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Reflections on Power Prediction Modeling of Conventional High-Speed Craft
To my teachers:

Prof. Borivoje Ribar—who taught me the basics of naval architecture

Prof. Borislav Djodjo—who taught me everything else that was necessary to become a teacher
Foreword

This book is about evolution, taking note of the history of technological progress for mathematical models to predict calm water resistance, trim and propeller characteristics for high-performance marine vessels. Dr. Dejan Radojičić has been an activist from early in his academic career to develop mathematical models using emerging techniques with validated predictions using available experimental data.

His goals have focused on calculation procedures to improve naval architect’s capability to reliably develop high-performance vessel hydrodynamic designs. With these improved resources, designers are able early on to optimize vessels with respect to their requirements to maximize the performance in their operational environment.

I have been a friend and colleague of Dr. Radojičić for more than 30 years. I have learned much from him and encouraged this documentation of his passion for improving the analytical prediction techniques. This book is one of the many achievements of Dejan’s life work resulting in especially useful prediction methods developed with artificial neural networks (ANNs). His recent ANN methods have been used to develop techniques sensitive to hull geometry input resulting in predictions of calm water resistance and trim near to that of towing tank quality.

Now retired after 60 plus years as a designer of high-performance vessels, I believe that you will also find this book to be very useful in your work and career.

Chesapeake, VA, USA
April 2018

Donald L. Blount, P.E.
Founder of Donald L. Blount and Associates, Inc.
Preface

This work was initially intended to be a review paper, but the manuscript grew—and is now a small book that fits the Springer Brief series. It was actually inspired by and envisaged as an extension of the seminal Blount (1993) paper titled “Reflections on Planing Hull Technology”. Hence, the titles are intentionally similar. This work is a summation of the author’s insights into, and experiences with, high-speed craft (HSC) design and modeling, lovingly accumulated over a 35-year career in the industry and academia, almost entirely focused on this specific topic.

The essence of the Blount 1993 paper (recently updated to a book in 2014) is today still very relevant. The focus of that work was on the planing hulls and is expanded here to the category described as conventional high-speed craft that covers the largest number of yachts and boats currently in existence or under construction.

The following statements from the abovementioned work inspired the author to write this book, with the principal statements underlined and with text in italics replacing the original verbiage shown in brackets, as appropriate:

- I have chosen to reflect upon power prediction modeling of conventional HSC (planing hull technology) in relationship to my personal experience.
- While reflecting on the past, I scanned many references and was reminded of the extensive quantity of useful data which has been published. Looking at my references, I find that only a limited number are “dog-eared” and most have not been referred to too frequently.
- Over the years, I believe my greatest contribution as a naval architect has been my focus on the power prediction modeling (practical applications of technology).

This text focuses on the practical and concrete topics and avoids unnecessary issues, mathematical derivations, and similar rigor. However, it is assumed that the reader has a basic university-level knowledge of ship hydrodynamics. Topics which can be found in other books and in the large number of referenced papers are not
repeated; they are regarded as companion sources. The author’s personal experiences are reflected in the many routines discussed here, since they were derived by him and his team. It is believed that similar reference source material on high-speed craft hydrodynamics does not exist. Consequently, this book is intended primarily for the naval architects who design and develop various types of conventional high-speed vessels, although it may be of use to anyone who is interested in the design of fast vessels.

The author expects that his colleagues and co-authors from the University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, will soon disclose some, or all, of the mathematical models and/or programs treated here. The Department’s Web site is: www.brodogradnja.org.

Belgrade, Serbia

Dejan Radojić

Reference

Blount DL. (1993) Reflections on planing hull technology. In: 5th power boat symposium, SNAME Southeast Section
I would like to thank Donald Blount who unselfishly shared his experience and knowledge over the last three decades. He was always inspirational and ready to support work on new topics. Don’s constructive suggestions and reviews of some of my manuscripts, including this one, certainly improved them.

Many thanks to Mike Morabito and Predrag Bojović who gave exceptionally useful comments and suggestions. Aleksandar Simić, Milan Kalajdžić, and Rade Pešterac helped with the diagrams. I am proud that the last four are my ex-students.

The consistent support and patience of my family should also be acknowledged. Normally, this is understood and goes unsaid, but since this book is a summary of my life’s work, the well-deserved acknowledgment is appropriate.
About this Book

High-speed craft is very different from conventional ships. This dictates the need, from the very outset, for special treatment in designing high-speed vessels. Professional literature, which is mostly focused on conventional ships, leaves a gap in the documentation of best design practices for high-speed craft.

The various power prediction methods, a principal design objective for high-speed craft of displacement, semi-displacement, and planing type, are addressed. At the core of the power prediction methods are mathematical models, based on experimental data derived on models representing various high-speed hull and propeller series. The regression analysis and artificial neural network (ANN) methods are used as an extraction tool for this kind of mathematical models. A variety of mathematical models of this type are discussed in the book.

The most significant factors for in-service power prediction are bare hull resistance, dynamic trim, and the propeller’s open water efficiency. Therefore, mathematical modeling of these factors is a specific focus of the book, although other less significant resistance components and hull-propeller interactions are also addressed. Furthermore, the book includes a summary of most of the power-prediction-relevant literature published in the last 50 years, and as such is intended as a reference overview of best modeling practices.

Note that once these mathematical models have been developed and validated, they can be readily programmed into software tools, thereby enabling the parametric analyses required for the optimization of a high-speed craft design. This book provides the foundational reference for these software tools and their use in the design of high-speed craft. It is aimed at the high-speed craft community in general and particularly at the naval architects who design and develop various types of high-speed vessels.

This book is a summation of the author’s insights and experiences accumulated over a 35-year career in the industry and academia, focused almost entirely on high-speed craft design and modeling.
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<tbody>
<tr>
<td>AEW</td>
<td>Admiralty Experiment Works, Haslar</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial neural network</td>
</tr>
<tr>
<td>ATTC</td>
<td>American Towing Tank Conference</td>
</tr>
<tr>
<td>BSRA</td>
<td>British Ship Research Association</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CPP</td>
<td>Controllable pitch propeller</td>
</tr>
<tr>
<td>DSDS</td>
<td>Delft Systematic Deadrise Series</td>
</tr>
<tr>
<td>DTMB (TMB)</td>
<td>David Taylor Model Basin</td>
</tr>
<tr>
<td>DTNSRDC (NSRDC)</td>
<td>David Taylor Naval Ship Research and Development Center</td>
</tr>
<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>HSC</td>
<td>High-speed craft</td>
</tr>
<tr>
<td>HSMV</td>
<td>High-speed marine vessels</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>ITTC</td>
<td>International Towing Tank Conference</td>
</tr>
<tr>
<td>KCA</td>
<td>Kings College Admiralty (Newcastle)</td>
</tr>
<tr>
<td>MARIN (Wageningen)</td>
<td>Maritime Research Institute of the Netherlands</td>
</tr>
<tr>
<td>MM</td>
<td>Mathematical model</td>
</tr>
<tr>
<td>NPL</td>
<td>National Physical Laboratory</td>
</tr>
<tr>
<td>NSS</td>
<td>Naples Systematic Series</td>
</tr>
<tr>
<td>NTUA</td>
<td>National Technical University of Athens</td>
</tr>
<tr>
<td>PHF</td>
<td>Planing Hull Forms</td>
</tr>
<tr>
<td>RINA (INA)</td>
<td>The Royal Institution of Naval Architects</td>
</tr>
<tr>
<td>SKLAD</td>
<td>Series tested in the Naval Institute in Zagreb</td>
</tr>
<tr>
<td>SNAJ</td>
<td>The Society of Naval Architects of Japan</td>
</tr>
<tr>
<td>SNAME</td>
<td>The Society of Naval Architects and Marine Engineers</td>
</tr>
<tr>
<td>SPP</td>
<td>Surface piercing propeller</td>
</tr>
<tr>
<td>SSPA</td>
<td>Swedish Maritime Research Centre</td>
</tr>
<tr>
<td>SVA</td>
<td>Potsdam Model Basin</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------------------------------------------------------------</td>
</tr>
<tr>
<td>SWATH</td>
<td>Small waterplane area twin hull</td>
</tr>
<tr>
<td>TUNS</td>
<td>Technical University of Nova Scotia</td>
</tr>
<tr>
<td>USCG</td>
<td>United States Coast Guard</td>
</tr>
<tr>
<td>VTT</td>
<td>Technical Research Centre of Finland</td>
</tr>
<tr>
<td>VWS</td>
<td>Versuchsanstalt für Wasserbau und Schiffbau (Berlin)</td>
</tr>
<tr>
<td>WEGEMT</td>
<td>EU Marine University Association</td>
</tr>
<tr>
<td>WUMTIA (Wolfson Unit)</td>
<td>Wolfson Unit for Marine Technology and Industrial Aerodynamics</td>
</tr>
</tbody>
</table>
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_D$</td>
<td>Developed propeller blade area ($m^2$)</td>
</tr>
<tr>
<td>$A_E$</td>
<td>Expanded propeller blade area ($m^2$)</td>
</tr>
<tr>
<td>$A_O$</td>
<td>Propeller disk area ($m^2$)</td>
</tr>
<tr>
<td>$A_O'$</td>
<td>Immersed area of SPP ($m^2$)</td>
</tr>
<tr>
<td>$A_P$</td>
<td>Projected propeller blade area ($m^2$)</td>
</tr>
<tr>
<td>$A_T$</td>
<td>Transom area ($m^2$)</td>
</tr>
<tr>
<td>$A_X$</td>
<td>Maximum section area ($m^2$)</td>
</tr>
<tr>
<td>$A_P/A_X$</td>
<td>Planing area coefficient</td>
</tr>
<tr>
<td>$A_T/A_X$</td>
<td>Transom area ratio</td>
</tr>
<tr>
<td>$B_{EF}$</td>
<td>Effective planing beam (m)</td>
</tr>
<tr>
<td>$B_M$</td>
<td>Beam at midship ($L_P/2$) (m)</td>
</tr>
<tr>
<td>$B_{PA} = A_P/L_P$</td>
<td>Mean beam over chines (m)</td>
</tr>
<tr>
<td>$B_{PT}$</td>
<td>Projected chine beam at transom (m)</td>
</tr>
<tr>
<td>$B_{TX}$</td>
<td>Maximal projected chine beam (m)</td>
</tr>
<tr>
<td>$B_{WL} = B = B_X$</td>
<td>Beam of hull on DWL (m)</td>
</tr>
<tr>
<td>$B_{XDH}$</td>
<td>Maximum beam of demihull (catamaran) (m)</td>
</tr>
<tr>
<td>$C = 30.1266 \cdot v/(L)^{1/4} \cdot (\Delta/2P_E)^{1/2}$</td>
<td>C factor (note: $v$ in kn; not non-dimensional coef.)</td>
</tr>
<tr>
<td>$C_A$</td>
<td>Correlation allowance</td>
</tr>
<tr>
<td>$C_{AA}$</td>
<td>Air resistance (allowance) coefficient</td>
</tr>
<tr>
<td>$C_{AP}$</td>
<td>Centroid of $A_P$ forward of transom (m)</td>
</tr>
<tr>
<td>$C_B = \nabla/(L \cdot B \cdot T)$</td>
<td>Block coefficient</td>
</tr>
<tr>
<td>$C_F$</td>
<td>Specific frictional resistance coefficient</td>
</tr>
<tr>
<td>$C_R$</td>
<td>Specific residuary resistance coefficient</td>
</tr>
<tr>
<td>$C_S = S/(\nabla \cdot L)^{1/2}$</td>
<td>Taylor wetted surface coefficient</td>
</tr>
<tr>
<td>$C_{TV} = R_T/(p/2 \cdot v^2 \cdot \nabla^{2/3})$</td>
<td>Total resistance coefficient</td>
</tr>
<tr>
<td>$C_{T^*} = T/(p/2 \cdot v_{0.7R^2} \cdot A_O)$</td>
<td>Thrust index (coefficient) of propeller</td>
</tr>
<tr>
<td>$C_{Q^*} = Q/(p/2 \cdot v_{0.7R^2} \cdot A_O \cdot D)$</td>
<td>Torque index (coefficient) of propeller</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$C_X$</td>
<td>$A_X/B \cdot T$</td>
</tr>
<tr>
<td>$C_A$</td>
<td>$\nabla/B_{PX}^3$ or $\nabla/B_X^3$</td>
</tr>
<tr>
<td>$C_V$</td>
<td>$C_{DL} = \nabla/(0.1 \cdot L)^3$</td>
</tr>
<tr>
<td>$D$</td>
<td>Maximum section area coefficient</td>
</tr>
<tr>
<td>$DAR = A_D/A_O$</td>
<td>Beam load coefficient</td>
</tr>
<tr>
<td>$DWL$</td>
<td>Volume displacement coefficient (also in use $\nabla/L^3$)</td>
</tr>
<tr>
<td>$EAR = A_E/A_O$</td>
<td>Propeller diameter (m)</td>
</tr>
<tr>
<td>$F_{nB} = C_V = v/(g \cdot B_{PX})^{1/2}$</td>
<td>Developed area ratio</td>
</tr>
<tr>
<td>$F_{nh} = v/(g \cdot h)^{1/2}$</td>
<td>Designed waterline at rest</td>
</tr>
<tr>
<td>$F_{nL} = F_n = v/(g \cdot L_{WL})^{1/2}$</td>
<td>Expanded area ratio</td>
</tr>
<tr>
<td>$F_{nV} = v/(g \cdot \nabla^{1/3})^{1/2}$</td>
<td>Beam Froude number</td>
</tr>
<tr>
<td>$F_{nV}/2$</td>
<td>Depth Froude number</td>
</tr>
<tr>
<td>$g$</td>
<td>Length Froude number</td>
</tr>
<tr>
<td>$h$</td>
<td>Volumetric Froude number</td>
</tr>
<tr>
<td>$h/D$</td>
<td>Volumetric Froude number of demihull (catamaran)</td>
</tr>
<tr>
<td>$i_c$</td>
<td>Acceleration of gravity (m/s$^2$)</td>
</tr>
<tr>
<td>$K_T = T/(\rho \cdot n^2 \cdot D^4)$</td>
<td>Water depth (m)</td>
</tr>
<tr>
<td>$K_T' = T/(\rho \cdot n^2 \cdot D^2 \cdot A_O')$</td>
<td>Immersion of SPP (m)</td>
</tr>
<tr>
<td>$K_Q = Q/(\rho \cdot n^2 \cdot D^5)$</td>
<td>Half angle of entrance of waterline at bow (deg)</td>
</tr>
<tr>
<td>$K_Q' = Q/(\rho \cdot n^2 \cdot D^3 \cdot A_O')$</td>
<td>Thrust coefficient</td>
</tr>
<tr>
<td>$L = T_a \cdot \sin(\psi + \tau) + N \cdot \cos(\psi + \tau)$</td>
<td>Revised thrust coefficient for SPP</td>
</tr>
<tr>
<td>$L_C$</td>
<td>Torque coefficient</td>
</tr>
<tr>
<td>$L_K$</td>
<td>Vertical propeller force (lift) (kN)</td>
</tr>
<tr>
<td>$L_M = (L_K + L_C)/2$</td>
<td>Chine wetted length (m)</td>
</tr>
<tr>
<td>$L_OA$</td>
<td>Keel wetted length (m)</td>
</tr>
<tr>
<td>$L_P$</td>
<td>Mean wetted length (m)</td>
</tr>
<tr>
<td>$L_{pp}$</td>
<td>Length overall (m)</td>
</tr>
<tr>
<td>$L_{WL}$</td>
<td>Projected chine length (m)</td>
</tr>
<tr>
<td>$L_{WL}/B_{WL}$</td>
<td>Length between perpendiculars (m)</td>
</tr>
<tr>
<td>$L_{WL}/\nabla^{1/3}$ or $L_{WL}/\nabla^{1/3} = (M)$</td>
<td>Waterline length (m)</td>
</tr>
<tr>
<td>$L_{p}/(\nabla/2)^{1/3}$</td>
<td>Length beam ratio</td>
</tr>
<tr>
<td>$LCB$</td>
<td>Slenderness ratio</td>
</tr>
<tr>
<td>$LCG$</td>
<td>Slenderness ratio of demihull (catamaran)</td>
</tr>
<tr>
<td>$LCG/L_P$</td>
<td>Longitudinal center of buoyancy (m)</td>
</tr>
<tr>
<td>$%LCG = (C_{AP} - LCG) \cdot 100/L_P$</td>
<td>Longitudinal center of gravity forward of transom (m)</td>
</tr>
<tr>
<td>$N$</td>
<td>Longitudinal center of gravity aft of $A_p$ centroid (%)</td>
</tr>
<tr>
<td>$n$ or RPM</td>
<td>Force normal to propeller shaft line (kN)</td>
</tr>
<tr>
<td></td>
<td>Propeller rotational speed (1/sec)</td>
</tr>
</tbody>
</table>
Symbols xxiii

\[ J = \frac{v_a}{n} \cdot D \quad \textit{Advance coefficient} \]
\[ J_\psi = \frac{v_a}{n} \cdot \cos(\Psi) \cdot D \quad \textit{Revised advance coefficient for SPP} \]
\[ P \quad \textit{Propeller pitch (m)} \]
\[ P/D \quad \textit{Pitch–diameter ratio} \]
\[ P_B \quad \textit{Brake power (kW)} \]
\[ P_{BTR} \quad \textit{Brake power trial conditions (catamaran) (kW)} \]
\[ P_D \quad \textit{Delivered power (kW)} \]
\[ P_E \quad \textit{Effective power (kW)} \]
\[ P_E^* \quad \textit{Effective in-service power (kW)} \]
\[ p_a \quad \textit{Atmospheric pressure (kPa)} \]
\[ p_h = \rho \cdot g \cdot h \quad \textit{Static water pressure (kPa)} \]
\[ p_v \quad \textit{Vapor pressure of water (kPa)} \]
\[ Q \quad \textit{Propeller torque (kNm)} \]
\[ Q_c = Q/(\rho/2 \cdot D \cdot A_p \cdot v_{0.7R}^2) \quad \textit{Torque load coefficient} \]
\[ RCG \quad \textit{Rise of center of gravity} \]
\[ R_F \quad \textit{Frictional resistance (kN)} \]
\[ R_n = \frac{v}{C_1} \quad \textit{Reynolds number} \]
\[ R_R \quad \textit{Residuary resistance (kN)} \]
\[ R_T = R \quad \textit{Total bare hull resistance (kN)} \]
\[ R_T^* \quad \textit{Total in-service resistance (kN)} \]
\[ R_{Th} \quad \textit{Total bare hull resistance in shallow water (kN)} \]
\[ R/\Delta = (R_T/\Delta)_{100000} \quad \textit{Resistance to weight ratio (for } \Delta = 100,000 \text{ lb = 45.36 t)} \]
\[ R_W \quad \textit{Wave making resistance (kN)} \]
\[ R_{Wh}/R_{Wd} \quad \textit{Shallow water resistance factor} \]
\[ S \quad \textit{Wetted surface area (m²)} \]
\[ (S) = S/\sqrt[2/3]{V} \quad \textit{Wetted surface area coefficient} \]
\[ t \quad \textit{Thrust deduction fraction} \]
\[ T = T_H \quad \textit{Hull draught at DWL (m)} \]
\[ T \quad \textit{Propeller thrust (kN)} \]
\[ T_a \quad \textit{Axial propeller force (kN)} \]
\[ T_h = T_a \cdot \cos(\psi+\tau) - N \cdot \sin(\psi+\tau) \quad \textit{Horizontal propeller force (kN)} \]
\[ v \quad \textit{Velocity of craft (m/s)} \]
\[ v_a = v \cdot (1 - w) \quad \textit{Speed of advance of propeller (m/s)} \]
\[ v_{0.7R} = \left[ v_a^2 + (0.7\pi n D)^2 \right]^{1/2} \quad \textit{Resultant water velocity at 0.7R (m/s)} \]
\[ w \quad \textit{Wake fraction} \]
\[ z \quad \textit{Number of propeller blades} \]
\[ \beta = \arctan \left[ v_a/(0.7 \cdot \pi \cdot n \cdot D) \right] \quad \textit{Hydrodynamic pitch angle at 0.7R} \]
\[ \beta_{EF} \quad \textit{Effective deadrise angle (deg)} \]
\[ \beta = \beta_M \quad \textit{Deadrise angle at midship (L_p/2) (deg)} \]
\[ \beta_{Bpx} \quad \textit{Deadrise angle at B_{PX} (deg)} \]
\[ \beta_T \quad \textit{Deadrise angle at transom (deg)} \]
\( \gamma \)  
Buttock angle (average centerline angle from \( L_p/2 \) to transom) (deg)

\( \delta_W \)  
Angle of transom wedge (catamaran) (deg)

\( \Delta = \nabla \cdot \rho \)  
Displacement, mass (tons)

\( \Delta K_T = K_{T_{\text{atm}}} - K_{T_{\text{cav}}} \)  
K\(_T\) reduction for cavitating conditions

\( \Delta K_Q = K_{Q_{\text{atm}}} - K_{Q_{\text{cav}}} \)  
K\(_Q\) reduction for cavitating conditions

\( \nabla \)  
Displacement volume (m\(^3\))

\( \varepsilon = \beta_M - \beta_T \)  
Warp angle (according to DUT terminology twist angle) (deg)

\( \varepsilon_B = P_B/\Delta \cdot g \cdot v \)  
Specific break power (catamaran)

\( \eta_B \)  
Propeller efficiency behind the vessel

\( \eta_D = P_E/P_D \)  
Propulsive efficiency (quasi-propulsive efficiency)

\( \eta_H = (1-t)/(1-w) \)  
Hull efficiency

\( \eta_O = (K_T/K_Q) \cdot (J/2\pi) \)  
Propeller open water efficiency

\( \eta_P = \eta_H \cdot \eta_R \cdot \eta_S \cdot \eta_O \)  
Overall (total) propulsive coefficient (OPC)

\( \eta_R = \eta_B/\eta_O \)  
Relative rotative efficiency

\( \eta_S \)  
Shaft efficiency (including gearing efficiency)

\( \nu \)  
Kinematic viscosity of water (m\(^2\)/s)

\( \rho \)  
Mass density of water (kg/m\(^3\))

\( \sigma = (p_A+p_H-p_V)/(\rho/2 \cdot v_a^2) \)  
Cavitation number based on advance velocity

\( \sigma_{0.7R} = (p_A+p_H-p_V)/(\rho/2 \cdot v_{0.7R}^2) \)  
Cavitation number based on resultant water velocity at 0.7 radius

\( \tau (\theta \text{ in some references}) \)  
Dynamic (running) trim relative to its value at zero speed (deg)

\( \tau_{BL} = \tau_O + \tau \)  
Baseline trim angle (deg)

\( \tau_c = T/(\rho/2 \cdot A_p \cdot v_{0.7R}^2) \)  
Thrust load coefficient

\( \tau_O \)  
Initial static baseline trim (deg)

\( \Psi \)  
Shaft inclination relative to buttock (deg)
Chapter 1
Introduction

1.1 Objectives

The main goals of this book are to:

- Review various statistically based Mathematical Models (MM) for power prediction
- Spotlight some very useful MMs
- Encourage the HSC designer to use existing MMs.

The core of this work are statistically based MMs based on the results of model experiments of various HSC series. A variety of regression analysis and lately Artificial Neural Network (ANN) methods were used to develop these MMs. The resulting MMs can be easily programmed into software tools, thereby enabling the parametric analyses required for design optimization.

The reason for the abovementioned objectives is the author’s belief that a large number of recently published papers are too complex to be useful in everyday practice. As a consequence, practicing naval architects in need of a power prediction, are indirectly forced to rely on commercial software whose essence is often not properly understood. Moreover, the few decades-old experimental results, MMs, etc., are often considered to be archaic, particularly by the younger engineers, and are hence frequently marginalized, although they have not been replaced by better MMs or routines.

Moreover, MM development is an evolutionary process, i.e. MM developers should be familiar with what their predecessors have done. Thus, one of the objectives of this work is to aid new MM developers by reviewing the existing models along with their principal characteristics and tradeoffs.

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1.2 Conventional High-Speed Craft (HSC)\(^1\)

The term *conventional HSC* is applied here to the high-speed craft of displacement, semi-displacement, and planing types which achieve speeds that include and/or exceed the main resistance hump. This corresponds roughly to the length Froude number \(F_{nL} > 0.4\), volume Froude number \(F_{nV} > 1\), and beam Froude number \(F_{nB} > 0.5\), approximately resulting in the following classifications:

- IMO according to which “HSC is a craft capable of maximum speed equal to or exceeding \(3.7 \cdot \sqrt[0.1667]{m/s}\)” (which is actually equivalent to \(F_{nV} > 1.18\)), and
- ITTC according to which “high-speed marine vehicles are defined to be vessels with a design speed corresponding to a Froude number above 0.45, and/or a speed above \(3.7 \cdot \sqrt[0.1667]{m/s}\), and/or where high trim angles are expected, or for dynamically supported vessels”.

The lowest speed for the dry or fully-vented transom approximately corresponds to \(F_{nL} > 0.3\) or \(F_{nV} > 1\) (Blount 2014).

The relatively wide speed range of HSC should be emphasized. Namely, a single vessel may travel in displacement \((F_{nL} < 0.40)\), semi-displacement \((0.40 < F_{nL} < 0.65)\), semi-planing\(^2\) \((F_{nL} > 0.65\) but \(F_{nV} < 3.0)\), and pure planing regimes \((F_{nV} > 3.0)\). Note that the approximate \(F_n\) values given in parenthesis are typical for slenderness ratio \(L/\sqrt[1/3]{\nabla} \approx 6.0\); see Blount (1995, 2014). Each regime has its peculiarities, so that different parameters are necessary to model the performance for each of them. For instance, for speeds below \(F_{nL} \approx 1\) it is better to use \(F_{nL}\) than \(F_{nV}\) and vice versa (see above). This makes modeling relatively difficult, as it is desirable to describe the performance over the entire sailing regime with the same parameters (input variables) and if possible, with a single continuous equation.

1.3 Resistance, Propulsion, and Power Prediction

Typically, one of the main design objectives is the minimization of power. To achieve this, optimization of the whole system—including resistance, propulsion, and engine

\(^1\)According to the 16th ITTC HSMV Panel, HSC are grouped and divided into following types: (a) Hydrofoils, (b) Hard chine planing craft, (c) Round bilge semi-planing, (d) SWATH ships, (e) Air Cushion vehicles (amphibious), (f) Surface Effect Ships (non-amphibious), and (g) Others. HSC belonging to groups (b) and (c) are treated here.

\(^2\)According to Savitsky (2014) “Vessels operating in the speed range between hull-speed and planing inception speed are totally supported by buoyant forces, hence the use of the terms ‘Semi-Planing’ or ‘Semi-Displacement’ hulls is inappropriate”. Nevertheless, the author of present book decided to continue using those well-established terms, for reasons of continuity and tradition.
1.3 Resistance, Propulsion, and Power Prediction

(with the gearbox)—is necessary, since separate optimization of the components, in isolation to the rest of the system, does not necessarily result in the same answer. The holistic system optimization, i.e. complex or integrated approach, is much more important for the HSC than for conventional displacement vessels. However, in order to achieve some clarity, the current work presents the subject in the conventional way, i.e. MM for resistance and propulsion predictions are presented separately, while the integrated approach is elaborated in Chap. 6. Separate treatment of resistance and propulsion enables independent investigation of the influence of hull and of propeller parameters on hydrodynamic performance. With an integrated approach these influences have to be examined simultaneously, which significantly complicates the evaluation.

One of the key lessons learned is that power prediction for a desired speed (or vice versa, speed prediction for installed power) must be considered from the very early design phases. Moreover, initial predictions of speed should be rechecked whenever any design changes or modifications that affect performance are initiated. Thus, neglecting power prediction during the various design phases often results in degraded performance, and the actual achieved speed is almost certainly below the predicted speed.

For power prediction \( (P_B) \) evaluation of in-service total resistance \( (R_T^*) \) and overall propulsive efficiency \( (\eta_P) \) are necessary as

\[
P_B = P_E^*/\eta_P = R_T^* \cdot v/\eta_P
\]

where \( P_B \) and \( P_E \) are effective and brake powers respectively. Note that routines that model bare hull resistance are usually valid for calm and deep water (denoted here as \( R_T \)). Various additional factors should be taken into account to predict actual in-service performance (e.g. appendages, air resistance, waves, restricted waterways, etc.) and “*” is used after \( P_E \) and \( R_T \) to denote this. Detailed subdivision of HSC total resistance, as well as various components that form \( R_T^* \) are given, for instance, in Müller-Graf (1997a, b), and will be discussed later.

The most significant portion of the overall propulsive efficiency \( (\eta_P) \) is the open water efficiency \( (\eta_O) \) of the selected, presumably optimal, propeller. Assessment of a propeller’s open water efficiency, however, is not a straightforward procedure; it is actually a separate task to determine the best (i.e. optimal) propeller for a given set of requirements. The optimal propeller should produce thrust that overwhelms in-service resistance for both design and off-design conditions. Consequently, the open water efficiency of a propeller is a result of a complete propulsion analysis.

As is well known, the dynamic trim angle \( (\tau) \) is very important for HSC resistance, propulsion, and performance in general. In a way, hull resistance mirrors the dynamic trim angle, and hence dynamic trim angle evaluations usually go hand-in-hand with the resistance evaluations. The relationship between hull resistance and dynamic trim is particularly pronounced for the hump speeds, which HSC cannot avoid, so that modeling this range is of the utmost importance.

Thus, the most significant factors that must be reliably evaluated for power prediction are:
• Bare hull resistance ($R_T$) and Dynamic trim ($\tau$), and
• Propeller’s open water efficiency ($\eta_0$).

Hence, this work is focussed on the mathematical modeling of these factors. Other quantities in the abovementioned equation are also important, but are typically less significant. They are essential parts of power prediction routines, but are not the subject of this work per se. For the sake of completeness, these components are briefly discussed in Chap. 5.

1.4 Common Mistakes

The most common power prediction mistakes are:
• An incorrect prediction model (MM) is selected, i.e. the vessel under analysis has different characteristics than those upon which the MM is based.
• Violation of the boundaries of applicability of MM.

Therefore, it is important to know how a particular MM was developed, the constraints and assumptions it used in formulation. This information is often missing, particularly when commercial power prediction software tools are used. For example, several very important hull or propeller characteristics may be “masked” (i.e. MMs are inherently valid for a particular hull form or propulsor type). These hidden characteristics, which may not be required by a MM should be regarded as additional and prescribed quantities that limit the applicability of a given MM. In other words, wise usage of readymade computer programs requires that the designers are familiar with the characteristics of the hull- and propeller-series the MM is based on, as well as with the technique used for its derivation.

MacPherson (1993) gives a good review of dos and don’ts concerning numerical prediction techniques. Some recommendations deserve to be cited:
• Not all methods are appropriate for all problems.
• Know your prediction method. The numerical procedure must be fully understood.
• Complete and reliable program cannot ignore the user. The human interface is very important.
• Numerical methods cannot eliminate model testing.

1.5 Excluded Topics

1.5.1 Resistance Evaluation Using Empirical Methods

Not addressed in this work is the Savitsky (1964) method. It is based on equations for prismatic hull forms and is by far the most frequently used amongst various empirical
methods. The other planing hull resistance prediction methods are mentioned in Almeter (1993). Savitsky’s method is applicable for higher planing speeds where hydrodynamic forces are dominant. Note that Savitsky’s method was modified a few times (see for instance Blount and Fox 1976; Savitsky 2012).

1.5.2 Resistance Evaluation Using Computational Fluid Dynamics (CFD)

It is believed that the CFD-based methods will become common everyday tools in the future. At this time however, CFD still depends very much on interpretation of the simulated results by the user. Therefore, these methods are typically not yet sufficiently mature to be used by regular engineers in everyday engineering practice. CFD’s subjective nature (Molland et al. 2011; Almeter 2008) is also not yet practical for application within broader numerical optimization tools (typically nonlinear multi-criterion optimization with constraints), where evaluations of resistance and propeller efficiency are just segments of an integrated approach. CFD applied to HSC is given for instance in Savander et al. (2010), Brizzolara and Villa (2010), Garo et al. (2012), and De Luca et al. (2016).

Actually, CFD and the MMs treated here are complementary methods, although they are fundamentally different techniques. Namely, MMs based on experimental data provide a low-cost and reasonably accurate preliminary design tool. If needed, further analysis, improvements and hull/propeller adjustments should be done using CFD and/or tow tank tests. Furthermore, designers typically do not do their own CFD evaluations; these are usually done by the CFD specialists, thereby resulting in ‘once-removed’ relationships that are similar to experimental facilities (tow tank, cavitation tunnel etc.). This may change in the future as CFD tools become more practical and useful to designers.

The state-of-the-art viewpoint on statistical power performance predictions and CFD, is given by Van Hees (2017):

- Statistical methods are fast, while CFD (including 3D hull modeling etc.) require time.
- In practice, CFD is used to supplement statistical methods, with the objective to further optimize the hull form.

1.5.3 Other Excluded Topics

High-Speed Ships

MMs based on the experimental series with hull forms that resemble displacement ships more than HSC are not treated here, although they are valid for relatively high
speeds (\(F_{nL}\) approaching 1 or so). In other words MMs for high-speed ships are not the subject of this work (for instance, Fung and Leibman 1993; Bojović 1997, etc.).

**Not Released Mathematical Model**

MMs for hull/propeller series for which complete and usable MMs have not been released are excluded. For instance, the following high-speed hull and propeller series are valuable, but have not been addressed here:

- MARIN systematic series of fast displacement hulls consisting of no less than 33 models, see Kapsenberg (2012), or
- SVA high-speed, 3-bladed, inclined shaft propeller series consisting of 12 models; see Heinke et al. (2009).

**Commercial Software**

MMs found in commercial software programs are also excluded. Note, however, that most of them are based on the routines that are discussed here.

**Waterjets**

Waterjets in general, as for their sizing cooperation with the waterjet manufacturer is usually required.

**References**

Fung SC, Leibman L (1993) Statistically-based speed-dependent powering predictions for high-speed transom stern hull forms. Chesapeake Section of SNAME
Savitsky D (1964) Hydrodynamic design of planing hulls. Mar Technol 1(1)
Chapter 2
Mathematical Modeling

2.1 Statistical Modeling

Mathematical modeling which is of interest for present work belongs to the *predictive modeling* class, as opposed to *explanatory* or *descriptive* modeling. According to Shmueli (2010): “Predictive modeling is a process of applying a statistical model or data mining algorithm to data for the purpose of predicting new or future observations... The goal is to predict the output value (Y) for new observations given their input values (X)”. The modeling process segregated into a set of steps is described in Fig. 2.1 (Shmueli 2010).

Note that the first three steps are usually performed by one team and the rest by another, although it would be desirable if the entire process was executed by a single multidisciplinary team. In addition, the entire modeling process (steps 1–8) is usually performed solely by the engineers, although knowledge of subject-matter mathematics, specifically statistics, is desirable (see for instance Weisberg 1980; Draper and Smith 1981).

The basic steps given in Fig. 2.1 are clear and logical, and MM developers naturally follow them. Note that Step 4, abbreviated EDA (Exploratory Data Analysis), usually requires transformation of the available data into a format suitable for mathematical modeling. EDA is a very important step because various variables, and their eventual transformations, should be considered at this point in the process. The choice of dependent (target), and most influential independent (input) variables (Step 5); statistical data modeling tool, i.e. MM extraction methods (Step 6); evaluation and selection of final MM amongst several considered (Step 7); and use of recommended MM together with reporting (Step 8); all follow Step 4 and are therefore affected by the decisions made there.
Datasets as treated here are usually scarce, so that data partitioning\(^1\) is often avoided and all available data is used for building of the MM. This, however, requires thorough MM validation (Step 7), particularly stability checking (possibility of wav- ing between the tested values). Moreover, the use of the entire dataset produces repeatable results, as the holdout samples are usually randomly selected.

The reliability of a MM (predictive accuracy or predictive power according to Shmueli 2010) is very important, particularly when MM is applied to everyday design problems when the correct value is not known, and the user relies on the MM’s predictive accuracy. Therefore, during the development phase, the following should be checked in order to verify the derived model:

- Statistics of the accuracy of the model versus the data set used to develop the model
- Discrepancies between evaluated and measured values
- Behaviour of the model between the data points, where there are no measurements (naturally within the applicability boundaries).

### 2.1.1 Statistical Modeling Applied to Ship Data

The author of this work never considered parameters of no physical significance or no physical meaning to be primary input variables, despite their possible high statistical correlation. Correlation analysis among the independent variables and versus the dependent variable, was always performed in order to ensure the validity of the selection. When methodical series data is used, the input variables are usually the same as the parameters varied during the model-based series’ testing.

Note that the main disadvantage of the statistical data modeling tools is that only a limited number of variables are used to adequately describe the HSC’s hull form and loading over a relatively wide speed range. For this reason, the secondary hull

\(^1\)Data partitioning, to data that are used for MM development (often called the training set), and to the holdout sample which MM “did not see” (expression from Shmueli 2010) is not unusual. The purpose of the holdout sample is to validate the MM, thus it is also named the validation set.
form parameters are important and should be regarded as a kind of supplement to the MM.

To clarify, the input parameters for a HSC could for example be \( L/\sqrt[3]{V} \), \( L/B \), and \( B/T \). These hull and loading parameters, although most significant, do not reflect the hull form, i.e. whether it is a hard chine or a round bilge type, and if hard chine then whether it is wide- or narrow-transom, etc. Additional hull description is obviously necessary. This is provided through the secondary hull parameters. However, the secondary hull parameters are often not explicitly specified, but the MM is instead described as being valid for, for instance, the NPL series. This therefore means that the MM is based on the semi-displacement round bilge hulls whose secondary parameters are \( C_B = 0.397 \), \( LCB = 6.4\%L \text{ aft. amidship} \), \( A_T/A_X = 0.52 \), etc. (see Table 3.1). Thus, the additional information typically given in the form of a comment such as “MM is valid for (or is based on) the NPL series” is a very important supplement of the MM. Similarly, the secondary parameters for the propellers would include information about the blade shape and section etc. Naturally, the MM user must be aware of this fact.

Statistical power performance predictions for conventional ships, with a focus on the developmental philosophy of prediction methods, are discussed in a related paper (Van Hees 2017). Amongst the observations is that the statistical methods should be “refreshed” when some new data is available.

### 2.2 Model Extraction Tools

The author used two methods—statistical data modeling tools—to extract (i.e. develop) the mathematical models for prediction of resistance and propulsive coefficients:

- Regression analysis, and
- Artificial Neural Networks (ANN).

Note that there are several types of regression and ANN methods, but further elaboration on this topic is beyond the scope of the present text.

#### 2.2.1 Regression Analysis

With regression analysis, and in particular with the linear multiple regression analysis (e.g. Weisberg 1980), the independent variables consist of two sets of input data:

- Basic independent variables, and
- Various transformations of basic independent variables.