2\right)$
C_p	Pressure coefficient
$C_{p_{fb}}$	Non-dimensional pressure drag on fore body
C_R	Non-dimensional residual resistance coefficient
C_T	Total resistance coefficient
c_{sail}	Chord of sail
D	Hull diameter
D	Propulsor diameter
D_{local}	Local diameter at element of propulsor
D_C	Distortion coefficient
$\bar{d}$	Diameter of equivalent ellipsoid of revolution
d_T	Diameter of the trip wire
F_D	Skin friction correction force
F_r	Froude number = $V/\sqrt{gL}$
G	Position of centre of gravity
G_F	Position of centre of gravity corrected for free surface
G_F	Position of centre of gravity of form displacement
G_H	Position of centre of gravity of hydrostatic displacement
GM	Distance between the centre of gravity and the metacentre
G_FM	Distance between the centre of gravity corrected for the free surface and the metacentre

GZ_{Max}	Maximum value of the righting lever
G_H	Stability index in the horizontal plane
G_V	Stability index in the vertical plane
g	Acceleration due to gravity
h	Vertical distance between the windage surface centre and the driftage surface centre
H	Distance from the water surface to the centreline of the submarine
H^*	Non-dimensional distance from the water surface to the centreline of the submarine = H/D
H^*	Coefficient values for use with Sen Sensitivity Index
$H_{1/3}$	Significant wave height
I	Second moment of area of the waterplane around the longitudinal axis
I_{xx}, I_{yy}, I_{zz}	Mass moments of inertia about the *x*-axis, the *y*-axis and the *z*-axis, respectively
I_{xy}, I_{yx}, I_{zx}	Products of inertia about *xy*, *yx* and *zx*, respectively
I'_{yy} and I'_{zz}	Non-dimensional moments of inertia in pitch and yaw, respectively
J	Propeller advance coefficient
J_T	Propeller advance coefficient achieved by the thrust identity method
J_Q	Propeller advance coefficient achieved by the torque identity method
K	Position of the keel
K_0, K_1	Coefficients used to define aft body of Suboff
K, M, N	Moments about the *x*-axis, the *y*-axis and the *z*-axis, respectively
K', M', N'	Non-dimensional moments about the *x*-axis, the *y*-axis and the *z*-axis, respectively = moment/($\frac{1}{2}\rho V^2 L^3$)
K_a	Coefficient of added mass
KB	Distance between the keel and the centre of buoyancy
KB_F	Distance between the keel and the centre of buoyancy of the form displacement
K_c	Casing factor
KG_F	Distance between the keel and the centre of gravity of the form displacement
KG_F	Distance between the keel and the centre of gravity corrected for free surface
KM	Distance between the keel and the metacentre
K_P	Ratio of pressure resistance to friction resistance
K_Q	Propeller torque coefficient = $Q/\rho D^5 n^2$
K_{QM}	Propeller torque coefficient measured on self-propelled model

K_{QT}	Propeller torque coefficient obtained by the thrust identity method
K_T	Propeller thrust coefficient = $T/\rho D^4 n^2$
K_{Ty}	Non-dimensional side force from the propeller
K_{TQ}	Propeller thrust coefficient obtained by the torque identity method
$K_{Q_{(J=0)}}$	Value of the torque coefficient for $J = 0$
K_{TM}	Propeller thrust coefficient measured on self-propelled model
$K'_{\delta X_i}, M'_{\delta X_i}, N'_{\delta X_i}$	Non-dimensional coefficient of moment due to the angle of appendage X_i about the x-axis, y-axis and z-axis, respectively
$K'_*, M'_*, N'_*, Y'_*, Z'_*$	Non-dimensional roll moment, pitch moment, yaw moment, sway force and heave force, respectively, when the submarine is travelling at steady state with $p = q = r = v = w = 0$ and no appendage deflection angles
k_s	Sail efficiency factor
k_{sp}	Sail plane efficiency factor
k_{WB}	Stern plane efficiency factor
k_x, k_y, k_z	Added mass coefficients for motion in the x, y, and z directions, respectively
L	Length
L_A	Length of aft body
Lbp	Length between perpendiculars
L_F	Length of fore body
Loa	Length overall
L_{PMB}	Length of parallel middle body
l_{app}	Horizontal coordinate of the centre of pressure, or centre of added mass, of an appendage
l_w	Wind heeling lever
M	Position of the metacentre
M_{in}, M_{out}	In-phase and out-of-phase components, respectively, of the measured pitch moment during a PMM test
M_{MEAN}	Mean pitch moment in waves
M'_{MEAN}	Non-dimensional mean pitch moment in waves = $M_{MEAN}/\rho g L D \zeta_w^2$
$M_m(t), Z_m(t)$	Measured pitch moment and heave force as a function of time
M_{RAO}	First–order pitch moment response amplitude operator
M'_{RAO}	Non-dimensional first-order pitch moment response amplitude operator = $M_{RAO}/\rho g L^2 D \zeta_w$
$M_{w_{app}}, M_{q_{app}}$	Rate of change of moment about the y-axis on an appendage as a function of heave velocity and pitch velocity, respectively
m	Mass of the submarine
m_{added}	Added mass

m'	Non-dimensional mass = m/(½ρL^3)
mg	Vertical downward force through the centre of gravity
N	Propulsor rate of rotation (revolutions per minute)
N_{in}, N_{out}	In-phase and out-of-phase components, respectively, of the measured yaw moment during a PMM test
$N_{v_{app}}, N_{r_{app}}$	Rate of change of moment about the z-axis on an appendage as a function of sway velocity and yaw velocity, respectively
n	Propulsor rate of rotation (revolutions per second)
n	Power for fineness factor (Eq. 4.19)
n_{PMB}	Power for parallel middle body factor (Eq. 4.19)
n_f	Coefficient defining the fullness of the fore body
O	Position of the origin
P	External vertical force due to grounding or contact with ice
P_B	Brake power (from engine)
P_E	Effective power
P_S	Shaft power
P_T	Thrust power
p, q, r	Angular velocities about the x-axis, the y-axis and the z-axis, respectively
$\dot{p}, \dot{q}, \dot{r}$	Angular accelerations about the x-axis, the y-axis and the z-axis, respectively
p', q', r'	Non-dimensional angular velocities about the x-axis, the y-axis and the z-axis, respectively = angular velocity $\times L/V$
Q	Torque on propeller
Q_M	Propeller torque in self-propulsion test
R	Radius of turning circle
R^*	Manoeuvring response parameter for use with Sen Sensitivity Index
$R_{control\,surface}$	Drag of control surface
R_e	Reynolds number = VL/ν
$R_{F_{flat}}$	Friction resistance of a flat plate
$R_{F_{form}}$	Frictional resistance including frictional-form resistance
R_P	Form drag
$R_{sail_{form}}$	Form drag of sail
R_T	Total resistance
r	Radius
r_h	Coefficient used in definition of Suboff aft body
r_{x_f}	Radius of the section of the fore body at a distance x_f from the rearmost part of the fore body
S	Wetted surface area
S	Sen Sensitivity Index
S_a	Planform area of lifting surface

S_{hull}	Wetted surface of submarine hull
S_{sail}	Wetted surface of sail
T	Thrust of propulsor
T_0	Wave modal period
T_M	Propeller thrust in self-propulsion test
t	Thrust deduction fraction
t	Time
t_{sail}	Thickness of sail
U_1	Streamwise velocity at the edge of the boundary layer
U_∞	Nominal streamwise velocity
u, v, w	Velocities in the x, y and z directions, respectively
$\dot{u}$, $\dot{v}$, $\dot{w}$	Accelerations in the x, y and z directions, respectively
u', v', w'	Non-dimensional velocities in the x, y and z directions, respectively = velocity/V
u_{aB}, u_{aR}, u_{aS}	Axial velocity at the bow plane, the rudder and the stern plane, respectively
u_c	Steady-state velocity in the x-axis at the set propeller rpm when the submarine has only velocity in the x-axis and has no control surfaces deflected
V	Velocity
V_a	Velocity of advance of the propulsor
V_B, V_R, V_S	Velocity at the bow plane, the rudder and the stern plane, respectively
$V_{B_{eff}}$, $V_{R_{eff}}$, $V_{S_{eff}}$	Effective velocity at the bow plane, the rudder and the stern plane, respectively
V_{eff}	Effective velocity (general)
V_{wind}	Wind speed (in knots)
V_θ	Local tangential velocity into the propulsor blade
V^*	Local axial velocity into the propulsor blade
v_R	Sway velocity at the rudder (uncorrected for the presence of the hull)
W	Downward force due to the mass = Δg
WOF	Wake Objective Function
w	Taylor wake fraction
$\bar{w}$	Average wake fraction at a given radius
w_Q	Taylor wake fraction obtained by the torque identity method
w_T	Taylor wake fraction obtained by the thrust identity method
$w_B w_s$	Heave velocity at the bow plane and stern plane, respectively (uncorrected for the presence of the hull)
X , Y, Z	Forces in the x-axis, y-axis and z-axis, respectively
$X,'$ Y', Z'	Non-dimensional forces in the x-axis, y-axis and z-axis, respectively = force/($\frac{1}{2}\rho V^2 L^2$)

$X'_{\delta X \delta X_i}$, $Y'_{\delta X_i}$, $Z'_{\delta X_i}$	Non-dimensional coefficient of force due to the angle of appendage X_i in the x-axis, y-axis and z-axis, respectively
x, y, z	Coordinates in the x-axis, y-axis and z-axis, respectively
x_A	Distance in the x direction aft of the forward most part of the aft body
x_B, y_B, z_B	Coordinates of the centre of buoyancy in the x-axis, y-axis and z-axis, respectively
x_{bow}, x_{rudder}, x_{stern}	x coordinate of the bow plane, the rudder and the stern plane, respectively
x_{CLR}	x coordinate of the position of the Centre of Lateral Resistance
x_{CP}	x coordinate of the position of the Critical Point
x_f	Distance in the x direction forward of the rearmost part of the fore body
x_{SUBOFF}	Distance in the x direction aft of the forward perpendicular (used for the definition of the shape of the DARPA Suboff)
x_G, y_G, z_G	Coordinates of the centre of gravity in the x-axis, y-axis and z-axis, respectively
x'_G	Non-dimensional x coordinate of the position of the centre of gravity = x_G/L
x_{NP}	x coordinate of the position of the Neutral Point
Y_{in} Y_{out}	In-phase and out-of-phase components, respectively, of the measured sway force during a PMM test
Y_r, Y_v, Z_q, Z_w	First-order coefficients of force as functions of velocities (q, r, v, and w)
$Y_{v_{app}}$, $Y_{r_{app}}$	Rate of change of force in the y-axis on an appendage as a function of sway velocity and yaw velocity, respectively
$Y'_{\dot{v}_{app}}$	Contribution of an appendage to the non-dimensional sway added mass coefficient
y_0, z_0	Amplitude of oscillation in the y-axis and z-axis, respectively, during PMM tests
Z_{in}, Z_{out}	In-phase and out-of-phase components, respectively, of the measured heave force during a PMM test
Z_{MEAN}	Mean heave force in waves
Z'_{MEAN}	Non-dimensional mean heave force in waves = $Z_{MEAN}/\rho g L \zeta_w^2$
Z_{RAO}	First-order heave force response amplitude operator
Z'_{RAO}	Non-dimensional first-order heave force response amplitude operator = $Z_{RAO}/\rho g L^2 \zeta_w$
$Z_{w_{app}}$, $Z_{q_{app}}$	Rate of change of force in the z-axis on an appendage as a function of heave velocity and pitch velocity, respectively
$Z'_{\dot{w}_{app}}$	Contribution of an appendage to the non-dimensional heave added mass coefficient
α	Angle of attack

α_t	Half tailcone angle
β	Angle of flow into propeller blade
$\gamma_B, \gamma_R, \gamma_S$	Flow straightening effect of the presence of the submarine hull for the bow plane, the rudder and the stern plane, respectively
δ	Appendage deflection angle
δ_B, δ_R, δ_S	Deflection angle of the bow plane, the rudder and the stern plane, respectively
$\delta_{B_{eff}}, \delta_{R_{eff}}, \delta_{S_{eff}}$	Effective bow plane angle, rudder angle and stern plane angle, respectively
δ_0	Amplitude of rudder angle oscillation in zigzag manoeuvre
Δ	Displacement
ΔC_F	Roughness allowance
Δ_F	Form displacement
Δ_H	Hydrostatic displacement
ζ_w	Wave height
η	Ratio of self-propulsion velocity for set value of rpm to actual velocity
η	Propeller efficiency
η_B	Efficiency of propeller when behind the submarine
η_H	Hull efficiency: ratio of effective power to thrust power
η_O	Open water propeller efficiency
η_R	Relative rotative efficiency
η_{RQ}	Relative rotative efficiency obtained by the torque identity method
η_{RT}	Relative rotative efficiency obtained by the thrust identity method
η_Q	Propeller efficiency obtained by the torque identity method
η_T	Propeller efficiency obtained by the thrust identity method
θ	Pitch angle
$\theta_0\ \psi_0$	Amplitude of oscillation about the *y*-axis and *z*-axis, respectively, during PMM tests
θ_0	Angle of heel under the action of a steady wind
θ_1	Angle of roll to windward due to wave action
θ_2	Angle of downflooding (θ_F) or 50°, whichever is less
θ_c	Angle of the second intercept between the wind heeling lever (l_{w2}) and the righting lever
θ_F	Angle of downflooding
v	Kinematic viscosity
ξ_{PMB}	Parallel middle body factor
ξ_{hull}	Hull form factor
ρ	Density of water
τ	Trim angle
ϕ	Roll angle/heel angle

ψ	Drift angle and heading angle
ψ_0	Amplitude of heading angle used for zigzag manoeuvre
ω	Frequency of oscillation
∇	Immersed volume

Abbreviations

ACS	Aft Control Surface(s)
AMC	Australian Maritime College, an Institute of The University of Tasmania
ATT	Aft Trim Tank
CFD	Computational Fluid Dynamics
CIS	Cavitation Inception Speed
CLR	Centre of Lateral Resistance
COTS	Commercial Off-The-Shelf
DARPA	Defence Advanced Research Projects Agency (US)
DDD	Deep Dive Depth
DERA	Defence, Evaluation and Research Agency, UK
DES	Detached Eddy Simulation
DGA	Direction Générale de l'Armement, the French Government Defence procurement agency
DRDC	Defence Research and Development Canada
DREA	Defence Research Establishment Atlantic
DST Group	Defence Science and Technology Group, Australia (formerly DSTO)
DSTO	Defence Science and Technology Organisation, Australia (now DST Group)
FCS	Forward Control Surface(s)
FSC	Free Surface Correction
FTT	Forward Trim Tank
GRP	Glass Reinforced Plastic
HPMM	Horizontal Planar Motion Mechanism
IHSS	Iranian Hydrodynamic Series of Submarines
IMO	International Maritime Organisation
ITTC	International Towing Tank Conference
LCB	Position of the Longitudinal Centre of Buoyancy
LCG	Position of the Longitudinal Centre of Gravity
LES	Large Eddy Simulation
MBT	Main Ballast Tank
MDTF	Marine Dynamics Test Facility
MED	Maximum Excursion Depth
MLD	Manoeuvring Limitation Diagram

NACA	National Advisory Committee for Aeronautics
PMB	Parallel Middle Body
PMM	Planar Motion Mechanism
QPC	Quasi-Propulsive Coefficient
RANS	Reynolds Averaged Navier–Stokes
RNLN	Royal Netherlands Navy
rpm	Revolutions Per Minute
SME	Safe Manoeuvring Envelope
SOE	Safe Operating Envelope
SOP	Standard Operating Procedure
SSBN	Nuclear-Powered Ballistic Submarine
SSK	Conventionally Powered Submarine
SSN	Nuclear-Powered Attack Submarine
SSPA	Swedish maritime consulting organisation
VPMM	Vertical Planar Motion Mechanism
WOF	Wake Objective Function