HYDRODYNAMICS OF HIGH-SPEED MARINE VEHICLES

Hydrodynamics of High-Speed Vehicles discusses the three main categories of high-speed marine vehicles, vessels supported by submerged hulls, air cushions, or foils. The wave environment, resistance, propulsion, seakeeping, sea loads, and maneuvering are extensively covered based on rational and simplified methods. Links to automatic control and structural mechanics are emphasized. A detailed description of waterjet propulsion is given, and the effect of water depth on wash, resistance, sinkage, and trim is discussed. Chapter topics include resistance and wash; slamming; air cushion–supported vessels, including a detailed discussion of wave-excited resonant oscillations in air cushion; and hydrofoil vessels. The book contains numerous illustrations, examples, and exercises.

Odd M. Faltinsen received his Ph.D. in naval architecture and marine engineering from the University of Michigan in 1971 and has been a Professor of Marine Hydrodynamics at the Norwegian University of Science and Technology since 1974. Dr. Faltinsen has experience with a broad spectrum of hydrodynamically related problems for ships and sea structures, including hydroelastic problems and slamming. He has published more than 200 scientific papers, and his textbook *Sea Loads on Ships and Offshore Structures*, published by Cambridge University Press in 1990, is used at universities worldwide.

Hydrodynamics of High-Speed Marine Vehicles

ODD M. FALTINSEN
Norwegian University of Science and Technology

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
40 West 20th Street, New York, NY 10011-4211, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521845687

First published 2005

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Faltinsen, O. M. (Odd Magnus), 1944–
Hydrodynamics of high-speed marine vehicles / Odd M. Faltinsen.
p. cm.
Includes bibliographical references and index.
ISBN 0-521-84568-8 (hardback)
1. Motorboats. 2. Ships – Hydrodynamics. 3. Hydrodynamics. 4. Hydrofoil boats. I. Title.
VM341.F35 2005
623.8′1231 – dc22 2005006328

ISBN-13 978-0-521-84568-7 hardback
ISBN-10 0-521-84568-8 hardback

Contents

Preface

Writing a book on the hydrodynamics of high-speed marine vehicles was challenging because I have had to cover all areas of traditional marine hydrodynamics, resistance, propulsion, seakeeping, and maneuvering. However, there is a need to combine all aspects of hydrodynamics in the design of which high-speed vessels are very different from conventional ships, depending on whether they are hull supported, air cushion supported, foil supported, or hybrids.

High-speed vessels are a fascinating topic, and I have been deeply involved in research on high-speed vessels since a national research program under the leadership of Kjell Holden started in Norway in 1989. We also started the International Conference on Fast Sea Transportation (FAST), which has a much broader scope than marine hydrodynamics. I have also benefited from being the chairman of the Committee of High-Speed Marine Vehicles of the International Towing Tank Conference (ITTC) from 1990 to 1993. Further, this book would not have been possible without the work done by the many doctoral students who I have supervised. Their theses are referenced in the book. Parts of the book have been taught to the fourth year, master of science students and doctoral students at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU).

My philosophy in writing the book has been to start from basic fluid dynamics and to link this to practical issues for high-speed vessels. Mathematics is a necessity, but I have tried to avoid this when physical explanations can be given. Knowledge of calculus, including vector analysis and differential equations, is necessary to read the book in detail. The reader should also be familiar with dynamics and basic hydrodynamics of potential and viscous flow of an incompressible fluid.

Computational fluid dynamics (CFD) are commonly used nowadays, but my emphasis is on giving simplified and rational explanations of fluid behavior and its interaction with the vessel. This is beneficial in planning and interpreting experiments and computations. I also believe that examples and exercises are important parts of the learning process.

Automatic control and structural mechanics of high-speed marine vehicles are two disciplines that rely on hydrodynamics. These links are emphasized in the book and are also important aspects of the Centre for Ships and Ocean Structures, NTNU, where I participate.

My presentation of the material is inspired by the book *Marine Hydrodynamics* by Professor J. N. Newman.

I am thankful to Professor Newman for reading through the manuscript and offering suggestions for improvement. Dr. Svein Skjørdal spent a lot of time giving detailed comments on different versions of the manuscript. He was also helpful in seeing the topics from a practical point of view. Sun Hui also did a great job in confirming all my calculations and providing solutions to all exercises. I have benefited from Professor K. J. Minsaas' expertise in propulsion and hydrodynamic design of hydrofoil vessels. Many other people should be thanked for their critical reviews and contributions, including Dr. Tony Armstrong, Professor Tor Einar Berg, J. Bloch Helmers, Professor Lawrence Doctors, Dr. Svein Ersdal, Lars Flæten, Professor Thor I. Fossen, Dr. Chunhua Ge, Dr. Marilena Greco, Dr. Martin Greenhow, Dr. Ole Hermundstad, Egil Jullumstrø, Dr. Toru Katayama, Professor Katsuro Kijima, Professor Spyros A. Kinnas, Dr. Kourosh Koushan, David Kristiansen, Professor Claus Kruppa, Dr. Jan Kvaalsvold, Dr. Burkhard Müller-Graf, Professor Dag Myrhaug, Professor Makoto Ohkusu, Professor Bjørnar Pettersen, Dr. Olav Rognebakke, Renato Skejic, Dr. Nere Skomedal, Professor Sverre Steen, Gaute Storhaug, Professor Asgeir Sørensen, Professor Ernest O. Tuck, and Dr. Frans van Walree.

The artwork was done by Bjarne Stenberg. Anne-Irene Johannessen and Keivan Koushan were helpful in drawing figures. Jorunn Fransvåg organized and typed the many versions of the manuscript in an accurate and efficient way, which required a tremendous amount of work.

The support from the Centre of Ships and Ocean Structures and the Department of Marine Technology at NTNU is appreciated.

List of symbols

A	area; planform area of foil
A_D	developed area, propeller blades
A_E	expanded area, propeller blades
A_{jk}	3D added mass coefficient in the jth mode due to kth motion
a_{jk}	2D added mass coefficient
A_O	area of propeller disc
AP	after perpendicular
A_R	rudder area
A_W	waterplane area
AHR	average hull roughness
B	beam
b	beam of section
BAR	blade area ratio
B_{cr}, b_{cr}	critical damping
B_{jk}	3D damping coefficient in jth mode due to kth motion
b_{jk}	2D damping coefficient
c	chord length; half wetted length in 2D impact; speed of sound
C_B	block coefficient, ship
C_D	drag coefficient
C_f	friction coefficient
C_F	frictional force coefficient
CFD	computational fluid dynamics
C_H	head coefficient
C_{jk}	restoring force coefficient in jth mode due to kth motion
C_L	lift coefficient
$C_{L\beta}$	lift coefficient for planing vessel
C_{L0}	$C_{L\beta}$ at zero deadrise angle
$C(k_f)$	Theodorsen function
C_M	midship section coefficient; mass coefficient in Morison's equation
COG	center of gravity
C_p	pressure coefficient
$C_{p\,min}$	minimum pressure coefficient
C_P	longitudinal prismatic coefficient
C_R	residual resistance coefficient
C_T	propeller thrust-loading coefficient; total resistance coefficient
C_W	wave-making resistance coefficient
C_{WP}	wave pattern resistance coefficient

C_Q	capacity coefficient
D	draft; drag force; propeller diameter
DNV	Det Norske Veritas
D_T	transom draft
E	Young's modulus of elasticity
EI	flexural rigidity of a beam
E_k	kinetic fluid energy
E(t)	energy
f	frequency (Hz); maximum camber
F	densimetric Froude number; fetch length
Fn	Froude number $U/\sqrt{gL}$
Fn_B	beam Froude number
Fn_D	draft Froude number
Fn_h	depth or submergence Froude number
Fn_T	transom draft Froude number
FP	forward perpendicular
F_v	volumetric Froude number
g	acceleration of gravity
$G(x,y,z;\xi,\eta,\zeta)$	Green function
$\overline{GM}$	transverse metacentric height
$\overline{GM_L}$	longitudinal metacentric height
$\overline{GZ}$	moment arm in heel (roll) about COG
h	water depth; submergence
h_j	height of the center of the jet at station S_7 (see Figure 2.54) above calm free surface
H	wave height; head
$H_{1/3}$	significant wave height
i	imaginary unit
I_{jk}	moment or product of inertia
i, j, k	unit vectors along x, y and z-axis, respectively
IVR	inlet velocity ratio
J	advance ratio of propeller
k	wave number; roughness height; form factor
KC	Keulegan-Carpenter number
k_f	reduced frequency
$\overline{KG}$	height of COG above keel
K_T	thrust coefficient
K_Q	torque coefficient
L	length of ship; lift of a foil; hydrodynamic roll moment in maneuvering
L_C	chine wetted length
LCB	longitudinal center of buoyancy
lcg	longitudinal center of gravity measured from the transom stern
LCG	longitudinal center of gravity
L_K	keel wetted length
L_{OA}	length, overall
L_{OS}	length, overall submerged

l_p	longitudinal position of the center of pressure measured along the keel from the transom stern
L_{PP}	length between perpendiculars
L_{WL}	length of the designer's load waterline
M	mass; moment; hydrodynamic pitch moment in maneuvering
M	fluid momentum vector
m	mass per unit length
M_{jk}	components of mass matrix
n	propeller revolutions per second
n	surface normal vector positive into the fluid
N	normal force; hydrodynamic yaw moment in maneuvering
O	origin of coordinate system
$O(\varepsilon)$	order of magnitude of ε
P	power; pitch of propeller; probability
p	pressure; roll component of angular velocity; half of the distance between the center lines of the demihulls of a catamaran; stagger between foils
p_a	atmospheric pressure
P_D	delivered power
p_o	ambient pressure; static excess pressure
p_v	vapor pressure of water
Q	propeller torque; volume flux; source strength
q	pitch component of angular velocity
r	yaw component of angular velocity
R	radius; resistance
R_{AA}	added resistance in air and wind
R_{AW}	added resistance in waves
r_{jj}	radius of gyration in rigid body mode j
RMS	root mean square
Rn	Reynolds number
R_R	residual resistance
R_S	spray resistance
R_T	total resistance
R_V	viscous resistance
R_W	wave-making resistance
s	span length of foil
S	area of wetted surface; cross-sectional area
S_B	body surface
$S(\omega)$	wave spectrum
t	time; thrust-deduction coefficient; maximum foil thickness
T	period; propeller thrust
T_0	modal or peak period
T_1	mean wave period
T_2	mean wave period
T_e	encounter period
T_n	natural period
T_S	surface tension

U	forward velocity of vessel
U_I	mean velocity at the most narrow cross-section of the waterjet inlet
U_S	propeller slip stream velocity
u	x-component of vessel velocity
v	y-component of vessel velocity
vcg	vertical distance between COG and the keel
V_g	group velocity
V_p	phase velocity
v^*	wall friction velocity
V	water entry velocity
W	weight
w	wake fraction; z-component of vessel velocity; vertical deflection
Wn	Weber number
x, y, z	Cartesian coordinate system. Moving with the forward speed in seakeeping analysis. Body-fixed in maneuvering analysis.
X	x-component of hydrodynamic force in maneuvering
X_E, Y_E, Z_E	Earth-fixed coordinate system
x_T	x-coordinate of transom
x_s	$L_K - L_C$
Y	y-component of hydrodynamic force in maneuvering
Z	z-component of hydrodynamic force in maneuvering

Greek symbols

α	angle of attack
α_c	Kelvin angle
α_f	flap angle
α_i	ideal angle of attack
α_0	angle of zero lift
β	wave propagation angle; deadrise angle; drift angle
Γ	circulation; gamma function; dihedral angle
γ	vortex density; sweep angle; ratio of specific heat for air
δ	boundary layer thickness; rudder angle; flap angle
δ^*	displacement thickness
Δ	vessel weight
ε	angle
ζ	surface elevation
ζ_a	wave amplitude
η	overall propulsive efficiency
η_H	hull efficiency
η_J	jet efficiency
η_k	wave-induced vessel motion response, where $k = 1, 2, 3 \ldots 6$ refers to surge, sway, heave, roll, pitch, and yaw, respectively
η_p	propeller efficiency; pump efficiency
η_R	relative rotative efficiency
η_S	sinkage
η_T	thrust power efficiency
θ	pitch angle; momentum thickness

Λ	aspect ratio of foil
Λ_L	ratio between full scale and model length
λ	wavelength
λ_w	mean wetted length-to-beam ratio
μ	dynamic viscosity coefficient
ν	kinematic viscosity coefficient
ξ	ratio between damping and critical damping
ρ	mass density of fluid (water)
ρ_a	mass density of air
σ	cavitation number; source density; standard deviation
σ_i	cavitation inception index
σ_o	propeller cavitation number
$\sigma_{0.7}$	propeller cavitation number defined at 0.7 R
τ	trim angle in radians; $\omega_e U/g$
τ_{deg}	trim angle in degrees
τ_{ij}	Newtonian stress relations
τ_w	frictional stress on hull surface
ϕ	heel (roll) angle
φ	velocity potential
ψ	yaw angle
ω	circular frequency in radians per second
$\boldsymbol{\omega}$	vorticity vector; vector of rotational vessel motion
ω_n	natural frequency
ω_e	frequency of encounter
ω_o	frequency of waves in an Earth-fixed coordinate system
$\boldsymbol{\Omega}$	vector of rotational vessel velocity
Ω	volume

Special symbols

∇	displaced volume of water; vector differential operator
∇^2	$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$