Cambridge University Press
978-1-107-14206-0 — Ship Resistance and Propulsion
2nd Edition
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1 Introduction

The estimation of ship propulsive power is fundamental to the process of designing and operating a ship. A 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 operating costs. The estimation of power entails the use of experimental techniques, numerical methods and theoretical analysis for the various aspects of the powering problem. The requirement for this stems from the need to determine the correct match between the installed power and the ship hull form during the design process. An understanding of ship resistance and propulsion derives from the fundamental behaviour of fluid flow. The complexity inherent in ship hydrodynamic design arises from the challenges of scaling from practical model sizes and the unsteady flow interactions between the viscous ship boundary layer, the generated free-surface wave system and a propulsor operating in a spatially varying inflow.

History

Up to the early 1860s, little was really understood about ship resistance and many of the ideas on powering at that time were erroneous. Propeller design was very much a question of trial and error. The power installed in ships was often wrong and it was clear that there was a need for a method of estimating the power to be installed in order to attain a certain speed.

In 1870, W. Froude initiated an investigation into ship resistance with the use of models. He noted that the wave configurations around geometrically similar forms were similar if compared at corresponding speeds, that is, speeds proportional to the square root of the model length. He propounded that the total resistance could be divided into skin friction resistance and residuary, mainly wavemaking, resistance. He derived estimates of frictional resistance from a series of measurements on planks of different lengths and with different surface finishes [1.1], [1.2]. Specific residuary resistance, or resistance per ton displacement, would remain constant at corresponding speeds between model and ship. His proposal was initially not well received, but gained favour after full-scale tests had been carried out. HMS *Greyhound* (100 ft) was towed by a larger vessel and the results showed a substantial level of agreement with the model predictions [1.3]. Model tests had been vindicated and the way opened for the realistic prediction of ship power. In a 1877 paper, Froude gave a detailed explanation of wavemaking resistance which lent further support to his methodology [1.4].

In the 1860s, propeller design was hampered by a lack of understanding of negative, or apparent, slip; naval architects were not fully aware of the effect of wake. Early propeller theories were developed to enhance the propeller design process, including the momentum theory of Rankine [1.5] in 1865, the blade element theory of Froude [1.6] in 1878 and the actuator disc theory of Froude [1.7] in 1889. In 1910, Luke [1.8] published the first of three important papers on wake, allowing more realistic estimates of wake to be made for propeller design purposes. Cavitation was not known as such at this time, although several investigators, including Reynolds [1.9], were attempting to describe its presence in various ways. Barnaby [1.10] goes some way to describing cavitation, including the experience of Parsons with *Turbinia*. During this period, propeller blade area was based simply on thrust loading, without a basic understanding of cavitation.

By the 1890s the full potential of model resistance tests had been realised. Routine testing was being carried out for specific ships and tests were also being carried out on series of models. A notable early contribution to this is the work of Taylor [1.11], [1.12] which was closely followed by Baker [1.13].

The next era saw a steady stream of model resistance tests, including the study of the effects of changes in hull parameters, the effects of shallow water and to challenge the suitability and correctness of the Froude friction values [1.14]. There was an increasing interest in the performance of ships in rough water. Several investigations were carried out to determine the influence of waves on motions and added resistance, both at model scale and from full-scale ship measurements [1.15].

Since about the 1960s there have been many developments in propulsor types. These include various enhancements to the basic marine propeller such as tip fins, varying degrees of sweep, changes in section design to suit specific purposes and the addition of ducts. Contra-rotating propellers have been revisited, cycloidal propellers have found new applications, waterjets have been introduced and podded units have been developed. Propulsion-enhancing devices have been proposed and introduced including propeller boss cap fins, upstream preswirl fins or ducts, twisted rudders and fins on rudders. It can of course be noted that these devices are generally at their most efficient in particular specific applications.

From about the start of the 1980s, the potential future of computational fluid dynamics (CFD) was fully realised. This would include the modelling of the flow around the hull and the derivation of viscous resistance and free-surface waves. This generated the need for high quality benchmark data for the physical components of resistance necessary for the validation of the CFD. Much of the earlier data of the 1970s were revisited and new benchmark data developed, in particular, for viscous and wave drag. Much of the gathering of such data has been coordinated by the International Towing Tank Conference (ITTC). Typical examples of the application of CFD to hull form development and resistance prediction are given in [1.16] and [1.17].

Propeller theories had continued to be developed in order to improve the propeller design process. Starting from the work of Rankine, Froude and Perring, these included blade element-momentum theories, such as Burrill [1.18] in 1944, and Lerbs [1.19] in 1952 using a development of the lifting line and lifting surface methods where

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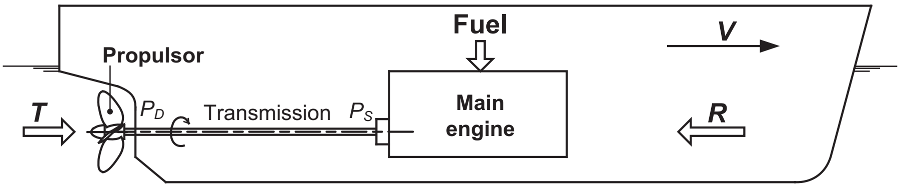

Figure 1.1. Overall concept of energy conversion.

vorticity is distributed over the blade. Vortex lattice methods, boundary element, or panel, methods and their application to propellers began in the 1980s. The 1990s saw the application of CFD and Reynolds-Averaged Navier–Stokes (RANS) solvers applied to propeller design and, bringing us to the current period, CFD modelling of the combined hull and propeller [1.20].

Powering: Overall Concept

The overall concept of the powering system may be seen as converting the energy of the fuel into useful thrust (T) to match the ship resistance (R) at the required speed (V), Figure 1.1. It is seen that the overall efficiency of the propulsion system will depend on:

Fuel type, properties and quality.
The efficiency of the engine in converting the fuel energy into useful transmittable power.
The efficiency of the propulsor in converting the power (usually rotational) into useful thrust (T).

The following chapters concentrate on the performance of the hull and propulsor, considering, for a given situation, how resistance (R) and thrust (T) may be estimated and then how resistance may be minimised and thrust maximised. Accounts of the properties and performance of engines are summarised separately.

The main components of powering may be summarised as the effective power P_E to tow the vessel in calm water, where $P_E = R \times V$ and the propulsive efficiency η, leading to the propulsive (or delivered) power P_D, defined as: $P_D = P_E/\eta$. This is the traditional breakdown and allows the assessment of the individual components to be made and potential improvements to be investigated.

Improvements in Efficiency

The factors that drive research and investigation into improving the overall efficiency of the propulsion of ships are both economic and environmental. The main economic drivers amount to the construction costs, disposal costs, ship speed and, in particular, fuel costs. These need to be combined in such a way that the shipowner makes an adequate rate of return on the investment. The main environmental drivers amount to emissions, pollution, noise, antifoulings and wave wash.

The emissions from ships include NOx, SOx and CO_2, a greenhouse gas. Whilst NOx and SOx mainly affect coastal regions, carbon dioxide (CO_2) emissions have a global climatic impact and a concentrated effort is being made worldwide towards

Table 1.1. *Potential savings in resistance and propulsive efficiency*

RESISTANCE (a) Hull resistance	Principal dimensions: main hull form parameters, U- or V-shape sections Local detail: bulbous bows, vortex generators Frictional resistance: WSA, surface finish, coatings
(b) Appendages	Bilge keels, shaft brackets, rudders: careful design
(c) Air drag	Design and fairing of superstructures Stowage of containers
PROPULSIVE EFFICIENCY (d) Propeller	Choice of main dimensions: *D, P/D, BAR*, optimum diameter, rpm. Local detail: section shape, tip fins, twist, tip rake, skew etc. Surface finish
(e) Propeller–hull interaction	Main effects: local hull shape, U, V or 'circular' forms [resistance vs. propulsion] Changes in wake, thrust deduction, hull efficiency Design of appendages: such as shaft brackets and rudders Local detail: such as pre- and postswirl fins, upstream duct, twisted rudders

their reduction. The International Maritime Organisation (IMO) is coordinating efforts in the marine field.

In order to promote energy-efficient ship design and to quantify, monitor and control CO_2 emissions from ships, the IMO has introduced an Energy Efficiency Design Index (EEDI), which came into force as a mandatory regulation from January 2013. This is described and discussed in Chapter 17.

The likely extension of a carbon dioxide based emissions control mechanism to international shipping will influence the selection of propulsion system components together with ship particulars. Fuel costs have always provided an economic imperative to improve propulsive efficiency. The relative importance of fuel costs to overall operational costs influences the selection of design parameters such as dimensions, speed and trading pattern. Economic and environmental pressures thus combine to create a situation which demands a detailed appraisal of the estimation of ship propulsive power and the choice of suitable machinery. There are, however, some possible technical changes that will decrease emissions, but which may not be economically viable. Many of the auxiliary powering devices using renewable energy sources, and enhanced hull coatings, are likely to come into this category. On the basis that emissions trading for ships and/or a CO_2 tax may be introduced in the future, all means of improvement in powering and reduction in greenhouse gas emissions should be explored and assessed, even if such improvements may not be directly economically viable. This is discussed further in Chapter 17.

The principal areas where improvements might be expected to be made at the design stage are listed in Table 1.1. It is divided into sections concerned first with resistance and then propulsive efficiency, but noting that the two are closely related in terms of hull form, wake fraction and propeller–hull interaction. It is seen that there is a wide range of potential areas for improving propulsive efficiency.

Power reductions can also be achieved through changes and improvements in operational procedures, such as running at a reduced speed, weather routeing, running at optimum trim, using hydrodynamically efficient hull coatings, hull/propeller cleaning and roll stabilisation. Auxiliary propulsion devices may also be employed, including wind assist devices such as sails, rotors, kites and wind turbines, wave propulsion devices and solar energy.

The following chapters describe the basic components of ship powering and how they can be estimated in a practical manner in the early stages of a ship design. The early chapters describe fundamental principles and the estimation of the basic components of resistance, together with influences such as shallow water, fouling and rough weather. The efficiency of various propulsors is described including the propeller, ducted propeller, supercavitating propeller, surface-piercing and podded propellers and waterjets. Attention is paid to their design and off-design cases and how improvements in efficiency may be made. Databases of hull resistance and propeller performance are included in Chapters 10 and 16. Worked examples of the overall power estimate using both the resistance and propulsion data are described in Chapter 18.

References are provided at the end of each chapter. Further more detailed accounts of particular subject areas may be found in the publications referenced and in the more specialised texts such as [1.21] to [1.30].

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2 Propulsive Power

2.1 Components of Propulsive Power

During the course of designing a ship it is necessary to estimate the power required to propel the ship at a particular speed. This allows estimates to be made of:

(a) Machinery masses, which are a function of the installed power, and
(b) The expected fuel consumption and tank capacities.

The power estimate for a new design is obtained by comparison with an existing similar vessel or from model tests. In either case it is necessary to derive a power estimate for one size of craft from the power requirement of a different size of craft. That is, it is necessary to be able to *scale* powering estimates.

The different components of the powering problem scale in different ways and it is therefore necessary to estimate each component separately and apply the correct scaling laws to each.

One fundamental division in conventional powering methods is to distinguish between the *effective power* required to drive the ship and the *power delivered* to the propulsion unit(s). The power delivered to the propulsion unit exceeds the effective power by virtue of the efficiency of the propulsion unit being less than 100%.

The main components considered when establishing the ship power comprise the ship resistance to motion, the propeller open water efficiency and the hull–propeller interaction efficiency, and these are summarised in Figure 2.1.

Ship power predictions are made either by

(1) Model experiments and extrapolation, or
(2) Use of standard series data (hull resistance series and propeller series), or
(3) Theoretical (e.g. components of resistance and propeller design).
(4) A mixture of (1) and (2) or (1), (2) and (3).
(5) Comparison with existing similar vessels.

2.2 Propulsion Systems

When making power estimates it is necessary to have an understanding of the performance characteristics of the chosen propulsion system, as these determine the operation and overall efficiency of the propulsion unit.

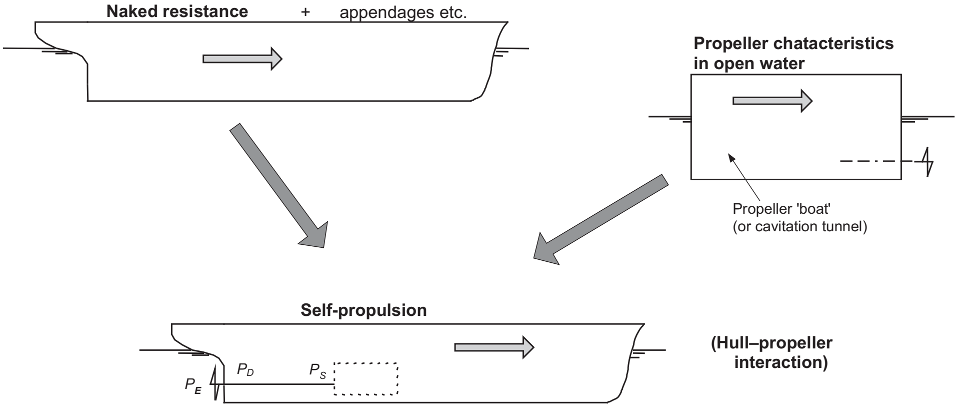

Figure 2.1. Components of ship powering – main considerations.

A fundamental requirement of any ship propulsion system is the efficient conversion of the power (P) available from the main propulsion engine(s) [prime mover] into useful thrust (T) to propel the ship at the required speed (V), Figure 2.2.

There are several forms of main propulsion engines including:

Diesel.
Diesel/LNG (dual fuel).
Gas turbine.
Steam turbine.
Electric.
(And variants/combinations of these.)

and various propulsors (generally variants of a propeller) which convert the power into useful thrust, including:

Propeller, fixed pitch (FP).
Propeller, controllable pitch (CP).
Ducted propeller.
Waterjet.
Azimuthing podded units.
(And variants of these.)

Each type of propulsion engine and propulsor has its own advantages and disadvantages, and applications and limitations, including such fundamental attributes as size, cost and efficiency. All of these propulsion options are in current use and the choice of a particular propulsion engine and propulsor will depend on the ship type and its design and operational requirements. Propulsors and propulsion machinery are described in Chapters 11 and 13.

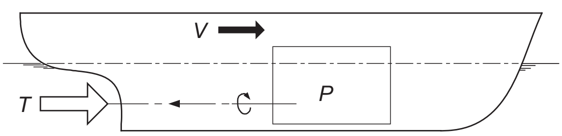

Figure 2.2. Conversion of power to thrust.

The overall assessment of the marine propulsion system for a particular vessel will therefore require:

(1) A knowledge of the required thrust (T) at a speed (V), and its conversion into required power (P),
(2) A knowledge and assessment of the physical properties and efficiencies of the available propulsion engines,
(3) The assessment of the various propulsors and engine-propulsor layouts.

2.3 Definitions

(1) Effective power (P_E) = power required to tow the ship at the required speed
= total resistance × ship speed
$= R_T \times V_S$
(2) Thrust power (P_T) = propeller thrust × speed past propeller
$= T \times Va$
(3) Delivered power (P_D) = power required to be delivered to the propulsion unit (at the tailshaft)
(4) Quasi-propulsive coefficient (QPC) (η_D) $= \dfrac{\text{effective power}}{\text{delivered power}} = \dfrac{P_E}{P_D}$.

The total installed power will exceed the delivered power by the amount of power lost in the transmission system (shafting and gearing losses), and by a design power margin to allow for roughness, fouling and weather, i.e.

(5) Transmission Efficiency (η_T) $= \dfrac{\text{delivered power}}{\text{power required at engine}}$, hence,
(6) Installed power (P_I) $= \dfrac{P_E}{\eta_D} \times \dfrac{1}{\eta_T}$ + margin (roughness, fouling and weather)

The powering problem is thus separated into three parts:

(1) The estimation of effective power
(2) The estimation of QPC (η_D)
(3) The estimation of required power margins

The estimation of the effective power requirement involves the estimation of the total resistance or drag of the ship made up of:

1. Main hull naked resistance.
2. Resistance of appendages such as shafting, shaft brackets, rudders, fin stabilisers and bilge keels.
3. Air resistance of the hull above water.

The QPC depends primarily upon the efficiency of the propulsion device, but also depends on the interaction of the propulsion device and the hull. Propulsor types and their performance characteristics are described in Chapters 11, 12 and 16.

The required power margin for fouling and weather will depend on the areas of operation and likely sea conditions and will typically be between 15% and 30% of installed power. Power margins are described in Chapter 3.

The overall components of the ship power estimate are summarised in Section 2.4.

2.4 Components of the Ship Power Estimate

The various components of the ship power estimate and the stages in the powering process are summarised in Figure 2.3.

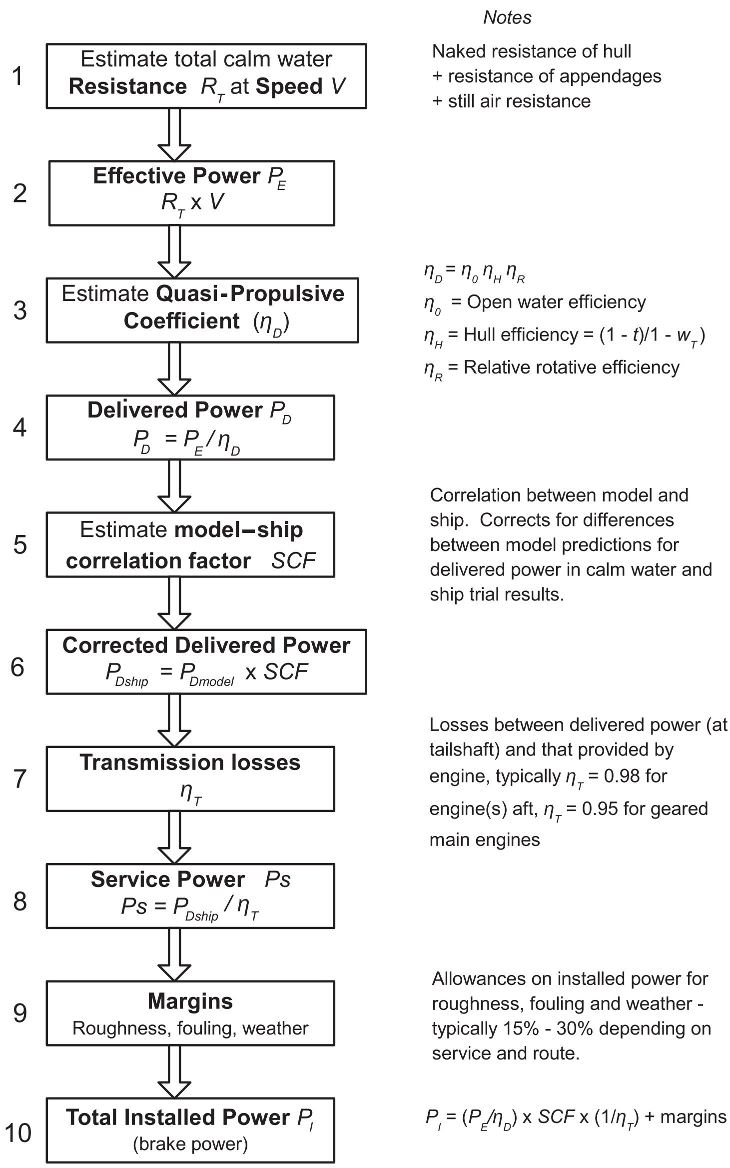

Figure 2.3. Components of the ship power estimate.