SHIP RESISTANCE AND PROPULSION

Ship Resistance and Propulsion is dedicated to providing a comprehensive and modern scientific approach to evaluating ship resistance and propulsion. The study of propulsive power enables the size and mass of the propulsion engines to be established and estimates made of the fuel consumption and likely operating costs. This book, written by experts in the field, includes the latest developments from applied research, including those in experimental and CFD techniques, and provides guidance for the practical estimation of ship propulsive power for a range of ship types. This text includes sufficient published standard series data for hull resistance and propeller performance to enable practitioners to make ship power predictions based on material and data contained within the book. A large number of fully worked examples are included to illustrate applications of the data and powering methodologies; these include cargo and container ships, tankers and bulk carriers, ferries, warships, patrol craft, work boats, planing craft and yachts. The book is aimed at a broad readership including practising naval architects and marine engineers, sea-going officers, small craft designers and undergraduate and postgraduate degree students. It should also appeal to others involved in transportation, transport efficiency and eco-logistics, who need to carry out reliable estimates of ship power requirements.

Anthony F. Molland is Emeritus Professor of Ship Design at the University of Southampton in the United Kingdom. For many years, Professor Molland has extensively researched and published papers on ship design and ship hydrodynamics including propellers and ship resistance components, ship rudders and control surfaces. He also acts as a consultant to industry in these subject areas and has gained international recognition through presentations at conferences and membership on committees of the International Towing Tank Conference (ITTC). Professor Molland is the co-author of *Marine Rudders and Control Surfaces* (2007) and editor of *The Maritime Engineering Reference Book* (2008).

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Ship Resistance and Propulsion

PRACTICAL ESTIMATION OF SHIP PROPULSIVE POWER

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Contents

Preface

New ship types and applications continue to be developed in response to economic, societal and technical factors, including changes in operational speeds and fluctuations in fuel costs. These changes in ship design all depend on reliable estimates of ship propulsive power. There is a growing need to minimise power, fuel consumption and operating costs driven by environmental concerns and from an economic perspective. The International Maritime Organisation (IMO) is leading the shipping sector in efforts to reduce emissions such as NOx, SOx and CO_2 through the development of legislation and operational guidelines.

The estimation of ship propulsive power is fundamental to the process of designing and operating a ship. Knowledge of the propulsive power enables the size and mass of the propulsion engines to be established and estimates made of the fuel consumption and likely operating costs. The methods whereby ship resistance and propulsion are evaluated will never be an exact science, but require a combination of analysis, experiments, computations and empiricism. This book provides an up-to-date detailed appraisal of the data sources, methods and techniques for establishing propulsive power.

Notwithstanding the quantity of commercial software available for estimating ship resistance and designing propellers, it is our contention that rigorous and robust engineering design requires that engineers have the ability to carry out these calculations from first principles. This provides a transparent view of the calculation process and a deeper understanding as to how the final answer is obtained. An objective of this book is to include enough published standard series data for hull resistance and propeller performance to enable practitioners to make ship power predictions based on material and data contained within the book. A large number of fully worked examples are included to illustrate applications of the data and powering methodologies; these include cargo and container ships, tankers and bulk carriers, ferries, warships, patrol craft, work boats, planing craft and yachts.

The book is aimed at a broad readership, including practising professional naval architects and marine engineers and undergraduate and postgraduate degree students. It should also be of use to other science and engineering students and professionals with interests in the marine field.

The book is arranged in 17 chapters. The first 10 chapters broadly cover resistance, with Chapter 10 providing both sources of resistance data and useable data. Chapters 11 to 16 cover propellers and propulsion, with Chapter 16 providing both sources of propeller data and useable data. Chapter 17 includes a number of worked example applications. For the reader requiring more information on basic fluid mechanics, Appendix A1 provides a background to the physics of fluid flow. Appendix A2 derives a wave resistance formula and Appendices A3 and A4 contain tabulated resistance and propeller data. References are provided at the end of each chapter to facilitate readers' access to the original sources of data and information and further depth of study when necessary.

Proceedings, conference reports and standard procedures of the International Towing Tank Conference (ITTC) are referred to frequently. These provide an invaluable source of reviews and developments of ship resistance and propulsion. The proceedings and procedures are freely available through the website of the Society of Naval Architects and Marine Engineers (SNAME), which kindly hosts the ITTC website, http://ittc.sname.org. The University of Southampton Ship Science Reports, referenced in the book, can be obtained free from www.eprints.soton.ac.uk.

The authors acknowledge the help and support of their colleagues at the University of Southampton. Thanks must also be conveyed to national and international colleagues for their continued support over the years. Particular acknowledgement should also be made to the many undergraduate and postgraduate students who, over many years, have contributed to a better understanding of the subject through research and project and assignment work.

Many of the basic sections of the book are based on notes of lectures on ship resistance and propulsion delivered at the University of Southampton. In this context, particular thanks are due to Dr. John Wellicome, who assembled and delivered many of the original versions of the notes from the foundation of the Ship Science degree programme in Southampton in 1968.

Finally, the authors wish especially to thank their respective families for their practical help and support.

Anthony F. Molland
Stephen R. Turnock
Dominic A. Hudson
Southampton 2011

Nomenclature

A	Wetted surface area, thin ship theory (m^2)
A_0	Propeller disc area [$\pi D^2/4$]
A_D	Propeller developed blade area ratio, or developed blade area (m^2)
A_E	Propeller expanded blade area ratio
A_P	Projected bottom planing area of planing hull (m^2) or projected area of propeller blade (m^2)
A_T	Transverse frontal area of hull and superstructure above water (m^2)
A_X	Midship section area (m^2)
b	Breadth of catamaran demihull (m), or mean chine beam of planing craft (m)
B	Breadth of monohull or overall breadth of catamaran (m)
B_{pa}	Mean breadth over chines [$= A_P/L_P$] (m)
B_{px}	Maximum breadth over chines (m)
B_{WL}	Breadth on waterline (m)
c	Section chord (m)
C_A	Model-ship correlation allowance coefficient
C_B	Block coefficient
C_{Dair}	Coefficient of air resistance [$R_{\mathrm{air}}/\frac{1}{2}\rho_a A_T V^2$]
C_f	Local coefficient of frictional resistance
C_F	Coefficient of frictional resistance [$R_F/\frac{1}{2}\rho_W S V^2$]
C_L	Lift coefficient
C_M	Midship coefficient [$A_X/(B \times T)$]
C_P	Prismatic coefficient [$\nabla/(L \times A_X)$] or pressure coefficient
C_R	Coefficient of residuary resistance [$R_R/\frac{1}{2}\rho S V^2$]
C_S	Wetted surface coefficient [$S/\sqrt{\nabla \cdot L}$]
C_T	Coefficient of total resistance [$R_T/\frac{1}{2}\rho S V^2$]
C_V	Coefficient of viscous resistance [$R_V/\frac{1}{2}\rho S V^2$]
C_W	Coefficient of wave resistance [$R_W/\frac{1}{2}\rho S V^2$]
C_{WP}	Coefficient of wave pattern resistance [$R_{WP}/\frac{1}{2}\rho S V^2$]
D	Propeller diameter (m)

D_{air}	Aerodynamic drag, horizontal (planing craft) (N)
D_{APP}	Appendage resistance (N)
D_F	Planing hull frictional resistance, parallel to keel (N)
Demihull	One of the hulls which make up the catamaran
E	Energy in wave front
F_H	Hydrostatic pressure acting at centre of pressure of planing hull (N)
F_P	Pressure force over wetted surface of planing hull (N)
Fr	Froude number $[V/\sqrt{g \cdot L}]$
Fr_h	Depth Froude number $[V/\sqrt{g \cdot h}]$
Fr_∇	Volume Froude number $[V/\sqrt{g \cdot \nabla^{1/3}}]$
Fx	Yacht sail longitudinal force (N)
Fy	Yacht sail transverse force (N)
g	Acceleration due to gravity (m/s^2)
G	Gap between catamaran hulls (m)
GM	Metacentric height (m)
h	Water depth (m)
H	Wave height (m)
H_T	Transom immersion (m)
i_E	Half angle of entrance of waterline (deg.), see also $\frac{1}{2}\alpha_E$
J	Propeller advance coefficient (V_A/nD)
k	Wave number
K_T	Propeller thrust coefficient $(T/\rho n^2 D^4)$
K_Q	Propeller torque coefficient $Q/\rho n^2 D^5)$
L	Length of ship (m)
L_{air}	Aerodynamic lift, vertically upwards (planing craft) (N)
L_{APP}	Appendage lift (N)
L_{BP}	Length of ship between perpendiculars (m)
l_c	Wetted length of chine, planing craft (m)
LCB	Longitudinal centre of buoyancy (% L forward or aft of amidships)
LCG	Longitudinal centre of gravity (% L forward or aft of amidships)
L_f	Length of ship (ft)
l_K	Wetted length of keel, planing craft (m)
l_m	Mean wetted length, planing craft $[= (l_K + l_c)/2]$
L_{OA}	Length of ship overall (m)
lp	Distance of centre of pressure from transom (planing craft)(m)
L_P	Projected chine length of planing hull (m)
L_{PS}	Length between pressure sources
L_{WL}	Length on waterline (m)
$L/\nabla^{1/3}$	Length–displacement ratio
n	Propeller rate of revolution (rps)
N	Propeller rate of revolution (rpm), or normal bottom pressure load on planing craft (N)
P	Propeller pitch (m)
P_{AT}	Atmospheric pressure (N/m^2)
P/D	Propeller pitch ratio

P_D	Delivered power (kW)
P_E	Effective power (kW)
P_L	Local pressure (N/m^2)
P_S	Installed power (kW)
P_V	Vapour pressure (N/m^2)
Q	Propeller torque (Nm)
R_{air}	Air resistance (N)
R_{app}	Appendage resistance (N)
Re	Reynolds Number ($\rho VL/\mu$ or VL/ν)
R_F	Frictional resistance (N)
R_{Fh}	Frictional resistance of yacht hull (N)
R_{Ind}	Induced resistance of yacht (N)
rps	Revolutions per second
rpm	Revolutions per minute
R_R	Residuary resistance (N)
R_{Rh}	Residuary resistance of yacht hull (N)
R_{RK}	Residuary resistance of yacht keel (N)
R_T	Total hull resistance (N)
R_V	Viscous resistance (N)
R_{VK}	Viscous resistance of yacht keel (N)
R_{VR}	Viscous resistance of yacht rudder (N)
R_W	Wave resistance (N)
R_{WP}	Wave pattern resistance (N)
S	Wetted surface area (m^2)
S_{APP}	Wetted area of appendage (m^2)
S_C	Wetted surface area of yacht canoe body (m^2) or separation between catamaran demihull centrelines (m)
sfc	Specific fuel consumption
S_P	Propeller/hull interaction on planing craft (N)
t	Thrust deduction factor, or thickness of section (m)
T	Draught (m), or propeller thrust (N), or wave period (secs)
T_C	Draught of yacht canoe body (m)
U	Speed (m/s)
V	Speed (m/s)
Va	Wake speed ($V_S(1 - w_T)$) (m/s)
V_A	Relative or apparent wind velocity (m/s)
V_K	Ship speed (knots)
$V_K/\sqrt{L_f}$	Speed length ratio (knots and feet)
V_R	Reference velocity (m/s)
V_S	Ship speed (m/s)
W	Channel width (m)
w_T	Wake fraction
Z	Number of blades of propeller
$(1+k)$	Form-factor, monohull
$(1+\beta k)$	Form factor, catamaran
$\frac{1}{2}\,\alpha_E$	Half angle of entrance of waterline (deg.), see also i_E

β	Viscous resistance interference factor, or appendage scaling factor, or deadrise angle of planing hull (deg.) or angle of relative or apparent wind (deg.)
δ	Boundary layer thickness (m)
ε	Angle of propeller thrust line to heel (deg.)
η_D	Propulsive coefficient ($\eta_0\eta_H\eta_R$)
η_O	Open water efficiency ($JK_T/2\pi\ K_Q$)
η_H	Hull efficiency $(1-t)/(1-w_T)$
η_R	Relative rotative efficiency
η_T	Transmission efficiency
γ	Surface tension (N/m), or wave height decay coefficient, or course angle of yacht (deg.), or wave number
ϕ	Heel angle (deg.), or hydrodynamic pitch angle (deg.)
λ	Leeway angle (deg.)
μ	Dynamic viscosity (g/ms)
ν	Kinematic viscosity (μ/ρ) (m^2/s)
ρ	Density of water (kg/m^3)
ρ_a	Density of air (kg/m^3)
σ	Cavitation number, or source strength, or allowable stress (N/m^2)
τ	Wave resistance interference factor (catamaran resistance/monohull resistance), or trim angle of planing hull (deg.)
τ_c	Thrust/unit area, cavitation (N/m^2)
τ_R	Residuary resistance interference factor (catamaran resistance/monohull resistance)
τ_W	Surface or wall shear stress (N/m^2)
θ	Wave angle (deg.)
ζ	Wave elevation (m)
∇	Ship displacement volume (m^3)
∇_C	Displacement volume of yacht canoe body (m^3)
Δ	Ship displacement mass ($\nabla\rho$) (tonnes), or displacement force ($\nabla\rho g$) (N)

Conversion of Units

1 m = 3.28 ft	1 ft = 12 in.
1 in. = 25.4 mm	1 km = 1000 m
1 kg = 2.205 lb	1 tonne = 1000 kg
1 ton = 2240 lb	1 lb = 4.45 N
1 lbs/in.^{2} = 6895 N/m^2	1 bar = 14.7 lbs/in.^{2}
1 mile = 5280 ft	1 nautical mile (Nm) = 6078 ft
1 mile/hr = 1.61 km/hr	1 knot = 1 Nm/hr
$Fr = 0.2974\ V_K/\sqrt{L_f}$	1 knot = 0.5144 m/s
1 HP = 0.7457 kW	1 UK gal = 4.546 litres

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Abbreviations

ABS	American Bureau of Shipping
AEW	Admiralty Experiment Works (UK)
AFS	Antifouling systems on ships
AHR	Average hull roughness
AP	After perpendicular
ARC	Aeronautical Research Council (UK)
ATTC	American Towing Tank Conference
BDC	Bottom dead centre
BEM	Boundary element method
BEMT	Blade element-momentum theory
BMEP	Brake mean effective pressure
BMT	British Maritime Technology
BN	Beaufort Number
BSRA	British Ship Research Association
BTTP	British Towing Tank Panel
CAD	Computer-aided design
CCD	Charge-coupled device
CFD	Computational fluid dynamics
CG	Centre of gravity
CLR	Centre of lateral resistance
CODAG	Combined diesel and gas
CP	Controllable pitch (propeller)
CSR	Continuous service rating
DES	Detached eddy simulation
DNS	Direct numerical simulation
DNV	Det Norske Veritas
DSYHS	Delft systematic yacht hull series
DTMB	David Taylor Model Basin
EFD	Experimental fluid dynamics
FEA	Finite element analysis
FP	Forward perpendicular, or fixed pitch (propeller)
FRP	Fibre-reinforced plastic
FV	Finite volume

GL	Germanischer Lloyd
GPS	Global Positioning System
HP	Horsepower
HSVA	Hamburg Ship Model Basin
IESS	Institute of Engineers and Shipbuilders in Scotland
IMarE	Institute of Marine Engineers (became IMarEST from 2001)
IMarEST	Institute of Marine Engineering, Science and Technology
IMechE	Institution of Mechanical Engineers
IMO	International Maritime Organisation
INSEAN	Instituto di Architectura Navale (Rome)
ISO	International Standards Organisation
ITTC	International Towing Tank Conference
JASNAOE	Japan Society of Naval Architects and Ocean Engineers
LCG	Longitudinal centre of gravity
LDA	Laser Doppler anemometry
LDV	Laser Doppler velocimetry
LE	Leading edge of foil or fin
LES	Large eddy simulation
LR	Lloyd's Register of Shipping
MAA	Mean apparent amplitude
MARIN	Maritime Research Institute of the Netherlands (formerly NSMB)
MCR	Maximum continuous rating
MEMS	Microelectromechanical systems
NACA	National Advisory Council for Aeronautics (USA)
NECIES	North East Coast Institution of Engineers and Shipbuilders
NPL	National Physical Laboratory (UK)
NSMB	The Netherlands Ship Model Basin (later to become MARIN)
NTUA	National Technical University of Athens
ORC	Offshore Racing Congress
P	Port
PIV	Particle image velocimetry
QPC	Quasi propulsive coefficient
RANS	Reynolds Averaged Navier–Stokes
RB	Round back (section)
RINA	Royal Institution of Naval Architects
ROF	Rise of floor
rpm	Revolutions per minute
rps	Revolutions per second
S	Starboard
SAC	Sectional area curve
SCF	Ship correlation factor
SG	Specific gravity
SNAJ	Society of Naval Architects of Japan (later to become JASNAOE)
SNAK	Society of Naval Architects of Korea
SNAME	Society of Naval Architects and Marine Engineers (USA)
SP	Self-propulsion
SSPA	Statens Skeppsprovingansalt, Götaborg, Sweden

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STG	Schiffbautechnische Gesellschaft, Hamburg
TBT	Tributyltin
TDC	Top dead centre
TDW	Tons deadweight
TE	Trailing edge of foil or fin
TEU	Twenty foot equivalent unit [container]
UTS	Ultimate tensile stress
VCB	Vertical centre of buoyancy
VLCC	Very large crude carrier
VPP	Velocity prediction program
VWS	Versuchsanstalt für Wasserbau und Schiffbau Berlin (Berlin Model Basin)
WUMTIA	Wolfson Unit for Marine Technology and Industrial Aerodynamics, University of Southampton

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