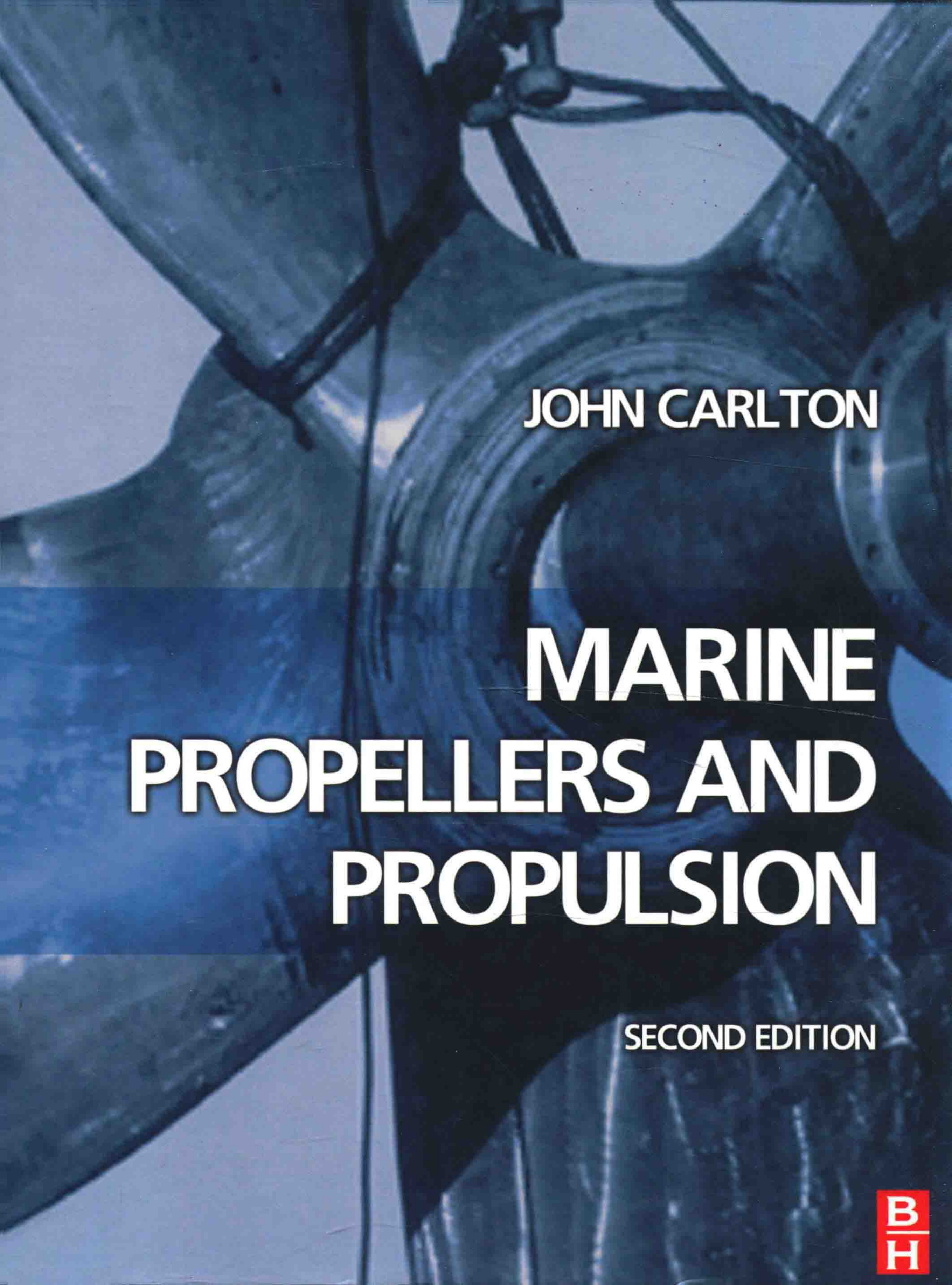

JOHN CARLTON

MARINE PROPELLERS AND PROPULSION

SECOND EDITION

B H

Marine Propellers and Propulsion

Second Edition

J S Carlton

Global Head of Marine Technology and Investigation, Lloyd's Register

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Preface to the second edition

It is now rather over a decade since much of the material was written for the first edition of this book. During that time advances have been made in the understanding of several branches of the subject and it is now time to incorporate much of that material into the text. These advances in understanding together with the natural progression of the subject relate particularly to cavitation dynamics, theoretical methods including the growing development of computational fluid dynamics in many parts of the subject and the use of carbon fibre materials for certain propeller types. Moreover, podded propulsors have emerged in the intervening years since the first edition was written and have become a propulsion option for certain types of ship, particularly cruise ships and ice breakers but with a potential to embrace other ship types in the future.

Some other aspects of the subject were not included in the original publication for a number of reasons. In this new edition I have attempted to rectify some of these omissions by the inclusion of material on high-speed propellers, propeller–rudder interaction as well as a new chapter dealing with azimuthing and podded propulsors and a substantial revision to the chapter on cavitation. These additions together with a reasonably extensive updating of the material and the removal of the inevitable typographical errors in the first edition form the basis of this new addition. Furthermore, experience in using the book over the last 10 years or so has shown that the arrangement of some of the material could be improved. As a consequence it will be seen that a certain amount of re-grouping of the subject matter has taken place in the hope that this will make the text easier to use.

Finally, thanks are once again due to many colleagues around the world who have made very valuable suggestions and comments as well as providing me with further material for inclusion from their own libraries and achieves. Furthermore, the normal day-to-day discussions that are held on various aspects of the subject frequently trigger thought processes which have found their way into various parts of the narrative. In particular, my thanks are due to Mrs W. Ball, Mr P.A. Fitzsimmons, Mr M. Johansen, Mr J. Th. Ligtelijn, Dr D. Radosavljevic , Prof. Dr T. van Terwisga and Mr J. Wiltshire. Thanks are also due to Dr P. Helmore who, having read the book some 10 years ago, kindly supplied me with a list of errata for this edition. Finally, thanks are also due to Jane, my wife, for her encouragement and support in undertaking this revision to the book in a relatively short-time frame.

J.S. Carlton
Hythe, Kent
December 2006

Preface to the first edition

Although the propeller normally lies well submerged out of sight and therefore, to some extent, also out of mind, it is a deceptively complex component in both the hydrodynamic and the structural sense. The subject of propulsion technology embraces many disciplines: for example, those of mathematics, physics, metallurgy, naval architecture and mechanical and marine engineering. Clearly, the dependence of the subject on such a wide set of basic disciplines introduces the possibility of conflicting requirements within the design process, necessitating some degree of compromise between opposing constraints. It is the attainment of this compromise that typifies good propeller design.

The foundations of the subject were laid during the latter part of the last century and the early years of this century. Since that time much has been written and published in the form of technical papers, but the number of books which attempt to draw together all of these works on the subject from around the world is small. A brief study of the bibliography shows that, with the exception of Gerr's recent book dealing with the practical aspects of the design of small craft propellers, little has been published dealing with the subject as an entity since the early 1960s. Over the last 30 or so years an immense amount of work, both theoretical and empirical, has been undertaken and published, probably more than in any preceding period. The principal aim, therefore, of this book is to collect together the work that has been done in the field of propeller technology up to the present time in each of the areas of hydrodynamics, strength, manufacture and design, so as to present an overall view of the subject and the current levels of knowledge.

The book is mainly directed towards practising marine engineers and naval architects, principally within the marine industry but also in academic and research institutions. In particular when writing this book I have kept in mind the range of questions about propeller technology that are frequently posed by designers, ship operators and surveyors and I have attempted to provide answers to these questions. Furthermore, the book is based on the currently accepted body of knowledge of use to practical design and analysis; current research issues are addressed in a less extensive manner. For example, recent developments in surface panel techniques and Navier–Stokes solutions are dealt with in less detail than the currently more widely used lifting line, lifting surface and vortex lattice techniques of propeller analysis. As a consequence a knowledge of mathematics, fluid mechanics and engineering science is assumed commensurate with these premises. Notwithstanding this, it is to be hoped that students at both undergraduate and post-graduate levels will find the book of value to their studies.

The first two chapters of the book are essentially an introduction to the subject: first, a brief history of the early development of propellers and, secondly, an introduction to the different propeller types that are either of topical interest or, alternatively, will not be considered further in the book; for example, paddle wheels or superconducting electric propulsion. Chapter 3 considers propeller geometry and, consequently, this chapter can be viewed as a foundation upon which the rest of the book is built. Without a thorough knowledge of propeller geometry, the subject will not be fully understood. Chapters 4 and 5 concern themselves with the environment in which the propeller operates and the wake field in particular. The wake field and its various methods of prediction and transformation, particularly from nominal to effective, are again fundamental to the understanding of the design and analysis of propellers.

Chapters 6–15 deal with propulsion hydrodynamics, first in the context of model results and theoretical methods relating to propellers fixed to line shafting, then moving on to ship resistance and propulsion, including the important subjects of propeller–hull interaction and thrust augmentation devices, and finally to consideration of the specific aspects of fixed and rotable thrusters and waterjets. Chapter 16 addresses the all-important subject of sea trials in terms of the conditions necessary for a valid trial, instrumentation and analysis.

Chapters 17–20 deal with the mechanical aspects of propellers. Materials, manufacture, blade strength and vibration are the principal subjects of these four chapters, and the techniques discussed are generally applicable to all types of propulsors. The final five chapters, 21–25, discuss various practical aspects of propeller technology, starting with design, then continuing to operational problems, service performance and, finally, to propeller inspection, repair and maintenance.

In each of the chapters of the book the attainment of a fair balance between theoretical and practical considerations has been attempted, so that the information presented will be of value to the practitioner in marine science. For more advanced studies, particularly of a theoretical nature, the data presented here will act as a starting point for further research: in the case of the theoretical hydrodynamic aspects of the subjects, some of the references contained in the bibliography will be found to be of value.

This book, representing as it does a gathering together of the subject of propulsion technology, is based upon the research of many scientists and engineers throughout the world. Indeed, it must be remembered that without these people, many of whom have devoted considerable portions of their lives to the development of the subject, this book could not have been written and, indeed, in subject of propeller technology could not have developed so far. I hope that I have done justice to their efforts in this book. At the end of each chapter a series of references is given so that, if necessary, the reader may refer to the original work, which will contain full details of the specific research topic under consideration. I am also considerably indebted to my colleagues, both within Lloyd's Register and in the marine industry, for many discussions on various aspects of the subject over the years, all of which have helped to provide a greater insight into, and understanding of, the subject. Particularly, in this respect, thanks are given to Mr C.M.R. Wills, Mr P.A. Fitzsimmons and Mr D.J. Howarth who, as specialists in particular branches of the subject, have also read several of the chapters and made many useful comments concerning their content. I would also like to thank Mr A.W.O. Webb who, as a specialist in propeller materials technology and colleague, has given much helpful advice over the years in solving propeller problems and this together with his many technical papers has influenced much of the text of Chapters 17 and 25. Also, I am particularly grateful to Mr J.Th. Ligtelijn of MARIN and to Dr G. Patience of Stone Manganese Marine Ltd, who have supplied me with several photographs for inclusion in the text and with whom many stimulating discussions on the subject have been had over the years. Thanks are also due to the many kind ladies who have so painstakingly typed the text of this book over the years and without whom the book would not have been produced.

J.S. Carlton
London
May 1993

General nomenclature

Upper case

A	Cross-sectional area
A_C	Admiralty coefficient
A_D	Developed area
A_E	Expanded area
A_M	Mid-ship section area
A_O	Disc area
A_P	Projected area
AR	Aspect ratio
B	Moulded breadth of ship
B_P	Propeller power coefficient
BAR	Blade area ratio
C_A	Correlation factor
	Section area coefficient
C_b	Ship block coefficient
C_D	Drag coefficient
C_F	Frictional resistance coefficient
C_L	Lift coefficient
C_M	Moment coefficient
	Section modulus coefficient
C_P	Pressure coefficient
	Ship prismatic coefficient
	Propeller power coefficient
C_T	Thrust loading coefficient
	Total resistance coefficient
C_W	Wavemaking resistance coefficient
D	Drag force
	Propeller diameter
D_b	Behind diameter
D_o	Diameter of slipstream far upstream
D_s	Shaft diameter
F	Force
	Fetch of sea
F_B	Bollard pull
F_n	Froude number

G	Boundary layer unique shape function
	Non-dimensional circulation coefficient
H	Hydraulic head
H_p	Pump head
I	Dry inertia
I_e	Polar entrained inertia
IVR	Inlet velocity ratio
J	Advance coefficient
J_p	Ship polar moment of inertia
K	Prandtl or Goldstein factor
K_n	Knapp's similarity parameter
K_p	Pressure coefficient
K_Q	Propeller torque coefficient
K_{QS}	Spindle torque coefficient
K_T	Thrust coefficient
K_{TN}, K_{TD}	Duct thrust coefficient
K_{TP}	Propeller thrust coefficient
K_Y	Side force coefficient
L	Length of ship or duct
	Lift force
	Section centrifugal bending moment arm
L_P	Sound pressure level
L_{PP}	Length of ship between perpendiculars
L_R	Length of run
L_{WL}	Length of ship along waterline
M	Moment of force
M_a	Mach number
N	Rotational speed (RPM)
	Number of cycles
	Number of fatigue cycles
N_S	Specific speed
P	Propeller pitch
P_B	Brake power
P_D	Delivered power
P_E	Effective power
P_G	Generator power
P_S	Shaft power
Q	Flow quantity
	Propeller torque
QPC	Quasi-propulsive coefficient
Q_S	Total spindle torque
Q_{SC}	Centrifugal spindle torque
Q_{SF}	Frictional spindle torque
Q_{SH}	Hydrodynamic spindle torque
R	Radius of propeller, paddle wheel or bubble
	Specific gas constant
R_{AIR}	Air resistance of ship
R_{APP}	Appendage resistance
R_e	Real part

R_F Frictional resistance
R_n Reynolds number
R_T Total resistance
R_V Viscous resistance
R_W Wavemaking resistance

S Surface tension
Ship wetted surface area
S_A Additional load scale factor
S_a Apparent slip
SBF Solid boundary factor
S_C Camber scale factor

T Temperature
Draught of ship
Propulsor thrust
T_A Draught aft
T_F Draught forward
T_N, T_D Duct thrust
T_p Propeller thrust

U_T Propeller tip speed

V Volume
Velocity
V_a Speed of advance
V_s Ship speed
X Distance along coordinate axis
Y Distance along coordinate axis

W Resultant velocity
Width of channel
W_e Weber number

Z Blade number
Distance along coordinate axis
Z_m Section modulus

Lower case

a Propeller axial inflow factor
a_1 Propeller tangential inflow factor
a_c Crack length
a_r Resistance augmentation factor

b Span of wing

c Wake contraction factor
Section chord length
c_d Section drag coefficient
c_l Section lift coefficient
c_{li} Ideal section lift coefficient
c_m Section moment coefficient
c_{max} Limiting chord length

f Frequency
Function of . . .

g Acceleration due to gravity
Function of . . .

h	Fluid enthalpy
	Height
	Hydraulic head
h_b	Height of bulbous bow centroid from base line in transverse plane
i	Counter
i_G	Section generator line rake
i_P	Propeller rake
i_S	Section skew-induced rake
i_T	Total rake of propeller section
j	Counter
k	Counter
k_c	Lifting surface camber correction factor
k_s	Mean apparent amplitude of surface roughness
k_t	Lifting surface thickness correction factor
k_x	Lifting surface ideal angle of attack correction factor
$(1+k)$	Frictional form factor
l	Counter
	Length
lcb	Longitudinal centre of buoyancy
m	Mass
	Counter
$\dot{m}$	Specific mass flow
n	Rotational speed (rps)
p	Section pitch
	Pressure
p_c	Cavity variation-induced pressure
p_H	Propeller-induced pressure
p_o	Reference pressure
	Non-cavitating pressure
	Pitch of reference section
p_v	Hull-induced vibratory pressure
	Vapour pressure
p^1	Apparent-induced pressure
q	Dynamic flow pressure
r	Radius of a propeller section
r_h	Hub or boss radius
s	Length parameter
t	Time
	Thrust deduction factor
	Section thickness
t_F	Thickness fraction
t_{max}	Maximum thickness
t_o	Notional blade thickness at shaft centre line
u	Local velocity

v	Local velocity
v_a	Axial velocity
v_r	Radial velocity
v_t	Tangential velocity
v_T	Tide speed
w	Downwash velocity
	Mean wake fraction
w_F	Froude wake fraction
w_{max}	Maximum value of wake fraction in propeller disc
w_n	Nominal wake fraction
w_p	Potential wake fraction
w_T	Taylor wake fraction
w_v	Viscous wake fraction
w_w	Wave-induced wake fraction
x	Distance along a coordinate axis
	Non-dimensional radius (r/R)
x_c	Distance along chord
	Radial position of centroid
x_{cp}	Centre of pressure measured along chord
x_o	Reference section
y	Distance along coordinate axis
y_c	Camber ordinate
y_L	Section lower surface ordinate
y_t	Thickness ordinate
y_U	Section upper surface ordinate
z	Distance along coordinate axis

Suffixes

m	Model
s	Ship
U	Upper
L	Lower
b	Bound, behind
F	Free
O	Reference value
x	Reference radius

Greek and other symbols

α	Angle of attack
	Gas content
α_d	Cavitation bucket width
α_i	Ideal angle of attack
α_K	Air content ratio
α_o	Zero lift angle
β	Advance angle
β_F	Hydrodynamic pitch in the ultimate wake
β_i	Hydrodynamic pitch angle
Γ	Circulation
γ	Local vortex strength
	Length parameter
	Ratio of drag to lift coefficient (C_d/C_e)
γ_g	Correction to angle of attack due to cascade effects

Δ	Change in parameter
	Displacement of ship
δ	Boundary layer thickness
	Linear displacement
	Propeller speed coefficient
ε	Thrust eccentricity
	Transformation parameter
ζ	Bendemann static thrust factor
	Damping factor
	Transformation parameter
η_b	Propeller behind hull efficiency
η_h	Hull efficiency
η_i	Ideal efficiency
η_m	Mechanical efficiency
η_o	Propeller open water efficiency
η_p	Pump efficiency
η_r	Relative rotative efficiency
θ	Pitch angle
	Transformation parameter
	Momentum thickness of boundary layer
θ_{fp}	Face pitch angle
θ_{ip}	Propeller rake angle
θ_{nt}	Nose–tail pitch angle
θ_o	Effective pitch angle
θ_s	Section skew angle
θ_{sp}	Propeller skew angle
θ_w	Angular position of transition wake roll-up point
Λ	Frequency reduction ratio
λ	Wavelength
	Source–sink strength
	Ship–model scale factor
μ	Coefficient of dynamic viscosity
ϱ	Density of water
ρ_a	Density of air
ϱ_L	Leading edge radius
ϱ_m	Density of blade material
σ	Cavitation number
	Stress on section
σ_a	Alternating stress
σ_F	Corrosion fatigue strength
σ_i	Inception cavitation number
σ_L	Local cavitation number
σ_{MD}	Mean design stress
σ_n	Cavitation number based on rotational speed
	Relative shaft angle
σ_o	Free steam cavitation number
σ_R	Residual stress
σ_s	Blade solidity factor
σ_x	Blade stress at location on blade
τ	Shear stress
τ_C	Thrust loading coefficient
υ	Coefficient of kinematic viscosity
ϕ	Angle of rotation in propeller plane
	Hull-form parameter
	Velocity potential
	Angular displacement
	Flow coefficient
	Shaft alignment angle relative to flow

ψ	Transformation parameter
	Gas content number
	Energy transfer coefficient
Ω	Angular velocity
ω	Angular velocity
∇	Volumetric displacement

Abbreviations

AEW	Admiralty Experiment Works, Haslar
AP	After Perpendicular
ATTC	American Towing Tank Conference
BHP	Brake Horse Power
BS	British Standard
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
cwt	Hundred weight
	(1 cwt = 112 lbf = 50.8 kgf)
DES	Design
DHP	Delivered Horse Power
DTNSRDC	David Taylor Naval Ship Research and Design Centre
EHP	Effective Horse Power
ft	Feet
HMS	Her Majesty's Ship
hp	Horsepower
HSVA	Hamburg Ship Model Basin
IMO	International Maritime Organization
ISO	International Standards Organization
ITTC	International Towing Tank Conference
LE	Leading edge
MARIN	Maritime Research Institute of the Netherlands
MCR	Maximum Continuous Rating
mph	Miles per hour
NACA	National Advisory Council for Aeronautics
NC	Numerically Controlled
NCR	Normal Continuous Rating
OD	Oil Distribution
PHV	Propulsor Hull Vortex
qrs	Quarters (4 qrs = 1 cwt; 1 cwt = 50.8 kgf)
RANS	Reynolds Averaged Navier Stokes
RH	Right Handed
rpm	Revolutions per minute
shp	Shaft horse power
SM	Simpson's Multiplier
SSPA	Statens Skeppsprovningsanstalt, Göteborg
TE	Trailing Edge
THP	Thrust Horse Power
VTOL	Vertical Take-Off and Landing

Contents