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**Developments in Fluid Mechanics Theory
and Ship Design before Trafalgar**

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DEVELOPMENTS IN FLUID MECHANICS THEORY AND SHIP DESIGN BEFORE TRAFALGAR

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Summary

The ships of Trafalgar were designed and built well before this famous battle. Their design is based on practical experiences and to a lesser extent on new theoretical insights gained throughout the 18th c. During that century new foundations were laid in fluid mechanics by such prominent scientists as Newton, the Bernoullis, Bouguer, Euler, D'Alembert, Jorge Juan and many others. On the other hand a pioneering group of naval architects including Sutherland, Blaise Ollivier, Duhamel du Monceau and Chapman are witnesses for early attempts of applying nascent, often still immature scientific insights to ship design.

In this paper an assessment of design methodologies and of the gradually increasing knowledge on hydromechanical performance will be presented for the fleets of Trafalgar, both for ships of the line and for frigates. This will tend to reveal a dominance of empirically based design, tempered at best by a growing physical understanding of sailing ship performance. In conclusion, this review will demonstrate how much we must respect the practical success of empirically based design of the great sailing warships despite still prevailing, but gradually diminishing deficits in ship fluid mechanics theory.

1. Introduction

This Congress deals with the technology of the ships of Trafalgar. This famous sea battle in 1805 is an important military and political event in the history of Europe. The ships that fought at Trafalgar represented the fleets of three major and traditional seafaring nations in Europe, the British Fleet under NELSON with 27 ships of the line, the Combined Fleet of the French/Spanish alliance under VILLENEUVE with 33 ships of the line, plus a few other smaller vessels in auxiliary roles on both sides. These ships, the pride of their nations in gallant seamanship, embodied the most advanced technological know-how, shipbuilding experience, design knowledge and physical understanding of their era. This knowledge, acquired in the course of several centuries in the development of the great sailing warships, a matter of the highest technological prestige, had reached a very far advanced level by the time of Trafalgar. An analysis of the technology of the ships of Trafalgar, their design, construction and performance, thus also mirrors the technical culture and scientific awareness of a whole era.

The development of the sailing warships with guns has lasted several centuries and has been promoted by many technological, military and political influences. Jan GLETE [1] has very aptly described the processes that led to the formation of those sailing navies and has distinguished the following major developments:

- (1) "The gunpowder revolution" (abt. 1450-1650): A technological development, resulting in a new type of sailing warship as a gun platform, gradually rendering rowed warships obsolete.
- (2) "The military revolution" (after 1700): The establishment of professional state armies and navies.
- (3) "The bureaucratic revolution" (after abt. 1650): The increasing dominance in national states of centralized administrative power over naval affairs.

To this we may add:

- (4) “The scientific revolution” (abt. 1600-1700): The growing influence of the natural sciences in the century from Galileo to Newton and their impact on technical applications, also in ship design.

In the 18th c., leading up to the navies of Trafalgar, all of these driving forces were still in full effect in naval developments in England, France and Spain as well as other maritime nations. In fact, it is during this period that the combined application of technological, administrative and scientific innovations was brought to bear on national naval developments. France under COLBERT and his successors responsible for the French Navy took an early lead in very deliberate efforts of applying science to technical decisions, especially in fleet development and ship design. Spain after mid-century followed a similar route; Britain did the same but much more hesitantly and much later. It is still a matter of dispute whether any such delayed acceptance of new scientific insights really mattered to the ships of Trafalgar. This issue will certainly be addressed in this paper and others at this Congress.

It can be argued that the terminology of “revolutions” for the leading motive forces of naval innovation, as used above, is exaggerated since all of these trends lasted for extended periods and in fact tended to be rather evolutionary. In fact, regarding the “Scientific Revolution”, a designation apparently first introduced by the French science historian Alexandre KOYRÉ in 1939, SHAPIN [2] has claimed that such a revolution never occurred. Such objections to such terminologies do not matter in the present context concerning the ships of Trafalgar. Rather we are interested in the question whether the attempted concerted application of technological, organizational, and scientific knowledge did or did not create any positive synergies in naval innovation for the ships of Trafalgar. This paper will focus on developments in ship fluid mechanics and in hydrodynamic ship design as a specific test case for this broader issue. In fact, the study will concentrate on ships of the line, which formed the dominant core of the battle fleets of Trafalgar, and on frigates in their subsidiary role, which as smaller, faster ships due to their different operational missions and functional requirements permit to highlight a different spectrum of achievements in naval technology.

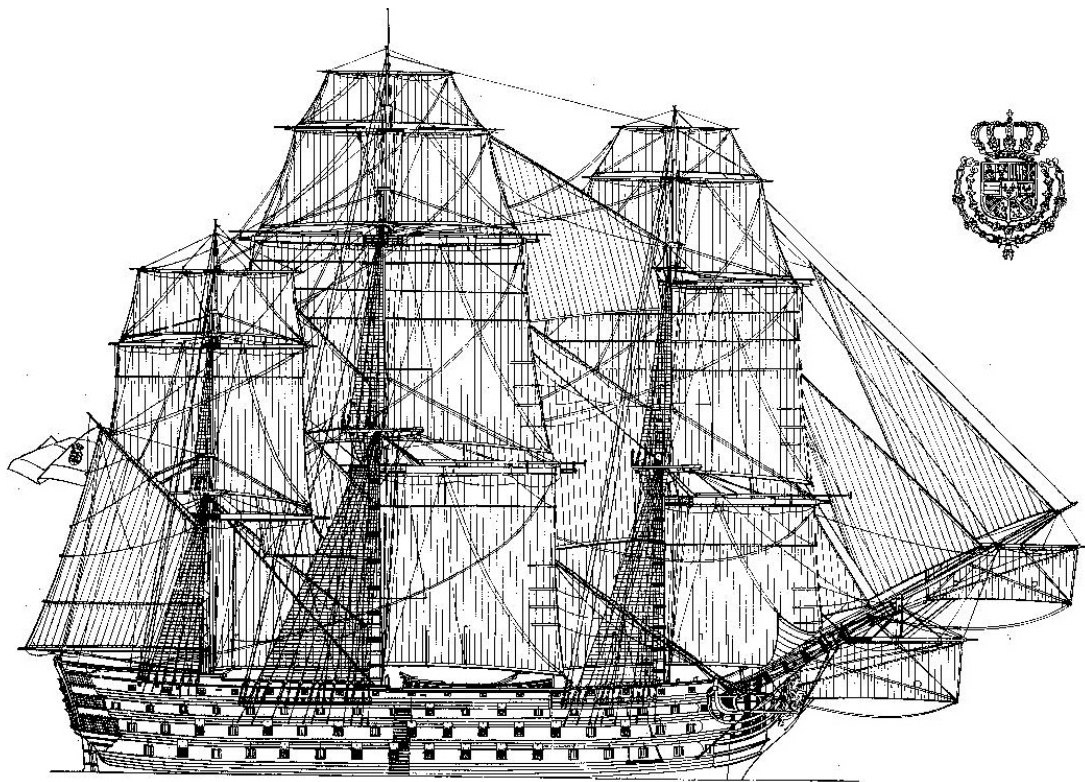


Fig. 1: Schematic silhouette of the Spanish ship of the line *Santísima Trinidad* (from [3]).

The method of investigation will be principally to look for the roots of the knowledge embodied in the actual ships, i.e., to trace the knowledge genesis and dissemination, to search for any changes in design approach and its knowledge background and to identify the consequences of new or still missing physical understanding. This method can be applied regardless of whether the source of the knowledge is strictly empirical or is augmented by hypotheses derived from interpretations of physical observations.

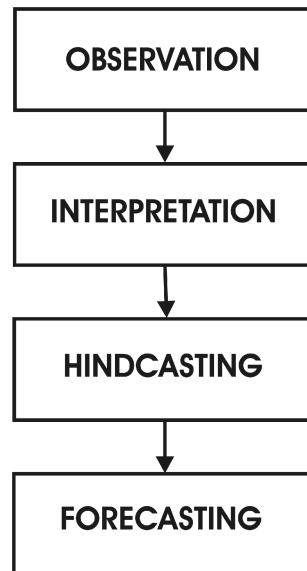


Fig. 2: Stages of the scientific learning process (knowledge genesis process)

The learning process in the transition from craftsmanship to scientifically founded technologies goes through several stages (Fig. 2):

- Observation of physical phenomena and the class of design objects in their physical environment
- Interpretation, i.e., physical explanation of observations, often based on correlation of empirical data
- Hindcasting, i.e., quantitative analysis based on assumed hypotheses for the performance of an object when built
- Forecasting, i.e., prediction of performance properties for an intended design before building

In the beginning of the 18th c. ship design was based almost solely on observation and its skilful interpretation. During that century it went through a transition to deliberate hindcasting and forecasting, more successfully in some areas than in many others. The ships of Trafalgar thus represent an early milestone in a much longer range development. This does not at all detract from the value of the new insights gained during the 18th c.

The main body of this paper is structured into three sections: The design objectives for the ships of Trafalgar (Section 2), the history of ship fluid mechanical knowledge during the 18th c. (Section 3), and an assessment of ships in their main hydrodynamic performance characteristics (Section 4).

In conclusion this discussion will help to answer some of the following questions with a view to the ships of Trafalgar:

- How were hydromechanically relevant design decisions taken in practice and how did this affect ship performance?
- Where did ship design actually benefit from growing scientific insight?

- Where and how did emerging new theories still fall short of practical applicability?

2. Design objectives

During the 18th c. the functional requirements for naval ships and their operational strategies, whether they were to be deployed offensively in sea battles or defensively in protective missions, had only very gradually further developed so that the design objectives for the naval fleets had become rather standardized. Different missions required specialized classes of ships, viz., ships of the line as floating gun platforms in sea battles, generally heavier and slower, and the lighter, faster frigates for cruising missions. (These were two-deckers with only one gun-deck with around 40 guns, which had gained increasing popularity since about 1750 (GARDINER/ LAVERY [4])). The following design objectives (Fig. 3) form a common denominator for both classes of ships, though with different orientations and priorities for each class.

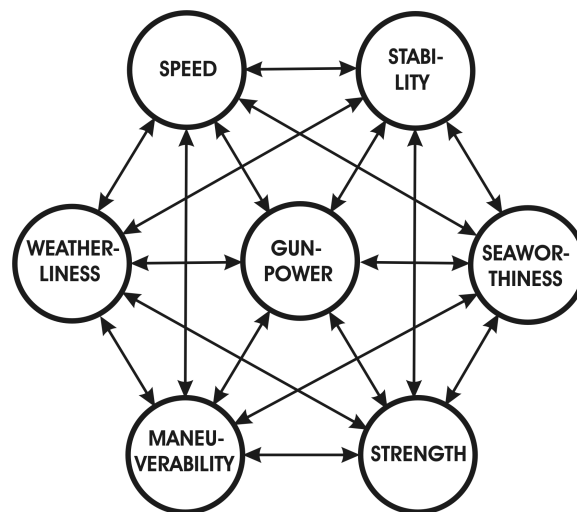


Fig. 3: Design objectives for sailing warships of the Trafalgar era

Gun-power,

measured by the number of guns, their caliber and range, is a core requirement in design, directly related to mission purposes and usually stipulated by the navy administration. Its significance corresponds to that of the payload in a cargo ship, although the weights of guns and ammunition amount to only about 10 percent of the displacement for ships of the line (BOUDRIOT [5]). The targeted gun-power is a main determining factor for ship size, both for the displacement and for the required space to arrange and operate the armament on the vessel's gun decks. The placement of heavy guns on one or more of the upper decks, well above the waterline, results in a critical top-heaviness in these ships, which has to be balanced by placing ballast deep in the hull and by other measures.

Gun shot calibers had become standardized for technological and economical reasons, reaching the advanced levels of 36-pounders in France and Spain, 32-pounders in Britain (GLETE [1]). The goal was the ability to fire heavy broadsides, often by many guns simultaneously, at short range of only a few hundred meters, in short intervals, say, of less than two minutes with a well-trained crew (HENDERSON [6]).

Speed

Ship speed is a valuable asset in combat missions as well as cruising. The attainable speed depends on hull resistance and the propulsive power provided by the rig. Both aspects were of significant concern to the designers. Speed and endurance determine the radius of action.

Stability

The ships must possess adequate transverse stability despite their top-heavy arrangement of guns. In battle condition they should be stiff enough to limit the heel angle under wind so as to be able to use the guns on the leeward side. Too much stiffness must be avoided, too, to prevent short roll periods and abrupt accelerations.

Weatherliness

is the ability of the ship to sail close to the direction of the wind. This gives advantages in cruising as well as in mobility during battle.

Seaworthiness

is based on the performance of the ship in a seaway aiming at limited ship motions and accelerations with sufficiently long natural periods of roll, heave and pitch.

Maneuverability

comprises good coursekeeping on steady cruising courses and good turning ability in critical maneuvers.

Strength

is of paramount importance in wooden warships. The structure of the vessel must be able to sustain extreme local loads to carry heavy guns on several decks, to protect itself against the enemy's heavy gunfire and possibly against the shocks of collision. At the same time the hull girder is strained in longitudinal deformation, aggravated by guns being placed near the ends of the vessel where buoyancy forces are small. These loads result in the much dreaded hull girder deformation called "hogging", a limiting factor to ship length.

These design objectives interact with each other (Fig.3) and often result in conflicting requirements. E.g. larger sails on higher masts and longer spars, also more slender underwater hull shapes, will improve sailing speeds, but do impair stability, thus reducing gun carrying capacity. As a result it is difficult to give superior speed to a large, heavily armed ship and conversely to turn a smaller, fast sailing vessel into a good gun platform. In consequence, during the era before Trafalgar two specialized classes of ships had been developed by the various navies:

- a) Ships of the line, i.e., large battleships concentrating on superior gun-power and staying power, but with lower speed and often limited seaworthiness.
- b) Frigates, i.e., smaller cruising vessels designed for high speed and good weatherliness and seaworthiness, but with more limited firepower.

Each of these ship classes in every major navy became highly standardized, down to the level of individual parts, during the second half of the 18th c. The advantages of such standardization were economical, logistical and tactical in operations.

It is the designer's task to reconcile these often partially conflicting design objectives. The quality of the compromise depends on the mission profile of the ship, which sets the priorities. For offensive roles and combat tasks e.g. the attained gun-power is usually the leading objective, though normally related to the building and operating cost of the ship since most navies were quite cost conscious. Thus the navy desired the most economical ship for a given gun-power. This generally led to the ship of the smallest size still accommodating its intended armament, though this principle was more strictly adhered to in Britain than in France or Spain (GLETE [1]). The other design objectives contributed to the overall success of the vessel, but served more as constraints providing permissible ranges for acceptable solutions.

Within such ranges the designer would choose a suitable ship size (displacement), length, breadth, draft and depth, principal form coefficients and local shape parameters, a hull shape and a rig design. The following sections will review the nature of these decisions more deeply against the background of the available technological, practical and scientific naval architecture knowledge in the 18th c.

3. Early ship fluid mechanics

1.1 Overview

During the 18th c. the essential foundations of modern rational fluid mechanics were laid. Flow phenomena and fluid forces acting on ships were among the earliest practical applications of fluid mechanics from these beginnings. Simultaneously practical shipbuilding by experience had accumulated a substantial body of knowledge. Both of these sources of expertise were able to contribute to the design of the ships for the era before Trafalgar. But how much dialogue went on between practitioners and scientists and how did they influence each other? How much of this knowledge is reflected in the ships of Trafalgar?

There exists an abundance of literature, both on the roots of modern fluid mechanics and on the practitioners' wealth of know-how. Many literary sources stem from contemporary writers of that era, numerous others from more recent reviews and secondary literature.

As for the origins of the science of modern fluid mechanics it is possible to distinguish several generations of key developments (similar to CALERO [7]):

(1) The precursors (before 1700):

Simon STEVIN (1548-1620), hydrostatics,
Blaise PASCAL (1623-1663), aerostatics,
Christiaan HUYGENS (1629-1695), resistance measurements.

(2) The founders (ca. 1700-1720):

Edmé MARIOTTE (1620-1684), discharge and resistance measurements,
Isaac NEWTON (1643-1727), laws of fluid motion and fluid forces,
Jakob BERNOULLI (1655-1705), system equilibrium, forces and moments on bodies.

(3) The classical era (ca. 1720-1740):

Daniel BERNOULLI (1700-1782), hydrodynamics,
Johann BERNOULLI (1667-1748), hydraulics,
Henri de PITOT (1695-1771), hydraulic machinery,
Pierre BOUGUER (1707-1751), ship stability, ship theory,
Benjamin ROBINS (1707-1751), ballistics.

(4) Field theory (1740-1760):

Jean Le Rond D'ALEMBERT (1717-1783), fluid motions in continuum mechanics,
Leonhard EULER (1707-1783), fluid forces, pressures, velocities based on field theory,
Alexis-Claude CLAIRAUT (1713-1765), hydrostatics founded on field theory.

(5) The new experimentalists (ca. 1760-1780):

Jean-Charles de BORDA (1733-1799), resistance measurements of simple shapes,
Charles BOSSUT (1730-1814), towing tests of simple shapes,
Jorge JUAN Y SANTACILIA (1713-1773), ship resistance, ship motions,

Frederik Henrik af CHAPMAN (1721-1808), hull shape, ship resistance tests,
Mark BEAUFOY (1764-1827), frictional resistance.

This synoptic listing, which cites many of the most outstanding scientists who were representative of their generation, serves only to characterize the dominant trends in each era, but is far from complete. Fortunately many excellent reviews and accurate, systematic accounts of the early history of fluid mechanics in the 18th c. exist. To name only a few of those most relevant to our present context: Clifford TRUESDELL's monograph [8] on "Rational Fluid Mechanics, 1687-1765" has become a classic text on the early history of fluid mechanics, written from the viewpoint of an analytical mechanist. István SZABÓ [9] embeds the theme of fluid mechanics in the general history of mechanics and of mechanical principles. Ludwig RANK [10] writes primarily on the history of sailing theory, sail forces and aerodynamics. Thomas WRIGHT [11] in his thesis at UMIST concentrates on the early history of ship hydromechanics, embodied in the mainstream of fundamental developments. Julián Simón CALERO [7] in his more recent, engineering flavored book presents a very thorough review of the genesis of scientific fluid mechanics with the major emphasis on the resistance of a solid in a fluid and the discharge of liquids from containers. Dirk BOENDEL's dissertation [12] of 2001 provides a comprehensive documentation and comparative analysis of the late 18th c. frigates from Britain, France and the USA, including their hydrodynamic design and performance. He will report his essential results at this Congress. Larrie D. FERREIRO [13] in his very recent thesis takes a broader view of the origins of naval architecture in the Scientific Revolution with special chapters on ship stability, resistance theory and maneuvering. Rupert A. HALL [14], the well-known science historian, takes an interesting outsider's glimpse at the early history of scientific naval architecture from the 17th to the 19th c. Taken together with the primary sources of the 18th c. this body of review literature leaves little to be desired for a comprehensive assessment.

It is thus not necessary and not intended here to recapitulate the chronology of important developments in that creative period to any great detail. Rather in the following let us concentrate on those key elements in the chain of events which are somehow relevant to ships and hence potentially to the design of the ships of Trafalgar, either as fundamentals of fluid mechanics or as direct applications to ships. The review to be presented here will therefore follow a thematic structure and contrast the increasing scientific understanding with the patterns of practical design decision-making.

The practitioners' body of knowledge fortunately is also reasonably well documented in treatises, reports and books written by contemporary witnesses and shipbuilders. We will for this purpose primarily refer to the treatises and monographs by Anthony DEANE [15], Nikolaes WITSEN [16], William SUTHERLAND [17], Blaise OLLIVIER [18], Henri-Louis DUHAMEL DU MONCEAU [19], Mungo MURRAY [20], Frederik Henrik af CHAPMAN [21], William HUTCHINSON [22] and David STEEL jr. [23].

3.2 Thematic Knowledge

Ø Ship Geometry

The "skeleton first" shipbuilding practice of large sailing ships in the 18th c. has its origins in medieval ancestors (RIETH [24]). In the "mediterranean method" (RIETH [25]), widespread in Italy, France and the Iberian peninsula, ship geometry was defined by a lofting process full scale on a lofting floor, which resulted in planar master templates, called sestis (in Venice), maître gabarîts (in France) etc. These templates, one master template per ship, were used in marking ship frames and some other planar parts for fabrication in the skeleton first method. This technology also resorted to certain rules of longitudinal interpolation to derive section shapes and hence frame contours at arbitrary stations throughout ship length from a single master template valid amidships. The master section shape amidships was traditionally composed of piecewise circular arcs, plus a few straight lines, hence also the derived section shapes at other stations. Longitudinal

fairness of the hull shape was further ensured during assembly by pegging provisional longitudinal ribbands against the initially erected skeleton of transverse frames for alignment. This technology was used until well into the 18th c., though gradually improved by other lofting approaches. It was well suited for accurate series production of ships, but was not very flexible in geometry variation and in the definition of more complex shapes.

The shipbuilder's drawing table for scale drawings of the hull shape originated before 1600 (e.g. by the English naval architect Mathew BAKER (see BARKER [26])). The ship lines plan, a drawing of ship lines in three orthogonal views, as a medium for developing and documenting ship geometry, evolved further during the 17th c. and had reached full maturity as a design representation by abt. 1700 in several European countries. The French navy required such lines plans as contractual documents after 1720 (see FERREIRO [13]). The technique soon spread from major yards, involved in government projects, to smaller, private yards. By that time the shipbuilder's drafting spline had become a well accepted tool in lines fairing (RAALAMB [27]). Section shapes remained predominantly composite circular arcs throughout the 18th c. However the lofting process for deriving fair sections from the master sections now benefitted from interpolation along "diagonals", i.e., oblique planar intersections of hull shape, by means of rules of proportionate subdivision (BOUDRIOT [28]). This rendered hull shape variation more flexible. The developments in lofting practices, especially with splines, are reviewed in [29] by NOWACKI.

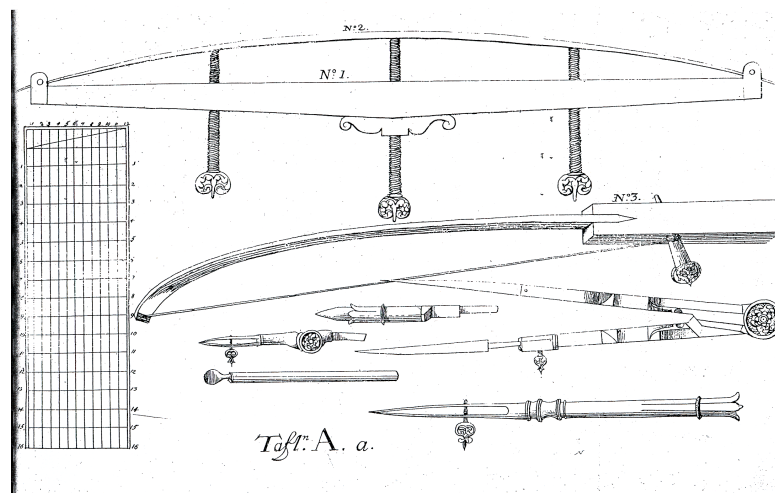


Fig. 4: Mechanical shipbuilding spline as a fairing tool (RAALAMB [27], 1691)

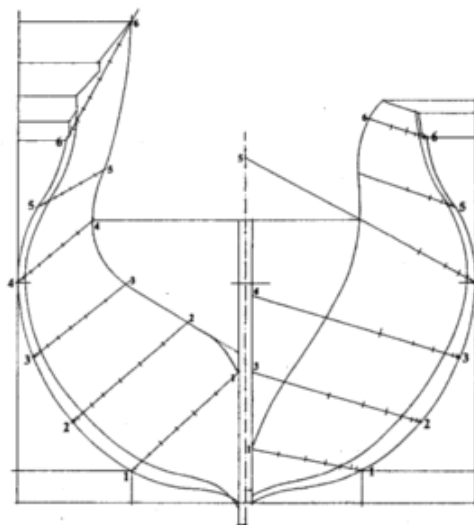


Fig. 5: Body plan generated with the aid of proportionately subdivided diagonals (BOUDRIOT [28]).

In Britain lofting methods had been somewhat different by tradition. They were also based on piecewise circular arcs for the midship section, but the longitudinal geometric operations involved a set of auxiliary lines, the “rising lines” and “narrowing lines”, which resulted in different rules for the section shapes at some longitudinal station inheriting shape elements from the master section. William SUTHERLAND [17] describes this process under the title of “whole-moulding”. In essence this approach, too, strongly adhered to circular arcs in the sections. The reasons for these practices, here as elsewhere, lay in a convenient adherence to traditional lofting methods and tools rather than in any functional advantages.

A change of consciousness slowly began around the middle of the 18th c., when Pierre BOUGUER [30], the French academician, not only criticized the stagnant methodologies of geometric design, but above all introduced the methods of calculus and numerical integration for measuring the properties of ship curves and volumes. This gave the designer new methods for quantitative assessment of the geometric characteristics of shape elements regardless of the drafting tools by which these shapes were generated. This is how an analytical and numerical perspective of ship geometry originated, quite aside of the advantage that the hydrostatic and stability properties of the ship could be measured by the same kind of process. To add to these achievements BOUGUER also first defined the block coefficient CB and the waterplane coefficient CWP as dimensionless measures of essential shape characteristics of underwater hull form. This facilitated direct comparisons between different hull shapes and designs.

Another important contribution to ship geometric design was made by Frederik Henrik af CHAPMAN [21], the Swedish naval constructor. He not only made a strong impression on his professional peers and the general public by his masterful graphical documentation of ship shapes by lines plans and perspective drawings in his “Architectura Navalis Mercatoria” [31]. There he demonstrated the maturity of drafting skills, which became so versatile that one may claim that “any desired shape” could be described in this fashion. But he also was scientifically well educated and mathematically oriented enough to base his design on numerical and analytical assessments of ship geometry. The profession also owes him the concept of the Sectional Area Curve (SAC), a diagram of underwater section areas against ship length, as a crucial tool in hull design for controlling the longitudinal distribution of the displacement.

In the 18th c. when geometry was much in vogue many other useful discoveries were made and applied to ship geometry. Essentially the definition of ship geometry, which had been an advanced trade skill by 1700, reached a new mature level by virtue of new scientific methods for evaluating geometric traits of ships. Thereby each ship could be so described geometrically that a quantitative reference was established to correlate all other observations on the performance of this hull, especially those in fluid mechanics, against an accurate definition of hull geometry. This is a main prerequisite for a scientific approach.

Ø Hydrostatics and ship stability

The physical principles of hydrostatics for floating bodies had first been investigated and described by ARCHIMEDES [32] in antiquity. The famous principle of ARCHIMEDES deals with the equilibrium of weight and buoyancy forces and holds for bodies of arbitrary shape, hence also ships. ARCHIMEDES also treated the hydrostatic stability of floating objects of simple shapes, a truncated sphere and a paraboloid of revolution. In this context he derived the restoring moments in an inclined position, hence indirectly the righting arms. His approach is reviewed by NOWACKI [33].

This knowledge lay dormant for almost two millennia. It was the Flemish/Dutch mechanicist and engineer Simon STEVIN [34] who first rediscovered and reestablished hydrostatics and extended its application also to ships. He introduced the concept of

“hydrostatic pressure” in a liquid, which was unknown in antiquity and in the Middle Ages, and equated the hydrostatic pressure head at a point in the liquid to the weight of a column of fluid resting on that point. Thus forces on vessels could be determined as a pressure resultant acting on boundaries. Blaise PASCAL [35] later proposed similar laws as a foundation for aerostatics.

Early attempts to measure and calculate ship displacement between two floating conditions of a ship, say, between the empty and fully loaded condition, are reported by Anthony DEANE [15] and Nikolaes WITSEN [16]. They relied on numerical quadrature rules, based on polygonal and circular approximants, as was common practice in volume measurement of containment vessels. Ship size determination by tonnage measurement rules had developed during several centuries, but was approximate in principle and often inaccurate. A more precise calculation of ship displacement became feasible only after the adoption of calculus in the 18th c.

Just before the middle of the 18th c. it was Pierre BOUGUER (“*Traité du Navire*” [30], 1746) and Leonhard EULER (“*Scientia Navalis*” [36], 1749) who almost simultaneously, but independently founded modern ship hydrostatics and ship stability theory, based on physical laws and infinitesimal calculus. The displacement was thus defined by the integral of the hydrostatic pressure distribution over the submerged hull surface. Likewise the transverse stability criterion was expressed by assuming the vessel slightly heeled and evaluating whether the couple formed by the downward ship gravity force (displacement) and the equal and opposite upward buoyancy force, the resultant of the hydrostatic pressures in the inclined position, produced a positive restoring action (Figs. 6 and 7). BOUGUER on this basis invented the “metacenter” as a discriminant for stability at small angles of heel, beyond which the center of gravity of the ship must not rise for positive stability. EULER instead derived the restoring moment of the heeled vessel directly via calculus, but came to the same criterion expression as BOUGUER. For a detailed comparison of these two approaches and their context, see NOWACKI AND FERREIRO [37].

In Bouguer’s case this new knowledge spread rather quickly to French naval constructors, hence to the French navy, and soon also internationally to other European navies and shipbuilding countries. It was fortunate that BOUGUER, an academician at the Paris Royal Academy, found strong support not only from the Minister of the Navy, MAUREPAS, but also from DUHAMEL DU MONCEAU, Inspector-General of the French Navy, BOUGUER’s loyal adherent and glowing admirer, who founded the first French School of

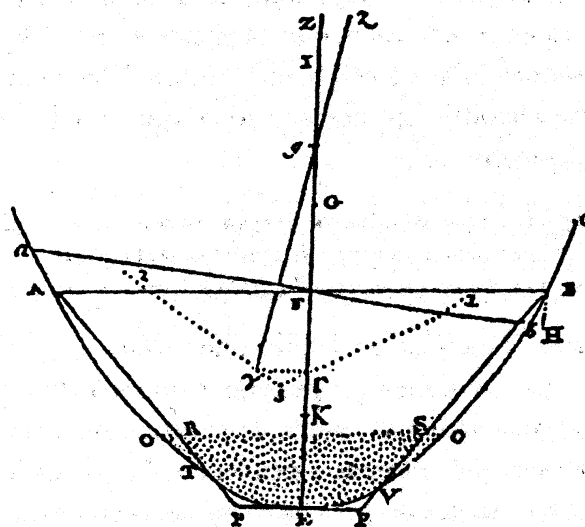


Fig. 6: Schematic diagram for deriving the metacenter as a stability criterion (BOUGUER [30], 1746)

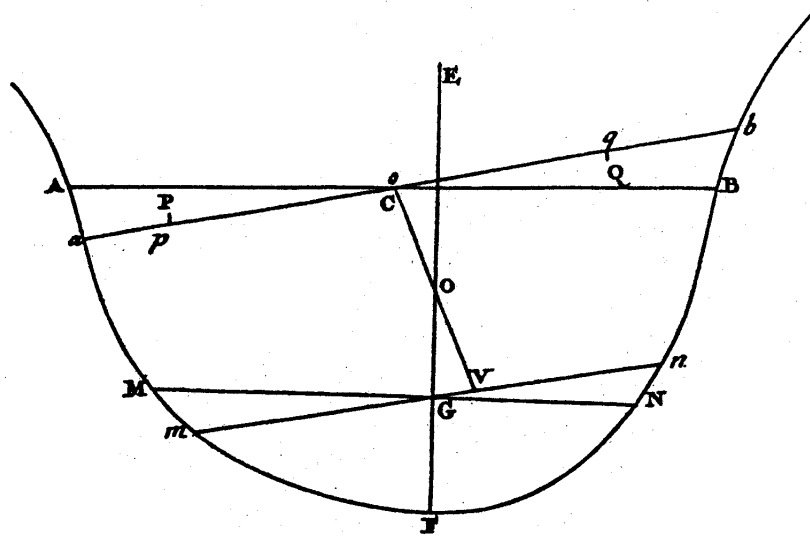


Fig. 7: Schematic diagram for deriving the initial restoring moment as a stability criterion (EULER [36], 1749)

Naval Constructors in Paris in 1741, wrote a famous textbook ([38], 1752) for the naval trainees with many practical helps for implementing BOUGUER's ideas, and made this knowledge an examination topic for French naval constructors. This included instructions for performing the required integrations by numerical quadrature using the trapezoidal rule, which was easy to implement. The French Navy then soon routinely performed calculations of displacement and metacentric height at the design stage for every new design. DUHAMEL's book spread to other countries, was translated or excerpted (Mungo MURRAY [39]) and helped to promote practical knowledge on ship stability. For many further details in these developments see the elaborate presentation by FERREIRO [13].

BOUGUER also furnished the physical foundations for performing inclining experiments to deduce the metacentric height by measuring the heeling inclination after applying a specified transverse heeling moment by excentric loads. Such experiments are known to have been made by 1748 (FERREIRO [13]). However practitioners for a long time continued to adhere to the traditional methods of observing heeling angles resulting from transverse shifts of internal weights (cargo or crew), a more qualitative test method. In France BORDA's Rule was used after abt. 1783 to measure initial stability by setting a standard for the allowable heeling inclination under a specified transverse weight shift (FERREIRO [13]).

EULER's heavy, two volume *Scientia Navalis* [36], written in Latin, took longer to reach and to be understood by practitioners, perhaps also because it did not offer numerical examples and calculation guidance. But his insights became better known when he later (1772) published a partly abridged, partly extended and updated French version of this book, the "Théorie complete de la construction et de la manœuvre des vaisseaux" [40]. An editorially modified reprint of this book in France also served as a textbook.

The attainment of this new level of knowledge in ship hydrostatics and stability must be regarded as a remarkable success for scientists and practitioners alike. For the first time historically an important performance parameter of the ship, governing its safety, could be evaluated at the design stage and the ship could be modified to meet the requirements before it was built. This may have saved many expensive later corrections or in fact prevented ship losses. This achievement probably also promoted the reputation of the French Navy of being scientifically oriented, and in this case with legitimate success.

BOUGUER and EULER also made many other practical suggestions for applications of ship stability theory in ship design and operations. This included predicting the effects of loading, unloading and weight shifts aboard etc. Yet it must also be kept in mind that their stability measures were not yet completely adequate to judge the ship's stability in all respects and in all critical conditions. The following aspects e.g. were still missing in the 18th c.:

- Stability at finite angles of heel:

Although both BOUGUER and EULER realized that their first criteria held only for "initial stability", i.e., for very small (infinitesimal) angles of heel and both hinted how this deficit might be removed, BOUGUER e.g. presented a metacentric curve for arbitrary heel angles, they did not in practice show how to perform such calculations. The first practical calculations of "righting arm curves (GZ)" for a ship through its full range of stability were performed by George ATWOOD and H.-S. VIAL DU CLAIRBOIS [41], [42] in 1796 and 1798, hence too late to influence any of the ships of Trafalgar. In fact, it took well into the 19th c. before righting arm curve calculations became a more routine matter.

- Stability loads:

Little quantitative knowledge, let alone scientific theories, existed to estimate the heeling moments experienced by a ship. This goes for wave loads in a seaway, wind forces on the rig (for lack of accurate sail force theories) as well as heeling moments due to the recoil actions of guns. Thus the required GM could not be specified on strictly physical grounds. Such knowledge was accumulated only much later, also by the experiences in ship classification.

- Dynamic effects:

The prediction of ship motions and of their effects on dynamic stability was still in its infancy.

- Damage stability.

The stability of ships in a damaged, partially flooded condition was not yet taken into consideration.

Despite these remaining open questions on certain physical aspects of ship stability it is fair to state that the developments of the 18th c. in the design integration of stability criteria was a success story for scientists and practical men. Design decisions thus gained a more rational basis by means of quantifiable criteria.

Ø Resistance and Speed

- Precursors

The resistance experienced by a body moving in a fluid is an ancient question of mankind. ARISTOTLE [45] already posed this question in the context of falling masses, ballistics and even sailing ships, though he did not offer a correct solution. In the modern era interest was revived by GALILEO and thereafter by applications in ballistics (resistance of projectiles in air), hydraulic machines and instruments (like windmills, waterwheels, pumps), but also by a growing practical interest in ship resistance and sail propulsion. By 1700 these issues had developed into a prestigious topic for early modern science, often substantially promoted by government interest and material support.

The scientific roots of modern ship resistance hydrodynamics can be found in the 17th century. Christiaan HUYGENS and Edmé MARIOTTE, both members of the Parisian Academy of Sciences and collaborators on this subject for a while, deserve prime credit for overcoming a long scholastic stalemate by resorting to experimental observations on the relationship between speed and resistance of an object in a fluid flow. HUYGENS

first conducted model tests with simple ship shapes in 1669 in a small towing tank using a falling weight apparatus (Fig. 8). He established experimentally that the resistance was proportional to velocity squared:

$$R \sim V^2$$

His results were not widely circulated and were only posthumously published in 1698 [46].

MARIOTTE by contrast used resistance objects at rest submerged in a moving fluid, e.g., by placing a flat plate in parallel inflow in a river current (Fig. 9) and measuring the resistance by a balance apparatus. He came to the same conclusions as HUYGENS regarding the quadratic velocity law. He also performed experiments in air and observed that the resistance of a shape was proportional to the density ρ of the fluid:

$$R \sim \rho V^2$$

MARIOTTE completed his tests by 1684; they were also posthumously published in 1686 [47].

Both HUYGENS and MARIOTTE offered explanations for the V^2 law based on an argument from solid mechanics: If e.g. you double the velocity, then the rate of flow impinging on the object is doubled and the impact transmitted per unit of mass is also doubled, hence the force is quadrupled.

HUYGENS' and MARIOTTE's essential experimental results of pre-Newtonian fluid mechanics were of lasting value and gave a structure to resistance research in the following century. The key remaining open question concerned the influence of object shape on flow characteristics and hence on resistance. NEWTON was probably not aware of these earlier results, published only after his work on the first edition of "Principia" (1687) was completed, though he should have known about them when he wrote his later editions. But he derived equivalent conclusions on his own grounds and in full agreement on these aspects. Thus to that extent a firm foundation was laid for ship resistance research in the following century.

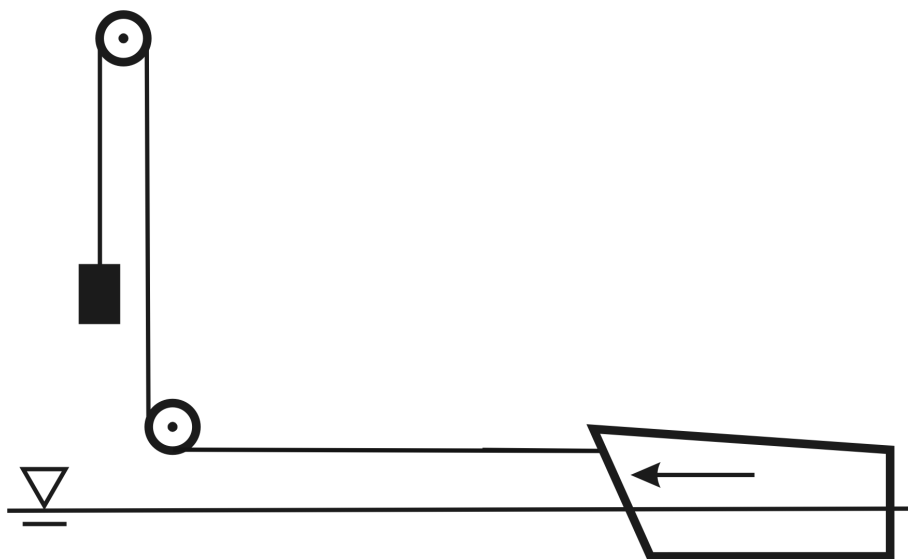


Fig. 8: Towing test apparatus using a falling weight after HUYGENS [46]

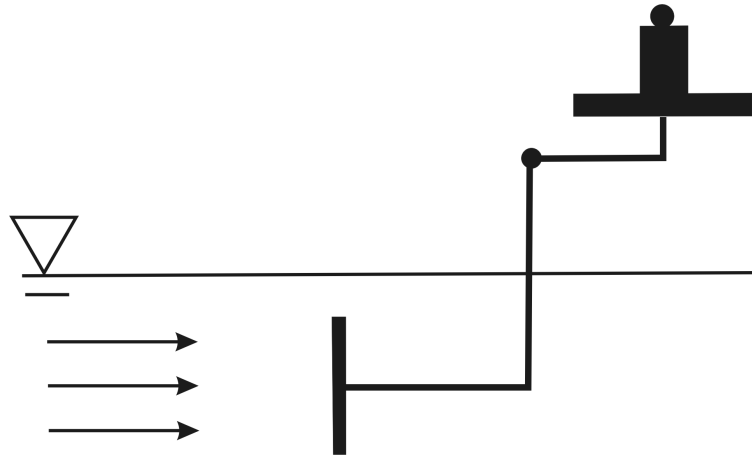


Fig. 9: Resistance measurement apparatus of a flat plate in parallel inflow after MARIOTTE [47]

o Newton

NEWTON's work in his *Principia* [48] is fundamental to the genesis of scientific fluid dynamics, based on physical principles and amenable to being expressed by mathematical models. NEWTON's physical interpretation of the laws of fluid flows created many original ideas of lasting value, but also generated several others that raised disputes and were eventually rejected. Yet there is no doubt that his propositions in fluid dynamics set the stage for a whole century of discussions and developments, thus marking a new starting point for a scientific approach. Again we refer to the literature for systematic reviews of NEWTON's contributions and shortcomings (e.g. TRUESDELL [8], CALERO [7]) and concentrate here on those fundamentals which became relevant to the fluid dynamics of ship resistance.

Book II of NEWTON's *Principia* ("On the Motion of Bodies" Part II) deals with the motion of fluids. NEWTON defines a *fluid* "as a body (of matter) whose parts yield to any applied force and in yielding are readily displaceable relative to each other". Note that this definition does not state anything on the properties of the fluid material. Subsequently NEWTON distinguishes between air and liquids (like water, oil, mercury) and introduces their properties for separate treatment later. It becomes apparent that his work was strongly motivated by his main interest in the ballistics of projectiles in air, though he also deals with applications in liquids.

Chapters I-III of Book II discuss the motion dynamics of a projectile in a fluid for the cases of assumed *linear* or *quadratic* or *hybrid* velocity laws of the resistance. Thus here the question of the dependence of the resistance on velocity is still left open. NEWTON performed experiments with a pendulum suspended on a string and swinging within a fluid (air or water) to determine the velocity exponent in the resistance law from the damping in this system. The results were inconclusive and left NEWTON hesitant about the correct resistance law in a real fluid.

NEWTON clearly recognizes the existence of inertial effects, i.e., of forces originating in the fluid's inertia, and of "lubricity" (his word for viscosity) effects. In view of his other work he is no doubt also aware of gravity effects on fluid matter. Yet a significant share of his discussion is confined to fluids in which the resistance is caused only by inertia mechanisms, analyzed by his *Lex Secunda* (force equals temporal change of momentum).

Chapter VII of Book II is the centerpiece of his discussion of resistance in fluid flow, where he addresses the issue of dynamic similitude between fluid systems, the dependence of resistance on some main parameters and the artifice of the "rare medium"

to derive specific resistance expressions. In Proposition 32, Theorem 26 he asserts: “If two systems (of fluid matter) are geometrically similar, corresponding particles being in correspondig locations and of proportional dimensions, and if they start a motion in a similar, proportionate way, and if the accelerative forces acting between the particles are proportional to velocity square and inversely proportional to the particle diameter etc., then the two systems will move in a similar way and continue to be similar. I.e. under these premises *geometric similitude* and *dynamic similitude* will be preserved. These premises hold in systems subject to inertial effects. Thus the theorem presents a definition of dynamic similitude for fluids subject to inertial forces, which is the starting point for NEWTON’s later deduction of his famous law of dynamic similitude.

In Prop. 33, Th. 27 he goes on to claim: “Under the same premises similar rigid bodies in similar fluid systems will experience resistance forces proportional to the fluid density ρ , the velocity square (V^2) and some characteristic diameter square (D^2)”. I.e. under the premises of Prop. 32 the resistance is caused by fluid particle motions, which are governed by corpuscular inertial effects (*lex secunda*), and hence dimensionally is proportional to $\rho V^2 D^2$. Thus this dependence of the resistance is justified by an argument based on the required dynamic similitude between similar systems. Thus the resistance of a body, originating in the fluid’s inertia, moving in such a fluid can be described by

$$R \sim \rho V^2 D^2$$

$$\text{or } R = C_D \rho V^2 A$$

where A = some reference area of the system, usually taken as a cross section of the body, projected on a plane normal to the onset velocity
 C_D = resistance coefficient of the given shape in the given onset flow

The remarkable fact is that under these assumptions C_D , the resistance or drag coefficient, is constant for the given shape, i.e., independent of speed V and area size A . This expression thus describes the resistance of a shape by a “*single term, constant drag coefficient resistance law*”. Note that this holds only in this case where only the category of inertia effects is taken into account.

The determination of the coefficient C_D can be pursued by measurement in experiments or analytically by further assumptions on the properties and behavior of the fluid. NEWTON tested both methods, but on the analytical track in view of the complexity of the general case of fluid flow was obliged to confine himself to special cases with further incisive simplifying assumptions. For this purpose he invents the artifice of a “rare medium”, i.e., a purely conceptual fluid medium of certain hypothetical properties which render the resistance problem amenable to treatment by his corpuscular, inertial force model. He does not claim that a rare medium does exist in physical reality, although he may have conjectured that air will act in a similar way to a rare medium, but he deduces the resistance of certain given shapes (sphere, cylinder, cone) in such a medium only for the case if one did exist.

A “rare medium” (Prop. 34, Th. 28) is introduced as a corpuscular medium whose particles are of equal mass and size and are moving in a flow with small, but finite distances. The particles are treated as non-interacting among themselves. The fluid is regarded as elastic (like air), i.e., when its particles strike the surface of an object they are reflected and bounce back as in elastic impact. NEWTON investigates the examples of the resistance of a sphere and a cylinder in parallel onset flow in a rare medium. In these derivations he lays the ground for what by his successors would later be formalized as “impact theory”. He assumes essentially that in this rare medium the particles in the onset flow will reach the object with undiminished velocity, strike the front face of the object, be reflected elastically and move on, again without interacting with other particles. The back side of the object and, for that matter, any parallel sides as in a cylinder, do not suffer any particle impact and hence do not contribute to resistance. The

resistance is found by summing the components in the direction of the onset flow of the particle impact forces over the face of the object. From these assumptions NEWTON derives e.g. that in a rare medium the drag coefficient of a sphere is half that of a cylinder:

$$C_{D\text{sphere}} = \frac{1}{2} C_{D\text{cylinder}}, \text{ and numerically } C_{D\text{sphere}} = 2, C_{D\text{cylinder}} = 4.$$

These numerical values were derived for an elastic rare medium, while in an inelastic one they would be halved. They are actually of no lasting consequence, were much disputed and later even modified by NEWTON himself. NEWTON stated very explicitly that water was not a rare medium. He nowhere even said that air was, though he may have had some thin gas in mind. More cautiously one should underscore that NEWTON did not even claim that a “rare medium” existed anywhere in nature. This caveat was blatantly ignored by his later successors and adherents who blindly applied “impact theory” to objects in water (and air). It is clear from NEWTON that he meant such fluids also to be subject to viscosity and gravity effects.

Later developments in the mechanics of similitude clearly demonstrated, if a fluid motion was caused or governed by inertia effects AND either gravity or viscous effects (two categories of forces), then the coefficient C_D could no longer be constant, but had to depend on one parameter of similitude (Reynolds or Froude number). Moreover, if all three classes of forces were acting simultaneously in a fluid, then a *single term, variable coefficient resistance law* was no longer sufficient, but for the case of two parameters of similitude *multiple term laws or more complex expressions* with more free coefficients are required (compare e.g. with FROUDE’s hypothesis). This is all obvious now, but was not to NEWTON’s contemporaries and successors in the 18th c. Rather several overzealous scientists then tried to fit their observation data (and theories) to the wrong structure of resistance expression (single term, constant coefficient). This method amounts to “data fitting”, has no physical justification and statistically applies only within a given sample. These advocates then “discovered” that for a constant C_D the “velocity law” was no longer square, but had to have a fractional exponent, a physical impossibility (violation of unit consistency). Thus many famous theories and experimental evaluations of the 18th c., based on single term expressions, were doomed to failure to start with, *not only* because of the unwarranted application of impact theory.

The failure of “impact theory” and other single term, constant coefficient resistance theories and test evaluations in the 18th c. cannot be blamed on NEWTON, who clearly said “real fluids” like water are not “rare media”. Ironically it was rather by NEWTON’s most glowing admirers and most ardent disciples, who overzealously and imprudently applied NEWTON’s resistance expression as a “common rule” far outside its stated range of validity, that the reputation of fluid dynamic theory for the resistance problem was damaged throughout the century before Trafalgar.

- Early applications of impact theory

Soon after the publication of NEWTON’s *Principia* a flurry of activities arose, mainly among mathematicians and mathematically inclined mechanicians, to apply the new theory to more and more test cases and to check its physical validity. The challenge was twofold: How could the new method be applied to further specific shapes and verified in each test case? If the method was correct, at least in certain practical applications, how could the best shape be designed for minimizing the resistance? NEWTON had asked these questions, too, but only provided a few first answers.

The first generation of his successors, who applied impact theory, also to the resistance in liquids disregarding the limitations in its premises, included such prominent scientists as Jakob BERNOULLI [49] (1693: Two-dimensional shiplike shape and sails), de l’HÔPITAL [50] (1699: Flat-nosed axisymmetric shape), FATIO [51] (1699: Flat-nosed parabolic axisymmetric shape) and Johann BERNOULLI [52] (1700: Parabolic axisymmetric shapes). The merits of these early studies lie in the convenient formulation

of expressions for the resistance by impact theory and its evaluation by calculus and by numerical calculations. The authors were interested in the relative merits of diverse shapes, not in the absolute values of resistance. Any differences between numerical results and values measured in water were not their immediate concern.

These mathematicians and many laymen were intrigued by NEWTON's suggestion that a unique shape could be found whose resistance by impact theory was a minimum, the famous "Solid of Least Resistance", for whose shape NEWTON had stated a "variational" problem formulation in a somewhat mystifying form and without proof. This triggered a wave of ambitious mathematical activity by his followers, who were soon successful in numerically solving the problem of finding a best shape within a given family.

In the meantime NEWTON had published the 2nd edition of his *Principia* [48] in 1713. Book II on fluid dynamics had been thoroughly revised in recognition of experimental results now available to him. Certain quantitative values, especially for the resistance in water, were changed, but the fundamental assumptions of impact theory remained the same.

It was also an achievement in this period that Johann BERNOULLI [53] in 1714 applied impact theory for the first time to the system of a ship in water and its sail in air, requiring equality of hull resistance and sail thrust. This work was performed in the context of studying the maneuvering performance of this system on a straight course (see later section on maneuvering). Johann BERNOULLI's work on resistance by pure impact theory culminated in his award-winning treatise [54], submitted to the Académie Royale in Paris, where he applied the theory to bodies of revolution of arbitrary shape and calculated numerical values of resistance. Thus the method had reached perfection, but failed to agree with measurements, the cause lying in its premises.

In 1727 the Académie Royale des Sciences invited submissions to a prize contest on the problem of "how to find the best way of masting the ships both with respect to the placement and to the number and height of the masts". Among the entries at least two found high acclaim, Pierre BOUGUER's treatise [55] "De la mâture des vaisseaux" ("On the masting of ships"), which won first prize, and Leonhard EULER's piece [56] "Meditationes super problemate nautico de implantatione malorum" ("Thoughts on the nautical problem of the arrangement of masts"), which came in second. Both authors had to contend with the practical problems of estimating hull resistance and sail forces, actually for a ship moving on a straight course with finite drift, heel and trim angles. BOUGUER approached the problem in a pragmatic way seeking compromises between theory and observation. He analyzed the forebody resistance in the spirit of impact theory, yet taking the resistance coefficient in water for the points of impact on the hull surface from measurements in accordance with the sine square law of inclined flat plate tests. His ideal was to find the "forebody of least resistance". He allowed the resistance of the afterbody, which he did not let vanish, to be estimated by some other theory combining hydrostatic considerations with TORRICELLI's law of discharge velocity. In his later work he elaborated on all of these ideas and extended them systematically to obtain numerical resistance calculations for actual ships.

The Swiss Leonhard EULER, then 20 years of age, encouraged by and in the footsteps of his teacher Johann BERNOULLI, by contrast still followed a more conservative course. He based his resistance and sail force analysis on pure impact theory. Both authors made major simplifications regarding the hydrostatic force terms and hence the angles of heel and trim. BOUGUER and EULER in these early studies still fell far short of their later monumental work in ship theory, although their genius showed first marks. The next few decades brought these beginnings to full maturity.

- The BERNOULLI era (1727-1742)

The developments toward a more realistic theory of ship resistance owes much momentum to the progress made in the following period in general fluid dynamics. The

net result was that the stalemate resulting from the blind and false application of NEWTON's impact theory was gradually overcome. The two perhaps most famous BERNOULLIs, Johann I (father) and Daniel (son), played a decisive role during this period.

It was actually Daniel, working in St. Petersburg at the Imperial Academy of Sciences from 1725 to 1733, who made the opening moves toward a fresh, uninhibited beginning. Several relevant publications of his appeared in the Transactions (Commentarii) of the Imperial Academy between 1727 and 1738. (See CALERO for an overview [7]). The most significant results are also presented in the broader context of his milestone book "*Hydrodynamica*", which appeared in 1738. Some of his most significant earlier results include:

- In 1727 Daniel BERNOULLI [57] compared NEWTON's result for the resistance of a flat plate (\approx cylinder), $C_D = 4$, with a conceptual model of his own, based on a jet impinging on a plate, where $C_D = 1$. He opted for his own conceptual model due to closer agreement with experimental evidence. For the sphere he obtained the same result as NEWTON ($C_D = 0.5$).
- Also in 1727 [58] he developed a new theory for "one-dimensional" flows through ducts or pipes (constant velocity distribution in each cross section) based on the principle of conservation of "living forces" (\approx energy conservation). This led to a new law of mutual dependence between pressure and velocity (in this special case), which he also demonstrated experimentally [59] in 1729. These ideas began the development toward the now famous BERNOULLI equation.
- A crucial blow to impact theory was given in 1736 [60] by a new paradigm for the flow approaching a flat plate (normal or inclined to the flow direction). The idea of "reflection after impact" was replaced by the concept of "deflection before contact" (Fig. 10). The corpuscular view of fluid matter was abandoned in favor of a curvilinear streamline model. This created the conceptual freedom for later field theories of continuum fluid mechanics.

As mentioned, his book "*Hydrodynamica*" [61] put many of these detailed results and other applications in a broader context and made a lasting contribution to fluid dynamics, also because it reached a wide audience. Unfortunately this fame was somewhat overshadowed by an unnecessary priority dispute with Daniel's father, Johann BERNOULLI, whose equally famous "*Hydraulica*" [62] appeared in print in 1742 and who claimed many similar and perhaps earlier insights. The much belabored controversy merits no further elaboration.

Johann BERNOULLI in his "*Hydraulica*" has more securely founded and thereby essentially extended the basic principles of fluid dynamics published earlier by his son Daniel. His essential new idea is the departure from an infinitesimal element of fluid volume to which he applies the laws of NEWTONian dynamics, so that the forces acting on it correspond to its change of momentum. To describe such local forces he invents the concept of local *internal* fluid pressure. NEWTON's *lex secunda* applied to the element of fluid mass subject to the internal pressures acting on it yields a *differential equation* as the equation of motion of the element. Its integration leads to the laws of pressure and velocity in streamline flow. In the special case of "one-dimensional" tubular flow the results by Daniel and Johann BERNOULLI are equivalent and amount to "the BERNOULLI equation". But the new justification is essentially more general and has become an important anchor point for later fluid dynamics in the field theory of fluid mechanics.

Soon after these contributions by the BERNOULLIS to general fluid dynamics two treatises appeared that can legitimately claim to be the first comprehensive scientific texts on the *theory of ships*. They are the monumental works by Pierre BOUGUER [30] "*Traité du Navire*" (1746) and by Leonhard EULER [36] "*Scientia Navalis*" (1749). Although they appeared only three years apart and cover many of the same subjects, it is

undisputed, also by the two authors, that they were written independently and without advance knowledge of the other author's work. BOUGUER apparently had completed his manuscript by 1741 while in absentia from Europe on a nine year French scientific Andean expedition in Peru, EULER likewise finished his manuscript much earlier by about 1741 during his final year in St. Petersburg. For more details on this duplication see also NOWACKI/FERREIRO [37].

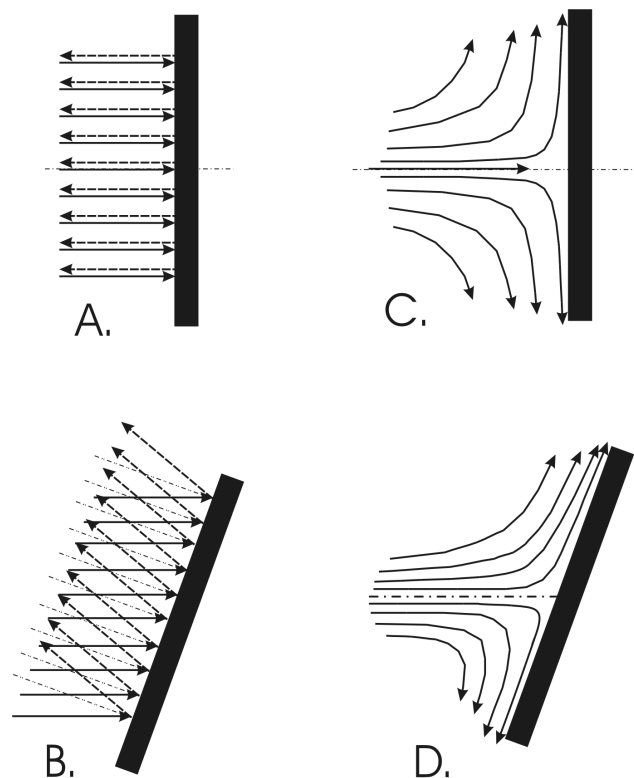


Fig. 10: Flow Patterns for Parallel Inflow into a Flat Plate according to NEWTON and Daniel BERNOULLI.

- A. NEWTON's impact theory in elastic "rare" medium (reflected particles), inflow normal to plate.
- B. Same theory, inclined plate.
- C. Daniel BERNOULLI's theory of deflected streamlines, normal inflow.
- D. Same for inclined plate.

Both books make many original contributions to ship geometry, ship hydrostatics and stability, ship resistance, ship motions and maneuvering. Often they provide equivalent results reflecting the current state of the art. In other matters they differ, though both are based on first principles as then known. Both are written in very clear language, BOUGUER's in French addressing mainly naval constructors and engineers, EULER's in Latin speaking to an academic audience. BOUGUER's text was widely read, also used as a textbook for naval constructors in France, EULER's heavy volumes found less immediate attention in practice, although his later, abbreviated and revised edition in French [38] did much better.

Regarding the topic of ship resistance it is fair to state that both still suffered from the shortcomings of fluid mechanics at mid-18th c. BOUGUER developed a theory for forebody resistance, based on impact theory tempered with drag coefficients from experiments, and used a different approach for the afterbody. The forebody was resolved into discrete panels for numerical integration of the local impact forces. This scheme was standardized and adopted by the French Navy for assessment of forebody shape in new

designs (see FERREIRO [13]). But its basis was too unrealistic to result in actual design improvements.

EULER in his *Scientia Navalis* pays even more lukewarm tribute to NEWTON's impact theory although he does not drop it for lack of a better approach. He applies the resistance equation by impact on a flat plate to the maximum cross section ("midship section") of the ship to establish an upper bound of resistance as a reference value. Then he asks for the reduction in this value by virtue of the slenderness of the forebody. The forebody resistance can be evaluated by discretizing the hull shape into panels whose drag is approximately estimated by an oblique flat plate impact formula (like BOUGUER) or much more approximately by taking a harmonic mean between the results for a parallelepiped and a pyramid. He complains that the afterbody resistance should not be neglected, but offers no remedy. He underscores the crudeness of this approach, but it will take until after 1755 that he will express outright, strong criticism of the impact theory. Disappointingly he does not even drop his crude approximations in the popularized French version of his work, the "*Théorie complète*" [38] of 1773.

At this stage it was important that encouragement for a new beginning in fluid dynamics leading beyond impact theory also came from observations by experimentalists. Georg KRAFFT [63] in 1736 in St. Petersburg performed experiments on the resistance of a flat plate in a horizontal jet, produced by the efflux from a container through a tubular mouthpiece. The jet velocity was known from the water level in the container and the plate resistance was measured by a balance. These experiments tended to confirm the earlier experimental results and theoretical predictions made by Daniel BERNOULLI and were in disagreement with NEWTON's. This gave support to the concept of the deflected jet streamline before striking the plate.

More widely known and more influential was the work performed by Benjamin ROBINS (1742) and described in his book "*New Principles of Gunnery*" [64], which was translated into German by EULER [65], 1745, who added extensive notes and his own commentaries. ROBINS had performed ballistic experiments with guns shooting spherical projectiles against a target board suspended on a "ballistic pendulum" which ROBINS had invented. The maximum amplitude swing of the pendulum was measured wherefrom the speed of the projectile when striking the target was calculated. By varying the distance between gun and target the resistance of the projectile in air could be reconstructed. The results were in serious conflict with NEWTON's impact theory. ROBINS proceeded to offer his own theoretical explanations of the projectile flow and resistance, categorically questioned the validity of NEWTON's corpuscular theory, investigated the velocity law and discussed the effects of afterbody flows on resistance. EULER concurred with ROBINS' findings in the footnotes of his translation, but was delighted to add many annotations based on his own theoretical concepts. Here in 1745 for the first time EULER pronounces, in concurring with ROBINS, that "rare media" do not exist in nature and he adds a few first thoughts on how to analyze the resistance by examining the flow deflected around and attached to the body and by looking at the "streamtubes" closest to the body surface. Here we see the first visible effects of the BERNOULLI streamline concepts on resistance analysis. (See TRUESDELL [8], CALERO [7] and SZABÓ [9] for more details on the ROBINS/EULER episodes).

Let us insert here a few remarks about the renowned Spanish Naval Constructor Jorge JUAN Y SANTACILIA, in this context mainly because he was well acquainted with Benjamin ROBINS, whom he had met in London in 1749, and may have been influenced by him. JUAN Y SANTACILIA as a young Spanish officer with close connections to the diplomatic service was a traveling fellow to Pierre BOUGUER on the French Andean expedition to Peru (1735-1745). He was probably first exposed to ship theory by BOUGUER. After his return to Spain he soon became a responsible Naval Constructor for the Spanish Navy, which reinforced his strong practical orientation. At the same time he maintained a high level of scientific education, which resulted in several publications, culminating in his famous late work "*Examen Marítimo*" [66] (1771), used as a naval textbook in Spain and several other countries. His scientific positions showed great independence. He rejected NEWTON's resistance theory on similar grounds as

ROBINS. Based on his own observations he recognized the importance of forebody and afterbody flows and underscored the substantial role of bow wavemaking. From this he developed an original theory for wavemaking resistance, based on gravity effects. In his model of wavemaking he still too strongly adhered to hydrostatic laws for interpreting the flow in waves. Yet in many of his theoretical suggestions he was well ahead of his time, shedding the bonds of earlier theories. He stands out as an example of practical experience and scientific education combined in one mind.

- Field theory

By 1750 no general theory of fluid dynamics existed. NEWTON's corpuscular theory was based on mass point dynamics and did not hold for general domains of deformable fluid matter. Despite some brilliant success stories in individual case studies a general theory based on first principles and accounting for the properties of fluid material was still missing. The corpuscular viewpoint had achieved some remarkable initial success, but had also clearly shown its limitations in coping with physical reality. What was needed was a theory applicable to the whole specified domain of fluid as a deformable medium. It should be based on the following set of assumptions for the fluid continuum:

- The principles of dynamics (NEWTON's laws)
- Constitutive equations, describing the properties of the fluid (e.g. as a perfect fluid) and the configuration of the fluid domain (boundary conditions)
- Conservation laws, in particular the conservation of matter (continuity equation).

In such a fluid domain or "field" the physical states were to be described by the distribution of a set of state variables, chiefly pressure and velocity. This required the equations of state holding in a two- or three-dimensional continuum and the state variables being multivariate functions of space coordinates. The mathematical tools for modeling this situation evolved simultaneously with their physical applications. The equations of state in the fluid were formulated as "Partial Differential Equations".

These were the objectives of the *field theory* of fluid dynamics developing after 1750. Jean LeRond D'ALEMBERT and Leonhard EULER were the pioneers of this new scientific approach.

D'ALEMBERT first approached the field theory via the subject of the equilibrium and motions in fluids in his treatise [67], published in 1744, and on this basis developed a theory of resistance in fluids [68], which appeared in 1752. He based his deductions on his principle of the "equilibrium of lost forces" in a system. In his theory he avoided the use of forces as fundamental quantities, as they appear in NEWTONian mass-point dynamics, and the explicit mention of pressures. Instead he derived the partial differential equations of fluid motion and solved for the streamlines. Regarding the resistance he was able to prove the absence of any such force on a closed body immersed in an ideal fluid (D'ALEMBERT's paradox). His results were in fundamental conflict with earlier corpuscular theories. His conclusions were basically correct, though not always clearly presented. In practice the acceptance of his theories was soon overtaken by EULER's line of thought that was founded on different, more intuitively appealing axioms.

First results on EULER's field theory were published in [69] (1752/1756), the full foundation and justification of that theory was given by EULER in a sequence of three treatises a few years later [70], [71], [72]. His approach has become so familiar today in basic texts on fluid dynamics that it is difficult to imagine it was new at the time. EULER applied the NEWTONian principles of dynamics to a volume element of fluid matter, described in terms of fluid internal pressure and velocity components, hence the change of momentum by forces acting on the element. This resulted in what is known today as EULER's (differential) equation of fluid dynamics. He postulated, at least initially, an ideal, loss free fluid, which served as his constitutive equations. He then expressed the conservation of matter, i.e., the continuity equation, in the now well-known form of a Partial Differential Equation. These are the foundations of his field theory and of

continuum fluid mechanics. To derive solutions for special applications with given boundary conditions suitable tools of analysis are needed which were developed in the following decades and centuries. EULER illustrated his results only by very few examples. In certain situations a potential exists for the velocity field, thus field theory has led to and benefitted much from the broad range of methods in potential theory.

The resistance of objects in a fluid was addressed by EULER with his new theory in [73] (1756/1760). For an ideal fluid, when the flow remains attached to the whole object, he of course arrives at the same result of zero resistance as others. But here he categorically refutes “impact theory” as “entirely false, for in fact the fluid before it reaches the body changes both its direction and its speed etc.”. He adds in referring to Daniel BERNOULLI’s streamline models that the afterbody of an object cannot be neglected in its contribution to resistance.

EULER [73] outlines the approach to be taken in field theory for finding the resistance when the fluid velocity field is known: Find the streamlines on the body surface, then the velocity distribution along streamlines, then the pressures by the equivalent of BERNOULLI’s equation, finally the force on the body by integration of the pressures. This is still the common engineering approach today.

Thus at this stage the field theory had reached a stable foundation, at least for ideal fluids, on which the mathematical analysis of the flow problem as a boundary value problem (BVP) could rest. How to find specific solutions to this BVP for given special or later arbitrary body shapes, required suitable analytical tools not yet available. Thus field theory as a prediction tool for ship flows remained immature until much after Trafalgar. But progress in fluid dynamics in the next two centuries has continued to rely on this problem formulation and has by now achieved its mature analytical, numerical and practical solutions.

- The experimentalists

The period from about 1760 to 1780 is characterized by the growing awareness that earlier resistance theories based on corpuscular models were too unrealistic to provide any guidance to ship designers, while new approaches based on the field theory of fluid dynamics were still too immature for such applications. This caused much dissatisfaction and disappointment among practitioners of design as well as scientists working on ship fluid mechanics. Quite a few therefore turned to the perhaps more promising option of learning by observation from experimental evidence. The objectives in these activities were varied. They ranged from fundamental questions on physical phenomena, especially those on which the theory had left open issues or impasses, to very practical and applied subjects of ship design. There were very empirical schools of thought who were looking for direct answers from tests for everyday applications and others who sought plausible explanations for observed phenomena based on theoretical grounds. A few examples will illustrate this spectrum.

In Britain a group of gentlemen who had founded the Society of Arts in London, a private club, decided in the period of 1758 to 1763 to engage in a prize competition of ship model trials. The whole episode is well described by HARLEY [74]. They invited models of specified size (scale 1:48) for a 74-gun ship and for a frigate. The designs were to be judged by “swift sailing, the greatest stiffness and the least likelihood to sail to leeward”. The trials included falling weight method calm water resistance tests in an open lake, the Peerless Pool in London, stability tests by means of a balance and even rough water tests in a tank as well as in open water with wind in a lake at Epping Forest. The models of about 1 m and 0.75 m length, respectively, were towed through 90 m distance in open water. The results measured with two models of a 74-gun ship and four competing designs for the frigate were carefully recorded. The relative merits could be judged and the prizes awarded. The whole venture was a courageous beginning without any pre-established methodology for interpreting the results. Today it is easy to point out that the small models surely suffered from scale effects, scaling laws were not known and the corresponding speeds to full size could not be defined. Yet the observations

made were a valuable and necessary experience to start this new branch of experimental science.

In France BORDA [75] in 1763 reported the results of his tests performed in the laboratory in air and in water with flat plates, prisms, pyramids, spheres and other simple shapes. He had devised rotating arm towing mechanisms, driven by a falling weight, so that his models moved on circular paths. He tested the validity of NEWTON's results, especially for the flat plate and the sphere. He confirmed the velocity squared resistance law, rejected the sine square dependence of flat plate resistance on the angle of plate inclination, instead showed a simple sine dependence. Importantly he declared the results of impact theory as "absolutely false and useless in ship design".

The famous Swedish naval architect and constructor Frederik Henrik af CHAPMAN was most competent as a design practitioner and quite familiar with the scientific literature of his era, too. He was as dissatisfied with the state of the art in resistance theory as his contemporaries and resorted to his own systematic model tests to gain some new insights for design, whose results he reported chiefly in his main work, the "Treatise on Shipbuilding" [21]. He developed a "systematic series" of model shapes, i.e., a family of seven simple, axisymmetric shapes, towed "fully" submerged, in which the location of the maximum cross section and hence the slenderness or fullness of the forebody and afterbody were systematically varied. This gave him qualitatively correct guidance for an important design issue which had puzzled his century.

CHAPMAN was well aware that the technology of model tests evaluation and interpretation was still rudimentary, yet badly needed. Despite the deficits in theoretical insights in his era CHAPMAN was convinced of the value of a theoretically based design approach. He stated: "Without a good theory design is just a game of hazard".

The abbot BOSSUT et al., being encouraged and funded by the French minister of finance TURGOT, performed extensive ship model tests in the open air basin of the École Militaire in Paris, which were reported in 1777 [76] and 1778 [77]. The test basin was of reasonably large dimensions, $l \cdot b \cdot d = \text{abt. } 32 \cdot 17 \cdot 2.1 \text{ m}$, permitting trial runs with models of nearly 2 m length through a distance of some 21 m. The falling weight towing method was used again. The project involved some 300 trials with 12 models of different shape. The majority of the shapes was of simple geometry, prismatic bodies with various pointed bow sections and tapered sterns, only two had more realistic shiplike forms. The interest was in fundamental, design related knowledge. The results again confirmed the proportionality of resistance to V^2 , disproved the sine square dependence of the resistance of inclined plates, and demonstrated a pronounced resistance increase in narrow and shallow canals, as Benjamin FRANKLIN had already found in 1769. The effects of pointed and bluff bow shapes were also examined, where the pointed shape reduced the resistance. Bow waves were noted and carefully recorded. A false conclusion was that the frictional drag was almost nil. Although again the interpretation of the results suffered from the lack of scaling laws, the observations were accurate and correct and gave valuable qualitative insights.

In the last decade of the 18th c. it was the work of Mark BEAUFOY that created new insights and opened up new lines of research (see WRIGHT [11] for more details). The British Society for the Improvement of Naval Architecture (SINA), which existed from 1792 to 1806, sponsored a comprehensive program of tests in the Greenland Dock in London. BEAUFOY, a very skilful experimentalist, built a falling weight towing apparatus to tow his models of considerable size through a distance of initially about 90 m, later reduced to about 50 m. He tested a variety of bow and stern shapes, and in particular, since he had early discovered the significance of friction, large flat planks in in-plane inflow. His largest planks were of dimensions $l \cdot b \cdot d = \text{abt. } 12.9 \text{ (later } 9) \cdot 1.1 \cdot 0.37 \text{ m}$. To eliminate leading edge effects of the planks he measured the friction force of submerged long and short planks of identical front end dimensions and used the difference as the friction force on the after end. The significant majority of his tests were performed with "deeply" submerged shapes (planks or bow/stern shapes) suspended from a towed carrier floating on the surface. The experimental skills applied deserve

admiration. As far as friction and plank tests are concerned his major contribution is the proof that friction is by no means negligible, but may be of considerable influence. Concerning the components of resistance of a shape he observed the following major contributions:

- Bow pressure force (“forebody resistance”), associated with a bow wave system
- Friction force along the midportion of the sides of the hull
- Stern (“negative”) pressure force (“afterbody resistance”)

Benevolently we might recognize in this terminology the ancestors of what today (or since William Froude) we would call “wave resistance”, “frictional drag” and “viscous pressure drag” (Froude’s “eddy resistance”). This was also the first inkling of major breakthroughs in the understanding of the nature of ship resistance, which did not materialize before the middle of the next century.

BEAUFOY’s plank tests suggested that the velocity law of frictional resistance required an exponent somewhat less than 2, as CHAPMAN had already suspected for the total resistance. Today we would argue in favor of retaining the exponent 2 and including the velocity dependence in the drag coefficient as a function of Reynolds number. Yet BEAUFOY’s observations were of course correct and new.

Unfortunately BEAUFOY was not a good report writer and advocate of his new ideas. He submitted short reports to his sponsor SINA in 1794 [78] and 1800 [79] and published excerpts of his results in 1814 [80]. But the wealth of his raw data from more than 1600 tests lay dormant for decades until posthumously his son Henry published the full set of results in 1834 [81].

- Summary

In the 18th c. theory and experiment both failed to furnish a physically correct basis for interpreting the phenomenon of ship resistance, let alone for predicting it at the design stage. This is unfortunately true despite a remarkable level of scientific activity and experimental efforts spent toward the advancement of physical knowledge on ship resistance in this century and despite a gradual knowledge increase in the cause and effect relationships in hydrodynamic ship design.

The most serious shortcomings stem from a lack of understanding of the components of resistance by physical causes and of the mechanics of similitude which follow different laws for different causes. NEWTON’s impact theory for “rare media” e.g. accounted only for inertia effects and neglected gravity and viscous forces. NEWTON was well aware that this simplification did not hold for the resistance in water, but his immediate successors ignored this fact. Theoretical approaches based on these grounds led astray and could not be corrected before wavemaking resistance (gravity) and fluid frictional and viscous pressure drag were discovered, e.g. by CHAPMAN and BEAUFOY later in this century, and taken into account in the following century. A ship resistance theory based on a single term, single coefficient model for multiple parameters of similitude simply is infeasible.

The same deficits also prevented a correct interpretation of experimental results on ship resistance. Without a breakdown of measured drag into components based on distinct parameters of similitude the explanation of flow phenomena, the extrapolation to full scale and the definition of corresponding speeds are not possible. Most experimentalists cautiously confined themselves to comparing relative merits of competing concepts, but even there scale effects may mislead. Statistical data fitting of very small samples of course held at best within the sample and did not allow any generalization and extrapolation. Yet in the school of Baconian empiricism the idea persisted for almost another century that the resistance problem should be solved by pure inductionism based on a sufficient number of full scale observations (see e.g. Thomas WRIGHT [11]). In the 18th century only a few far-sighted scientists like CHAPMAN and BEAUFOY realized

that this naïve position was untenable. They were convinced that physical understanding of and technical solutions for the ship resistance problem required knowing the theoretical principles underlying the problem.

Meanwhile whatever evidence from observations on the model scale and full scale did exist, served to understand qualitative trends in resistance dependence on principal dimensions and thus to avoid the worst mistakes. The tendency by the major navies to standardize designs and to avoid risky innovation did not help to collect empirical information over a wider range of hull form variation. Evolutionary changes did occur and brought the existing classes of hull form to maturity and relative success.

Ø Sail Forces

The forces acting on a sailing rig, whose components in the direction of the course are providing the propulsive energy to a sailing vessel, depend on many factors, notably the number, size and placement of the masts and their sails, the force and direction of the wind, the angle between sails and apparent wind and several other influences. Although sailors and navigators have accumulated much practical and in part intuitive knowledge during many centuries, it is by no means a trivial task, even today, to accurately predict the performance of a rig at the design stage for a spectrum of operating conditions. In the 18th c. scientific methods of prediction evolved only gradually from modest beginnings and despite much continuing effort fell short of quantitative, design-oriented prediction capability. Yet it seems worthwhile to examine the insights gained during this period as a qualitative background to designers' decisions.

To analyze the performance of individual sails and of the entire rig the following basic issues must be understood:

1. The dynamic equilibrium situation of the system composed of the hull with rudder and the rig for some given operating condition, e.g., constant speed on a straight course in a given wind, fundamentally to be viewed as a six degree of freedom rigid system. For, although the rig itself can be characterized by two force components, drag and lift, and a moment, the attitude of the rig on the hull depends on the equilibrium of all forces and moments acting on the system, hence also on the displacements in heel, drift angle, trim and sinkage. Fig. 11 gives an overview of the forces acting on the system and their directions. The notation is defined by:

V_H = hull velocity (or inflow velocity) in the direction of ship course

V_A = apparent wind velocity

D_H = hull resistance

D_A = drag force of the rig

C_H = hull lateral resistance (against swaying)

C_A = resultant lift force of the rig

β = drift angle

ε = apparent wind angle to plane of symmetry

$\chi_A = \beta + \varepsilon$ = angle between course and apparent wind

δ_R = rudder angle

2. The magnitude and direction of the aerodynamic sail forces, hence also the center of pressure of the rig force resultant.
3. The issue of how to design the rig for the best thrust and hence speed in various wind conditions, also aiming at good weatherliness.

These required insights advanced only gradually during the 18th c. as will be discussed by looking at a few major milestones. The developments in the theory of sailing are reviewed in a much broader context by Ludwig RANK in his excellent monograph [10], ranging from antiquity to the modern era. The thesis by FERREIRO [13] and the book by CALERO [7] concentrate more selectively on events in the 17th and 18th c.

Earlier scientific activities date back to the 17th c., when Father PARDIES [83] (1673), RENAU [84] (1689), even HUYGENS [85] (1693) and Jakob BERNOULLI [86] (1696) took first cuts at the sail force problem. The recognition of the drift angle (French: *dérive*) between the ship's centerplane and its steady course direction dates back to PARDIES. HUYGENS associates sail forces with a V^2 law. Jakob BERNOULLI clearly defines the apparent wind velocity, i.e., the vectorial difference between true wind and ship speed, as relevant for the sail force.

Johann BERNOULLI [53] in 1714 after a heated controversy with RENAU, earlier also involving HUYGENS, published a treatise characteristic of the state of the art in the early 18th c. In his analysis he used NEWTON's impact theory, applied to the forebody of the ship only, for finding the hull force, but also directly for the sail force and the center of pressure of the sail. He does derive an estimate of the the drift angle, though only for simple shapes, noting however its dependence on hull shape. Heel and trim are neglected here.



Fig. 11: System Equilibrium of a Maneuvering Ship, Forces and Angles (adapted from WAGNER [82])

A decade later BOUGUER [55] and EULER [56] submitted their entries to the 1727 Parisian Academy prize contest on optimum masting. Both still adhered to NEWTON's impact theory, but especially EULER treaded closely in the footsteps of Johann BERNOULLI. Interestingly even in their much later work, BOUGUER's *Traité du Navire* [30] (1746) and EULER's *Scientia Navalis* [36] (1749) and in EULER's later *Théorie Complète* [38] (1773), they did not revise these assumptions, but only elaborated on the implementation of these methods. This led both of them to very similar variations on the theme of the "point vélique" as an instrument of rig optimization and placement.

The "point vélique", a favorite topic in the 18th c., is defined as the point of intersection of the hull resistance resultant, which according to impact theory acts only on the forebody obliquely upward (Fig. 12), with the aerodynamic sail force resultant, hence the point N in BOUGUER's figure. By design strategy via placement and height of the masts this point should be located as follows: Hull force NR and sail force NP form a resultant NT whose horizontal components in steady motion cancel so that NT is vertical. Ideally N should be placed in the same vertical plane as the center of gravity (and buoyancy) so that the force NT would not create a trimming moment about the CG. (This reasoning neglects the negative parallel sinkage caused by this force NT).

EULER even in his much later *Théorie Complète* still adhered to the same concept on hull and sail forces. He went so far as to suggest to fit a spherical sector bow as the forebody of the ship (Fig. 13) so that all impact forces would act through the same point,

the center of the sphere W. This point being known, sail sizing and placement could then be performed so that W would become the “point vélique”.

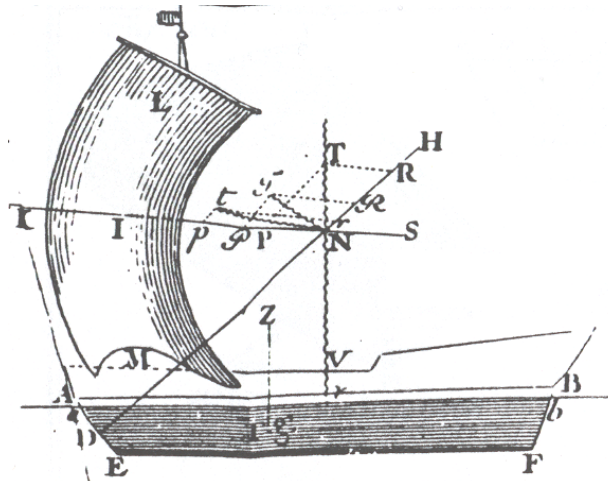


Fig. 12: Hull Resistance and Sail Forces Intersecting in the “Point Vélique” (from BOUGUER [30])

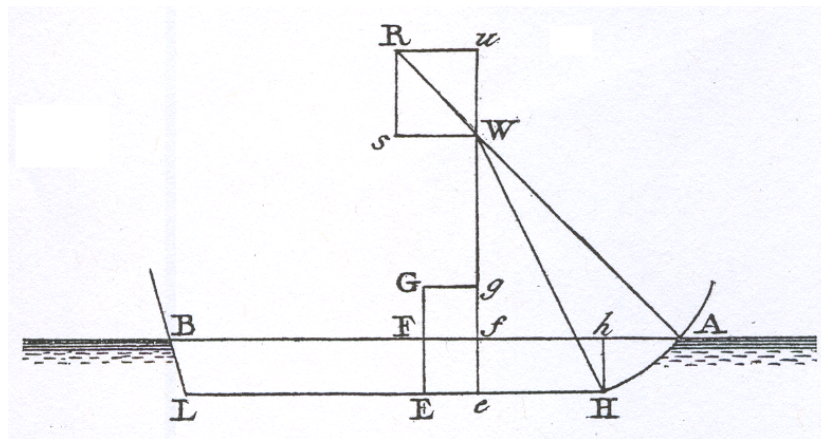


Fig. 13: Hull Resistance and Sail Forces Intersecting in the “Point Vélique” (from EULER [36])

In their calculations of system equilibrium both BOUGUER and EULER therefore neglected trim. The heeling effect caused by the couple of hull and sail forces was still neglected in 1727, but later accounted for in the 1746/49 treatises.

This whole argument surrounding the “point vélique” for practical purposes is totally useless. It refers to a fictitious point as the intersection of two fictitious forces whose magnitude and direction based on impact theory are both false. The hull force neglects the afterbody and thus suffers from grave errors in magnitude and orientation. The sail force is not accurate enough either. Despite that the concept was promoted in textbooks [19] and in naval constructor training in France (see FERREIRO [13]). In practice trimming moments by the bow between hull resistance and sail force do occur, but can be compensated in part by ballast redistribution, in part by the natural hydrostatic reaction of the hull.

Another unfortunate detour was taken also with respect to the dependence of the sail force on the angle of incidence of the apparent wind. Impact theory for a flat plate and similar arguments which prevailed at least through 1750 predicted a $\sin^2\alpha$ law for the

resistance of an inclined plate, where α = angle of incidence. This false conjecture was only gradually overcome when experiments disproved this relationship and impact theory fell out of favor. Jorge JUAN [66], BOSSUT [77] and CHAPMAN [21] were foremost among those who opposed the $\sin^2\alpha$ law.

Still in the 18th c. apparently the first model tests on actual sail models were performed by EDGEWORTH [87] (1782) on planar and cambered sail shapes of various aspect ratios. He was able to reject the $\sin^2\alpha$ law, but also the idea of “flat sails”, which other scientists had favored. He advocated cambered sails, which produced more lift, perhaps a first pretaste of foil and wing theories in later centuries.

In summary the best one can say is that scientists in the 18th c. were able to develop correct concepts on the contributing factors to system equilibrium with a complex set of forces, moments and displacements. But the quantification of sail forces by magnitude and direction failed entirely. This also had adverse effects on the prediction of ship maneuvers. The lack of realistic relationships between lift, drag and angle of incidence of the sail was the main deficit.

Ø Maneuvering

The subject of ship maneuvering refers to the dynamics of rigid body motions of a ship in its six degrees of freedom, where the three principal motions in maneuvers are forward motion, lateral or swaying motion and yawing motion. The issues of greatest technical interest are the ability of the ship to stay on a straight course (coursekeeping ability) and its responsiveness in turning maneuvers (turning ability). The knowledge required for analyzing these maneuvers includes:

- Hull, sail and rudder forces and moments for oblique inflow
- The effects of system dynamics, mainly the inertia terms and the resistance terms
- Solutions to the equations of motion by integration

The historical developments in this subject in the 18th c. are again thoroughly reviewed by RANK [10] and FERREIRO [13]. Jean BOUDRIOT [5] gives a comprehensive overview of the actual maneuvering systems aboard 74-gun ships and of their practical maneuvering methods and capabilities.

For course stability investigations, in particular the line of action for the sway resistance (C_H in Fig. 11) on the underwater hull through the lateral plan center of pressure and the line of action of the lateral component of the rig force (Y_{HA} in Fig.11) through the rig center of pressure must be known. In the steady state these two forces are forming a couple of equal and opposite quantities causing the vessel to heel. At the same time they may cause a yawing moment tending to turn the ship (bow) into the wind or away from it, unless they are acting in the same vertical plane. To compensate the yawing moment some rudder action will be required to sail on a straight course, which incurs a rudder drag. Ideally in design the two centers of pressure should be placed in close longitudinal proximity to minimize this yawing moment.

Traditionally in the 18th c. the center of pressure of a sail or of the lateral plan of the hull would be estimated as the area centroid, which is consistent with impact theory. This is reasonable for a sail before the wind. But on other courses as the apparent wind angle of incidence becomes small, say, in sailing into the wind, the center of pressure aerodynamically moves toward the leading edge of the sail. Multiple sails on multiple masts were often combined into a single “equivalent sail” by lumping the sail areas into their combined centroid. This neglects the interaction of sails and their partial self-obstruction. The underwater hull center of pressure also varies with the flow angle of incidence. Yet these phenomena and errors were qualitatively understood by scientists and practitioners so that empirical corrections were applied, either in design based on similar ships or in operation when setting the sails.

Regarding the turning ability of the ship the equations of motion for yawing require estimates of the hull, rig and rudder forces and lines of action as well as the mass moment of inertia term associated with the yawing acceleration. The most mature formulation of this problem in the 18th c. was probably achieved by EULER, particularly in his *Théorie Complète* [38] (1773). Although in his text he mainly discusses maneuvers on a straight course, he does devote a section to rudder forces and turning motions. His analysis of hull, sail and rudder forces is again still based on impact theory, hence quantitatively incorrect. But he does correctly model the rotary inertia term for the hull, wherefrom he arrives at an estimate of the angular acceleration of turning produced by the rudder force and turning moment. His approach still neglects the influence of the ship's hydrodynamic mass moment of inertia in turning, which can be of the same order of magnitude as that of the hull. But we do owe him a correct method for modeling the system dynamics of the ship in six degrees of freedom including the maneuvering motions as will be addressed again in the section on Ship Motions. The approach taken by him to state the equations of motion for the ship is still our basis today.

In conclusion the theory of maneuvering in the 18th c. suffered from the same deficits in hydrodynamic and aerodynamic force prediction as other application fields. Thus it was not of immediate quantitative use in ship design. But knowledge in system dynamics was far enough advanced to correctly enumerate the influences that were contributing to system equilibrium. This may have helped qualitatively to take suitable corrective actions in design and above all in ship operations.

Ø Ship Motions

The motions of ships in their oscillatory degrees of freedom, roll, pitch and heave, are a decisive factor in determining the seaworthiness of the vessels, their operational limits and their safety in rough seaways. Thus their prediction at the design stage and their control during operation had always been a prime concern of all navies. But a scientific approach for treating ship motions appeared rather late. Initially the prediction of the natural periods of these oscillations was much desired and became achievable in the mid-18th c. The dating of this new capability is more secure than for other events because an important prerequisite for calculating these natural periods is an analytical understanding of the inertia and restoring forces and moments in these degrees of freedom. As soon as these influences could be calculated for ships, motion predictions became feasible.

The hydrostatic restoring forces and moments for ships became amenable to numerical analysis by the work on ship stability, where BOUGUER and EULER were already mentioned as pioneers. The inertia terms, notably the concept of the mass moment of inertia, were defined on the basis of calculus and became known in the dynamics of extended rigid body systems by about 1735. At the time of the 1727 Parisian Academy contest on ship masting neither BOUGUER nor EULER had a correct physical understanding of ship stability and restoring forces, they had to circumnavigate the problem. But both worked hard to resolve this open issue and by the end of the next decade has adequate answers, which they published in their treatises [30], [36] in 1746 and 1749.

It is fortunate that a large body of correspondence between EULER and Johann and Daniel BERNOULLI has been conserved and is available publicly now in summarized form in the *Commercium Epistolicum* volume [88] of EULER's Collected Works. There exist in particular seven letters exchanged between EULER and Johann BERNOULLI in the period between 1738 and 1740, which are relevant to early work on ship motions (Letters 206, 208, 209, 210, 211, 214, 215 in [88]). During those years EULER was working on his *Scientia Navalis*, which included the theme of ship oscillations. He stimulated his teacher Johann BERNOULLI and his friend Daniel BERNOULLI to work on similar topics independently and in parallel. It is evident from the correspondence that EULER claims to have found an analytical solution for the natural period of roll in 1738 and Johann BERNOULLI likewise for heave, also in 1738. EULER's results appeared in *Scientia Navalis* [36], completed by 1741, pulished in 1749. Daniel BERNOULLI's

results on pure roll and coupled roll/heave oscillations were presented to the St. Petersburg Academy in 1738/39 and published also after long delay in 1747/50 [89].

EULER and the BERNOULLIs had discovered the striking analogy between the isochronous physical pendulum, whose theory had been far advanced by GALILEO, HUYGENS and others, e.g., for clockmaking, and the oscillating ship moving isochronously at small amplitudes. This led EULER to suggest that the “equivalent pendulum length” l_{EQU} of a rolling ship can be derived from the ratio of the “mass moment of inertia” ($\Theta_{\text{ROLL}} = \Delta i_T^2$) to the “hydrostatic restoring moments” (ΔGM):

$$l_{\text{EQU}} = (\Delta i_T^2) / (\Delta GM) = i_T^2 / GM$$

The natural period of this “pendulum” or period of roll for the equivalent ship is then:

$$T_{\text{ROLL}} = 2 \pi \sqrt{l_{\text{EQU}} / g} \quad \text{in EULER's formulation}$$

or, substituting, in our familiar notation:

$$T_{\text{ROLL}} = 2 \pi i_T / \sqrt{gGM}$$

where Δ = displacement

$\Theta_{\text{ROLL}} = \Delta i_T^2$ = mass moment of inertia in roll

i_T = radius of inertia of ship in roll

GM = metacentric height

g = acceleration of gravity

Corresponding results were obtained by Johann BERNOULLI for heave oscillations (in 1738) and by EULER and Daniel BERNOULLI also for the natural period of pitch.

Pierre BOUGUER, again independently and simultaneously, worked on the same questions and came to similar results, published in his *Traité* [30]. In Book II, Section III he correctly recognizes the pendulum analogy and convincingly justifies the choice of the center of gravity of the ship as the appropriate reference point for all terms in the dynamics of the system. He proceeds to outline a calculation procedure for the mass moment of inertia, the hydrostatic terms being known from his earlier chapters. His approach is numerically oriented avoiding definitions in calculus to suit his practical readers. Yet his methods were incorporated in several textbooks and spread more rapidly than EULER's and the BERNOULLI's analytical results.

EULER was often cited, too, and made further important contributions, in particular by his work on the general equations of motion of a six-degree of freedom solid [90] and by his introduction of the principal axes of inertia as a suitable reference frame in system dynamics in 1761 [91].

What were the practical conclusions and recommendations derived from the new results on the natural periods of oscillation? The main strategy was to reduce the amplitudes, but in particular the accelerations, which constitute a heavy load on ship and rig in a rough seaway, in the ship's transient response by increasing the natural periods. In roll the stability of the ship (GM) could not be endangered, thus leaving only the choice of raising the moments of inertia by seeking favorable weight distributions (“Heavy weights away from the CG!”). This was to be practiced in ship design and operations.

The important steady-state response of ships in forced oscillations initially was not taken into account, although by 1757 Daniel BERNOULLI's prize-winning treatise [92] dealt with this problem for sinusoidal excitation and emphasized the urgency of avoiding resonances. Thus knowing and perhaps modifying natural periods in advance obtained a further significance. Longer natural periods might be of advantage also in forced oscillations in a seaway because at least in moderate beam or quartering seas waves of that period might be rare. Roll response is then in the “supercritical” frequency range.

Of course the newly available analytical tools were only a modest beginning and did not permit a comprehensive “seaworthiness” analysis of the design. The major deficits, which lasted at least through the end of the 18th c., remained:

- No consideration of hydrodynamic mass and damping terms. The omission of added mass influences is a serious error in natural frequency calculations, at least for heave and pitch.
- No physical knowledge of exciting forces and moments, no understanding of the seaway.
- Limitation to small amplitudes, neglecting nonlinear effects.
- No analysis of extreme conditions.

Qualitatively a correct understanding of the interplay between inertia terms and hydrostatic restoring terms had begun to develop. Several open questions remained on the agenda.

Ø Ship Strength and Hogging

The ships of Trafalgar and earlier periods by the standards of modern strength analysis were all “small ships” in terms of their length and displacement. Thus, their transverse and local strength requirements dominated the design rather than any concerns of longitudinal bending moments and stresses. Moreover the hull girders, due to a reasonable freeboard and hence depth, were not excessively low (L/D for ships of the line generally less than 5), so that their longitudinal bending deflections in a homogeneous material should not have become critical.

On the other hand it is well known that the large wooden sailing ships of that era suffered from “arching” or “hogging”, i.e., a pronounced sagging of the ship ends under the predominance of weights (gun weights) over buoyancy there, even in calm water and at rest. This was feared as a cause of leakage, lack of structural integrity and increase in resistance. Since the severity of hogging grew with ship length, designers were very cautious in progressing to greater lengths.

In the age before Trafalgar it would have been possible to get some first estimates for the magnitudes of longitudinal bending moments, stresses and perhaps deflections. EULER suggested in [41] how to apply linearized beam theory to a ship hull girder in order to assess the maximum bending moment amidships. The problem of the deflection line under a given load distribution (“elastica”) had been solved except for the still missing factor EI, and especially the modulus of elasticity. The material properties of wood and in particular wooden plank assemblies with their anisotropic behavior were a wide open question. But civil engineers and architects by about 1800 were able to dimension building structures making use of beam theory (EYTELWEIN [42]).

In practice, however, the effects of longitudinal strength by overall hull girder bending moments do not appear to have been the main cause of hogging or arching in historical sailing vessels. This is already indicated in the literature and convincingly summarized by COATES ([43], 1985) who on the basis of historical and more recent sources stated that hogging deformations (and the possible associated “breaking of the sheerline”) of wooden ships is primarily a technological problem unrelated to or at best triggered by longitudinal bending. The failure mode is different from breakage in longitudinal bending. Rather in the traditional wooden ship construction of the 18th c. the shell planks were secured between adjoining strakes only by the caulking friction and were able to slip longitudinally against each other once they overcame that friction. Thus under the influence of predominantly downward end loads the ships ends would arch down as the upper shell planks slipped more than the lower ones and would develop a longitudinal slack. This often began immediately when the ship was launched, transiting from its dry load distribution under its own weight into the one when floating with buoyancy loads

added, promoting a convex deflection. The hogging then increased gradually as the slack between planks got more pronounced and became a permanent condition before long.

This hogging phenomenon was well known in all navies and certain remedies were applied by some. BOUGUER [30] already reports about various schemes of diagonal structural reinforcements, including the use of diagonal riders mounted against the inside of the hold frames, for which he gives credit to the French naval constructor GOBERT in the early 18th c. Similar technological remedies were applied in other navies occasionally to limit the damaging effects of hogging. In Britain an effective cure was found soon after Trafalgar when the slipping of planks was much reduced by “diagonal bracing” or “diagonal framing” of the shell planking (SEPPINGS [44], 1814). COATES [43] is quoting a source that thereby the slippage was reduced by a factor of about 10. He also mentions that in the wreck of the *Mary Rose*, sunk in 1545, they found that she already had diagonal members installed. This technology seems to have been forgotten, later rediscovered. Had they systematically applied a technology like this in the 18th c., they could have significantly limited hogging and afforded to go to greater ship lengths without violating this constraint.

3.3 Practitioners’ Knowledge

The most direct testimony to a ship constructor’s competence and skills are the ships he designed and built himself. Unfortunately it is ill documented how the shipbuilders of long past centuries arrived at their practical design and construction decisions. How did they justify their decisions, what was the rationale behind their solutions? Although in the 18th c. – as today – many decisions in ship design were evidently based on long experience and good craftsmanship, it is also clear that certain innovative ideas were born out of new observations, insights and contemporary background knowledge, some of it also reflected in changing educational systems and curricular substance. Thus to capture a flavor of that practitioners’ knowledge it is mandatory to look at the written evidence from that period presented by practical ship designers and shipbuilders or their associates in their published treatises and monographs. Fortunately there exist several such documents from actual practitioners of that era since the motivation to put their knowledge on record in print for the benefit of their sponsors, their contemporaries and professional peers and their apprentices and students was comparatively high, also in that early age of science and technology. These treatises are an ideal interface between the existing practical approaches and the methods for achieving success, improvement and innovation. Thus we will review a small, but characteristic sample of treatises on ship design and construction written by responsible practitioners. In the present context we will limit ourselves to issues of basic design, ship geometry and principal dimensions, hence to certain aspects of basic naval architecture, leaving aside matters of detailed ship construction.

Several treatises of this kind date back to the 17th c. and earlier. They reflect the state of the art of shipbuilding knowledge in that era. E.g. in the late 17th c. we may refer to the work by Anthony DEANE [15], Nikolaes WITSEN [16] and Cornelis VAN YK [93], to mention only a few of the latest and most elaborate treatises. These treatises have been republished, edited and commented fairly recently by LAVERY, HOVING and LEMMERS in [15], [94] and [95]. All of these treatise authors and some of their contemporaries deserve credit for an advanced level of knowledge in ship geometry and in the application of constructive geometry to hull form definition and ship construction. DEANE e.g., Master Shipwright at the Harwich Dockyard (1664-1668) and later at Portsmouth, then a Royal Navy consultant under King Charles II, perhaps the leading British naval architect of his period, in his book of 1670 elaborately describes the British method of hull form definition, an advanced form of “whole-moulding”. He develops the lines plan, a newly evolving design medium on paper, from a few principal characteristics. DEANE also promoted and applied a new method of displacement calculation as a function of draft to be used at the design stage, which prevented expensive errors in gunport freeboard as built. His method is based on discretization of the hull surface into panels and numerical summation of volume elements between

waterlines, based on hydrostatic principles quoted from STEVIN and HUDDE. Cornelis VAN YK, a former Master Shipwright in Delfshaven, in his 1697 book elaborately describes then current Dutch techniques for hull form definition and ship construction. He displays excellent practical knowledge in constructive ship geometry.

However, none of these treatises written before 1700 by practitioners made any direct reference to hydrodynamic or aerodynamic considerations in ship design. Indirectly stability vs. speed tradeoffs were occupying the minds, but a quantitative grasp did not yet exist for either. It appeared almost as if those issues to designers were not yet matters of practical concern. Rather e.g. in Britain as of 1677 the dimensions and proportions of the classes of great sailing warships began to be standardized (“The Establishment of 1677”).

William SUTHERLAND, former Master Carpenter, later Inspector of Shipwrights in the Portsmouth and Deptford Yards, in his treatise [17] of 1711 addresses many practical issues of shipbuilding, material supply management, rigging etc., though one of his main themes is again ship geometry. He describes the processes from lines plan development to mould lofting and marking of parts, again in the context of “whole-moulding”. The lines plans are reaching a mature, complete and standardized level. Section shapes in this British method consist solely of circular arc segments and a few straight lines, as they did for several centuries in other countries (“mediterranean method”, “sesto method”), while contemporary techniques using lines plans in France and Holland are beginning to turn to more flexible fairing methods, using spline generated lines (see NOWACKI [29]). SUTHERLAND pays verbal tribute to the “Incomparable Sir Isaac NEWTON” and his “Solid of Least Resistance”, of which NEWTON had hinted that it “may be useful for building ships”. But he soon leaves that subject and does not return to any physical reasoning for ship dimensions. But he modestly states in his preface: “Neither Theory nor Practice has hitherto been so far advanced, but both are yet capable of very great improvements”.

Blaise OLLIVIER, a Naval Constructor for the King of France, Master Shipwright of the shipyard in Brest, wrote a famous report [18] about his visits to England and Holland in 1737, where he spent three months in Britain seeing four major shipyards and six weeks in Holland visiting five marine arsenals. He was sent there on a secret mission by French Minister of the Navy Maurepas to compare shipbuilding technologies in these maritime countries with those in France. His report exhaustively deals with many facets of shipbuilding with great accuracy and competence. We will here concentrate on those comparisons which pertain to hull shape design and its consequences. Many of the characteristic tendencies pointed out in 1737 still prevailed much longer and often still lasted in the ships of Trafalgar.

Comparing *English and French* vessels, especially ships of the line:

- For equal gun armament the French ships tend to be longer at gun deck level or in the waterline than the English. This allows for more gun handling space and sharper deck ends.
- The English ships of the line have a wider breadth than the French. OLLIVIER observes that the English sailing vessels have higher deadwork above water (“topheaviness”) and therefore require more stability, hence beam. This also tends to increase their leeward drift and reduce their weatherliness.
- The French ships have greater hold depth and deeper draft. This goes along with more slender section shapes and a more slender hull shape (lower C_B) overall. By contrast English ships have fuller sections, greater C_B and less draft.
- In consequence of their greater length and deeper draft and because of their heavier hull construction the French ships tend to weigh a bit more and have a somewhat greater displacement.
- The English ships have lower masts and smaller sail area. But OLLIVIER points out that this does not per se make them slower. The French ships with their higher masts and more slender hull form require more ballast to secure adequate stability, which adversely affects displacement and speed.

- Overall the English ships are a little less prone to hogging. OLLIVIER attributes this to their shorter, lighter ends, stiffer planking, their caulking being carried all the way up to main deck before launching etc.
- OLLIVIER criticizes the English constructor for “lack of scientific method” because e.g. they do not calculate the displacement at the design stage. In France this practice is just beginning.

Comparing *Dutch and French* vessels, based on OLLIVIER’s visit in Holland and in particular at the Van Zwijndrecht shipyard in Rotterdam, let us just quote one thought from OLLIVIER’s report:

- The Dutch ships of comparable armament have less draft, usually a flat bottom, to navigate in Dutch coastal and estuary waters. They may be more difficult to control on a straight course and in maneuvers.

OLLIVIER’s comparisons are generally fair and without prejudice, as he had himself postulated from a good constructor. He has a remarkably sound engineering judgment of ship design well before any helpful scientific theories.

Henri-Louis DUHAMEL DU MONCEAU (1700-1782) played a prominent role in French naval affairs and in the introduction of a scientific approach into the education of French Naval Constructors. Soon after he was appointed Inspector-general of the French Navy in 1739 he got approval to open a small school for training naval constructors in Paris in 1741, which established itself and grew so that by 1753 it was moved to a prestigious location in the Louvre Palace. It was for this school that DUHAMEL wrote his famous textbook on the elements of naval architecture [19]. It combines much practical information for the ship constructor with the theoretical fundamentals of ship geometry, hydrostatic stability, ship resistance, sail forces and maneuvering. The theoretical subjects are directly based on the *Théorie du Navire* by BOUGUER, with whom DUHAMEL kept close contact while he wrote his book. This fortunate alliance facilitated the rapid acceptance of BOUGUER’s scientific ideas by practitioners.

DUHAMEL’s book became of course a mandatory textbook in French naval constructor training, but was also translated into several other languages so that its knowledge contents soon spread throughout Europe. Mungo MURRAY [20] in Britain cited many essential ideas from it, but apparently without receiving a strong echo from practitioners in his country. However the book was influential in Scandinavia, Holland and other countries. Very fortunately the German translator Captain C.G.D. MÜLLER [96] provided the original text with many annotations and comments of his own so that we owe him rich amplification and visualization of the concepts of DUHAMEL’s book.

To focus again on matters of hull design and performance we find many interesting observations in the second chapter of the book:

- Design requirements for sailing warships encompass gunpower, the lowest gundeck being 4 to 5 foot above waterline, swift speed, good steering, small leeward drift and easy ship motions. DUHAMEL favors a balanced practical and scientific approach in design.
- *Length* is governed by gunport arrangements. MÜLLER adds the note that increased length (or L/B) facilitates course steadiness and a low resistance, convenient placement of guns and masts, but tends to result in aggravated hogging and pitching as well as a greater turning radius.
- *Beam* for ships of the line is around L/ 3.5 (closer to L/ 4. for frigates). MÜLLER discusses pros and cons of beaminess, resistance vs. stability etc., but concludes with recommending a narrow beam, just wide enough for convenient gun handling on the gun decks.
- In his chapters on *ship stability* DUHAMEL gives an elaborate, tabular explanation of numerical calculations of the metacenter, perhaps the most rewarding fruit of the scientific approach for the French Navy and for other followers.

- In other chapters on *resistance, sail forces, point vélique etc.* DUHAMEL moves still in the wake of impact theory like BOUGUER and other contemporaries.

In France these elements of naval constructor knowledge soon became routinely integrated in ship design, contracting, ship documentation, trials and delivery terms. See FERREIRO [13] for more details.

In Spain the Naval Constructor Jorge JUAN Y SANTACILIA (1713-1773), as mentioned, after his initial exposure to ship theory by BOUGUER and to experimental science by ROBINS had become an influential practitioner, being appointed to Chief Naval Constructor of the Spanish Navy from 1752 to 1754, while constantly remaining in touch with theoretical developments. However, he developed much skepticism regarding the practical value of his contemporary ship science. He flatly rejected impact theory for resistance and sail force estimates in all of its variations. He did not even apply the metacenter in practice, whose derivation he trusted, perhaps because of the lack of reliable estimates of the center of gravity at the design stage. He performed model tests and developed his own resistance theory, recognizing the significance of wavemaking phenomena, but falling short of an applicable prediction method. Despite these limitations his book *Examen Marítimo* [66] (1771) captured the state of the art of his period in ship theory, including his own original thoughts, and became rather influential as a textbook in Spain and in its translations also in Europe. E.g. VIAL DU CLAIRBOIS' comprehensive *Encyclopédie méthodique marine* [97], which appeared in 1783, alluded to Jorge JUAN in several sections, notably those on ship motions in roll and pitch, and concurred with him in rejecting impact theory. Jorge JUAN will be remembered as a scientific pragmatist.

Frederik Henrik af CHAPMAN (1721-1808) is perhaps the scientifically best educated practitioner of ship design and construction in the 18th c. He traveled extensively abroad in England (1741-44 in London, again from 1750), France (Brest) and Holland. After his return to Sweden in 1757 he resumed his work as responsible naval constructor and by 1782 became Chief Constructor of the Swedish Navy. He made his mark by the ships he designed and built, by his work in design methodology, by his experimental and scientific work and last, not least by his most famous publications *Architectura Navalis Mercatoria* [31] (1768) and *Traktat* [21] (1775). He was familiar with the contemporary literature on ship theory by Johann and Daniel BERNOULLI, by BOUGUER and EULER, and perhaps indirectly by DUHAMEL. His own practical and scientific contributions to ship design and construction include:

- CHAPMAN was a master of ship lines plan development and ship geometry definition. He drew about 2000 lines plans in his lifetime. His drafting tools were carved, free-form templates, later called French curves, and most probably fairing splines. Thus he was liberated of any constraints that resulted from the earlier circular arc constructions.
- CHAPMAN "invented" the Sectional Area Curve (SAC) as a measure of the longitudinal distribution of cross-sectional area and thereby displacement. This gave him advance control of displacement and volume centroid (LCB), a crucial help in systematizing hull forms.
- The hull form was characterized by principal dimensions and form parameters.
- He adopted Thomas SIMPSON's Rule (1743) for numerical integration of curves and applied it in area and volume integrations of the ship. Displacement calculations and estimates of the metacenter were routinely performed in his designs, likewise for other hydrostatic data.
- The sail force heeling moment was estimated by the expression of (sail area) * (wind force per unit area) * (lever arm between sail center of pressure and hull center of gravity).
- He applied impact theory for resistance following DUHAMEL, but did not trust it. His own experiments remained largely inconclusive.
- His design method was aimed at meeting functional requirements: Payload at the given draft/ adequate stability/ acceptable seaworthiness/ good sailing performance and easy rudder control.

- He tended to recommend high (L/B) and low draft for low resistance and good weatherliness.

CHAPMAN always advocated good practical design being based on a solid theoretical foundation. He is an outstanding example of a practitioner benefitting from openness to his contemporary science.

A contrasting type of practitioner is William HUTCHINSON, a seaman, formerly Commander of a frigate (1750), Master of merchant ships, lately (1794) Dockmaster at Liverpool, who wrote an elaborate treatise on merchant ship hull form design [22]. To quote only a few of his main recommendations:

- The popular adage “Full bows and clean tails” has its drawbacks by promoting large bow waves and poor course control. He recommends “middling full bows and buttocks”. Long and slender ships pitch too much at the bow, but ships with full bows may suffer slamming at the stern under a flat transom.
- Stability is of prime concern in merchant ships. Ship losses are due to want of more beam and a fuller bottom. He recommends: “Merchantmen should be just stable enough when light to right themselves without ballast, but stiff enough when loaded to carry their mast away before capsizing”.

These few remarks may be illustrative of the intuitive understanding of ship performance acquired by an experienced seaman by long personal observation. The individual conclusions are often correct in the given context, but the physical causes of the phenomena are sometimes not fully understood, thus the analysis of the design tradeoffs is not deep.

Finally let us take a look at the *Shipwright's Vade-Mecum*, written chiefly by David STEEL sr. before 1800, extended and edited by his son David STEEL jr. by 1803 and published posthumously by his widow Penelope STEEL in 1805 [23]. This voluminous handbook contains a wealth of information collected and documented for the practical shipwright, but also one more general section “Observations on the Figure and Construction of Ships and Vessels in General”. Regarding hull design the following statements may be noteworthy:

- The design process must satisfy the following functional requirements, especially for sailing warships: Structural integrity (strength), capacity (tunnage), speed, stability, seaworthiness in winds and waves.

The steps of the decision process include:

- Fixing the height of gundeck above water level and the keel drag, if any.
- Fixing the length of gundeck (like DUHAMEL). Lengthening the ship is good for sail area and speed, but bad for pitching and hogging.
- Determining the breadth in the waterline. STEEL is advising against narrow bow to avoid risk of deeper pitching.
- Examining stability. STEEL favors gaining stability by wide breadth despite higher building costs. Stable ships can go faster, carrying more sail.
- Keeping the afterbody slender for good steering.
- Checking for weatherliness. Full hulls are adverse. Increased length and draft are favorable.

STEEL qualitatively follows a similar pattern of design decisions as DUHAMEL. However he does not make use of any explicit performance calculations or stability measures. He seems to offer more conservative solutions favoring rather shorter, beamier, fuller ships as was the tendency in Britain and he is cautious about long, narrow, more slender hull shapes, as are built in France. This may reflect a certain satisfaction with the status quo. But the *Vade-Mecum* is hardly the place for revolutionary ideas. But he also says in all fairness and modesty:

“Many who have despaired of establishing these points (Note: Least Resistance Hull Shapes) by mathematical rules, have applied themselves wholly to their own local observations and experience, which may, and doubtless have, in some cases, served as a substitute for more correct science. Yet, although it may in this manner have been discovered that some vessels have had bad qualities from which others were exempt, and the contrary, it could not be determined wherein the fault or the advantage lay; whether in the Hull, in the Sails, or in the Rigging. Hence no remedy could be applied, no certain rule deduced”.

Such remarks and others from that age show practitioners and scientists united in their dissatisfaction with the state of the art, but there is no denying either that ship design and construction in the course of the 18th c. had become a more rational, cause and effect related decision process rather than a game of hazard.

4. The ships

4.1 Choice of examples

The ships of Trafalgar have always fascinated a wide-ranging community by their historical, technological and esthetic appeal. It is thus not surprising that there exists an abundance of literature depicting and documenting these ships. Quoting only a sample of more technologically oriented references, whose information has been helpful for the present paper, I can easily assemble a major list of classical and very recent books. Let me mention and give credit to at least the following in their chronological order: CLOWES [98], CHAPELLE [99], HENDERSON [6], MACGREGOR [100], BOUDRIOT [5], WHIPPLE [101], GRUPPE [102], HOWARD [103], LAVERY [104], GARDINER/LAVERY [4], BOUDRIOT [105], GARDINER et al. [106], GARDINER [107], BOENDEL [12], GOODWIN [108]. It is not intended here to reiterate the detailed ship descriptions which can be found in these sources and others. Rather we will limit ourselves to choosing a few examples to illustrate some of the technological properties of this large class of ships. The small sample to be chosen cannot claim to be statistically representative or even close to the average ship types. It is however intended to exhibit some of the most typical ship characteristics.

The ships of Trafalgar encompass essentially ships of the line and frigates. Ships of the line are the heavy gun platforms of the battle fleet, the large sailing warships conceived to fight in the battle line and to dominate by superior gunpower. The frigates are much smaller ships, carrying only about half the displacement, but they are designed for fast sailing, are much more mobile, and are intended for independent operation worldwide in colonial or regional military missions or for a subsidiary role to a large battle fleet. At Trafalgar the British and the Combined French/Spanish fleets together comprised 60 ships of the line and 9 frigates. But despite the numerical preponderance of the ships of the line we will include both types of ships in our sample because they are technologically distinct entities with different design objectives and solutions. Fig.14 gives an idea of the silhouettes, the gun deck arrangements and armament of these two principal vessel types.

In the category of ships of the line several of the older ships were still of the heaviest armament of 1st and 2nd rate vessels, but more than half of the ships in all fleets were of 3rd rate, 74-gun type. This type of ship had evolved as a cost-effective solution since about 1755 and had dominated the more recent building programs in all three nations since about 1780.

The 5th rate frigates, whose history goes back to the mid-17th c., had become very popular in France and England after 1750 [6], [105], [107]. French frigates were highly esteemed for their greater size and speed, and when some were captured by the British (Hébé: 1782, 1260 tons, 40 guns; Pomone: 1794, 44 guns), they served to set a trend to heavy and large frigates in Britain, too (Apollo Class: 1798, 1431 tons, 44 guns).

Table I gives an overview of the ships chosen in our sample set of ships of Trafalgar. The table describes the principal characteristics of two 1st Rate Ships, the *Victory* (E) and the *Santísima Trinidad* (Sp), three 74-gun ships, a French reconstruction by BOUDRIOT [5], the *Mars* (E) and the *San Ildefonso* (Sp), and two classes of frigates, the *Apollo Class* (E) and the *Venus Class* (F). Their dates of commissioning, their constructors and their armament are stated. Most data serve to document the principal dimensions and form characteristics of these ships. Some data are uncertain or suspect, they are denoted by question marks. Usually accurate data on displacement and draft and hence the corresponding form coefficients are scarce and sometimes contradictory. Speed in knots and Froude number F_n are cited with an average cruising speed under favorable wind conditions and a maximum value quoted for peak performance.

4.2 Properties

○ Geometry

The principal hull form characteristics of some typical ships of Trafalgar are compared in Table I. Fig. 15 in addition shows the body plans of six of those ships, two each of the classes of 1st, 3rd and 5th rate ships (frigates). Complete lines plans can be found in the quoted sources. Our comparisons will concentrate on the principal dimensions and form coefficients of these ships. These data set the main trends in performance even if local features in hull form may differ.

Nondimensionally the different classes (rates) of Trafalgar ships show more similitudes than differences. The most striking feature in this generation of sailing warships was their unique low length/beam ratio. The ships were short and stubby. The ratio of L/B varied with time and ship type. It varied from $L/B = \text{ca. } 3.0$ early in the 18th c. toward almost 4.0 in 1800. It was lower in the older 1st rate ships than in the later 74-gun ships, and the greatest increase was desired and achieved in the latest frigates. The reasons for these trends will be discussed under stability, resistance, hogging resistance and in Section 4.3.

The other proportions show nothing critical hydrodynamically or structurally. The form coefficients C_B , C_P and C_M indicate a slender, “elegant” hull form, perhaps more than required for the relatively low cruising speeds achieved. The waterplane coefficient C_{WP} tends to be on the high side, probably in the interest of stability.

○ Stability

The initial stability of the Trafalgar ships appears to have been adequate, as desired, in lying between a lower bound dictated by safety under sail and by recoil loads when firing broadsides and an upper bound set by the requirement of avoiding too much stiffness and violent roll accelerations. To achieve this satisfactory stability the English constructors relied a little more on ample beam and less on ballast, the French vice versa in the interest of a lower resistance. Ballast of course reduced the payload or increased the displacement, which in turn negated part of the resistance gain. Likewise, as mentioned by OLLIVIER (see above), the English ships tended to have lower masts and less sail area, hence reduced stability requirements in operation, which also helped them to save ballast and thus unnecessary displacement.

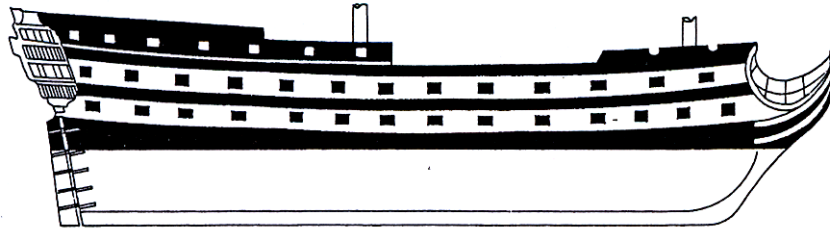
In any case the required beam of the ships was generally fixed within narrow limits once the gun deck arrangements were defined and the stability could be evaluated.

It should be added that the ship masters and sailors knew their ships and were able to compensate for certain weaknesses in stability by operational measures under sail, sometimes at the expense of speed losses.

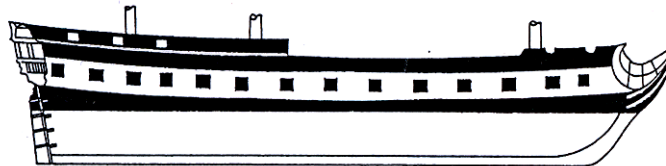
The physical understanding of stability phenomena and criteria by scientists, designers and seamen had much improved during the decades before Trafalgar.

Table I: Dimensions and Proportions of Some Ships of Trafalgar

	<i>Victory</i>	<i>Santísima Trinidad</i>	<i>French 74 Gun Ship</i>	<i>Mars</i>	<i>San Ildefonso</i>	<i>Apollo Class</i>	<i>Venus Class</i>
Year	1765	1769	Ca. 1750	1794	1785	1798	1780
Constructor	Thomas Slade	Mateo Mullan	Recon- struction	Henslow	Romero de Landa	Rule	Sané
Rate: Guns x Caliber	1 st : 104 x 42 pdr	1 st : 120 x 36 pdr	3 rd : 74 x 36 pdr	3rd: 74 x 32 pdr	3rd: 74 x 24 pdr	5th: 44 x 18 pdr	5 th : 38 x 18 pdr
Source	[108]	[108]	[5]	[108}	[108]	[12]	[12]
LWL (m)	56.0	56.0 ?	52.65	52.10	52.9	44.14	45.88
B (m)	15.86	16.13	14.00	14.95	14.4	11.43	11.86
Depth of Hold (m)	6.57	8.31	6.5	6.1	6.95		
Draft (m)	7.16 ?	8.00	6.17	6.39 ?	6.5	5.11	4.74
Depth D to Main Deck	11.6 ?		11.4			6.80	6.29
LWL/B	3.53	3.47	3.76	3.48	3.67	3.86	3.87
B/T	2.2	2.02	2.27	2.34 ?	2.22	2.24	2.50
LWL/T	7.82	7.0	8.53	8.15 ?	8.14	8.64	9.68
LWL/D	4.83 ?		4.62	4.29		6.49	7.29
B/D	1.37 ?		1.23	1.23		1.68	1.89
Δ (m. tons)	3505 ?	4627	2864		2938	1431	1260
Tons of burthen	2142	4902		1842	1600	944	1063
C _B	0.55 ?	0.64	0.60 ?		0.59	0.523	0.46
C _P	0.67 ?	0.72	0.80 ?		0.69 ?	0.695	0.629
C _{WP}	0.825	0.86	0.80 ?		0.84 ?	0.846	0.805
C _M	0.82	0.89	0.75 ?		0.83 ?	0.774	0.759
Speed (Kn)	7-10	7-10	7-10	7-10	7-10	10-13	10-13
F _n	0.15-0.22	0.15-0.22	0.16-0.23	0.16-0.23	0.16-0.23	0.25-0.33	0.24-0.32



a) *Ship of the Line, Third Rank ,74 Guns, Example: Mars (1794)*



b) *Frigate, Fifth Rank, 36 Guns, Example: Dryad (1795)*

Fig. 14: Silhouettes of Trafalgar ship types (from BOENDEL [12])

o Speed and Resistance

The ships of the line, in part due to their unfavorable principal dimensions (L/B), were slow sailers for their size and length, cruising at speeds between 7 and at best 10 knots. Thus on the average their Froude number in this condition was very low, say, around $F_n = 0.15$, so that their resistance was primarily frictional and viscous pressure drag. Their wave resistance was almost negligible in this condition. These considerations were of course unknown to scientists and designers at the time.

In this range of low Froude numbers it must be the designer's aim to minimize the frictional drag and the viscous pressure drag. The Reynolds numbers of these great sailing vessels are around 10^8 , thus the flow is turbulent. There is therefore a chance to keep the flow attached in the afterbody without a large extent of separation. The prevalent design philosophy in the 18th c. was to place the maximum cross section well before amidships, as some experimentalists had also verified. This measure facilitates the flow remaining attached in the afterbody as does the design for "clean tails", i.e., sharp waterlines aft. In this regard practitioners by experience and intuition made the best of the given situation.

However the low L/B ratio still suggests that some separation near the stern cannot be completely avoided. Modern era test results on bluff axisymmetric shapes reported by HOERNER [109] and HUCHO [110] confirm that a noticeable viscous pressure drag increase caused by some extent of separation is still inevitable at $L/B \approx 3.5$ and is somewhat alleviated at $L/B = 4.0$ (and more so beyond). Thus in the Trafalgar era the evident desire to go to greater lengths for higher speed has a very plausible physical explanation. Conversely the status quo before Trafalgar in ships of the line was far from optimal hydrodynamically due to conservative limits on ship length.

The frigates fared better with respect to L/B and did indeed make much better speed, also because of their lower displacement, of course. But since they were operating at higher Froude numbers, their wave resistance was not negligible. Thus they should have benefitted from moving the center of buoyancy abaft amidships, which according to BOENDEL [12] in actuality they did not exploit. Nevertheless, given the unfavorable L/B constraint, their slender hull form with adequate beam for stability was an elegant solution to the challenge of good cruising speeds.

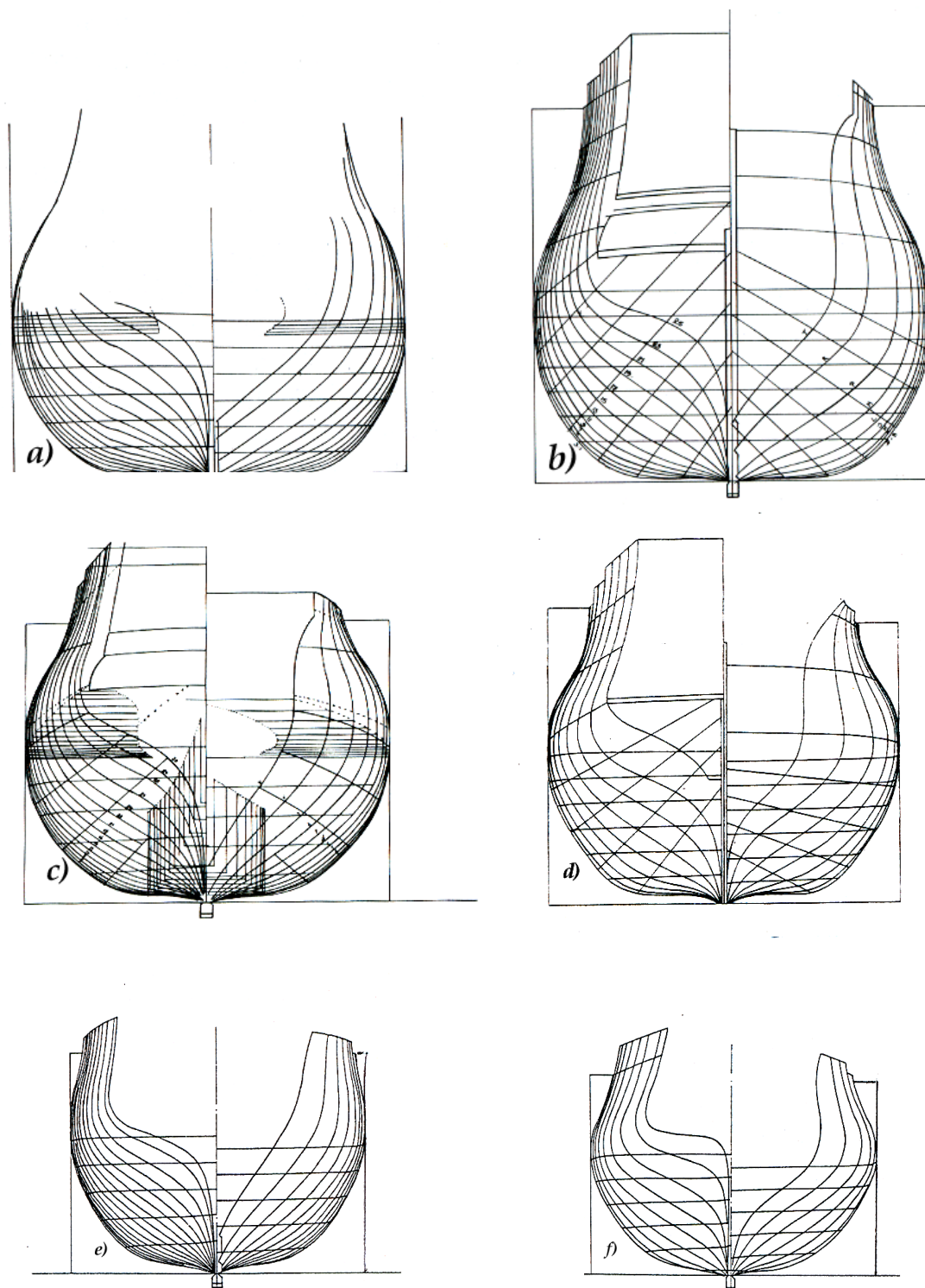


Fig. 15: Body Plans of Trafalgar Ships:

- a) *Victory*, 1st Rate, 104 guns (from GOODWIN [108]),
- b) *Santísima Trinidad*, 1st Rate, 120 guns (from GOODWIN [108]),
- c) *Bellerophon*, 3rd Rate, 74 guns (from GOODWIN [108]),
- d) *French 74-gun ship* (from BOUDRIOT [5]),
- e) *Apollo Class*, Frigate, 44 guns (from BOENDEL [12]),
- f) *Venus Class*, 38 guns (from BOENDEL [12]).

- Weatherliness and Maneuverability

Weatherliness, i.e., the aptitude of a sailing ship to make speed while pointing high into the wind, depends on its ability to balance the forces and moments acting on its hull and rig while developing a positive forward thrust on such a course. Leeward drift and major drift angles are adverse influences since they are indicative of a system imbalance causing an increase in resistance. The sway resistance of the underwater hull and the lateral component of the rig force (C_H and Y_{HA} in Fig. 11) form a couple which does exert a heeling moment and may cause a yawing moment and thereby produce a drift angle. Since the magnitude of the hull and rig lateral forces cannot be influenced much by simple design measures once the dimensions and proportions of the hull and rig are chosen, the designers' attention concentrates on avoiding a major yawing moment. This can be achieved by bringing the centers of pressure approximately into the same vertical plane. Placement of the masts and thereby locating the rig center of pressure is of significance. Nominally the centers of pressure of hull and rig were assumed to be located in the centroids of underwater lateral plan area and sail area. Actually in oblique inflow with small angles of incidence the centers of pressure move forward toward the leading edges, though not by the same distance. Thus in new designs the magnitude of the yawing moments was not accurately predictable. Actually many of the ships of Trafalgar were reported to be excellent sailers, also in this regard, but others had earned a poor reputation by leeward drift and mediocre speed.

Regarding the weatherliness achievable by the Trafalgar sailing ships the performance of the rig played a decisive role. The polar curves of lift and drag coefficients as a function of the angle of incidence of the apparent wind characterize the performance of the rig. Unfortunately I have no access to such data for the rigs of the ships of Trafalgar.

However we have at least indirect evidence on the achievable performance of two frigates of the age of Trafalgar from the systematic reconstruction study performed by HARRIES, BOENDEL et al. [111]. They have carried out extensive model tests at various speeds and angles of heel and yaw to measure the hydrodynamic force components of the hull for a wide range of operating conditions. The two frigates were the French *Hébé* (1782), belonging to the *Venus Class* design by Sané, and the Swedish *Bellona* (1778), designed by the Swedish constructor CHAPMAN. The principal dimensions and proportions of the two ships are very similar. The *Hébé* resembles the *Venus Class* example in Table I. The *Bellona* does not differ much in length and beam ($L/B = 3.94$), but draws a little less ($T = 4.6$ m) and displaces $\Delta = 1210$ t. Adopting the polar curves of a comparable square rig published by WAGNER [82] the authors then have reconstructed the sailing performance of the two frigates. The velocity diagrams in Fig. 16 show the speed made good on a range of courses to true wind for different wind velocities (Beaufort scale 3, 4 and 5). It is not surprising that the two similar ships show a very similar sailing performance. Sailing close-hauled they can point as high as 6 points (67.5 deg) off the wind. This conforms with reports on other classical square riggers. (Modern high performance rigs for merchant ships with special sail materials and advanced aerodynamic design, e.g. the PROELL six-mast cargo sailer, may achieve a sailing course of 4 points (45 deg) off the wind [82]).

Regarding the turning ability of the Trafalgar ships their short length acted in their favor. The rudder area of about 2-3 percent of lateral plan area may be regarded as normal by modern standards. But the high aspect ratio of many rudders (abt. 5) would tend to result in small stall angles (abt. 15 deg), thus limit rudder effectiveness.

- Seaworthiness

The ships of Trafalgar by modern standards were "small ships" of 45 to 55 m waterline length. This is a basic handicap for their seaworthiness. For one thing this causes their natural frequencies of pitch, heave and roll to be relatively high so that they will experience frequencies of encounter in near resonant conditions even in moderate sea states. For another the smaller ships will oscillate with relatively larger amplitudes in a given sea state. The acceleration amplitudes, proportional to the motion amplitudes times

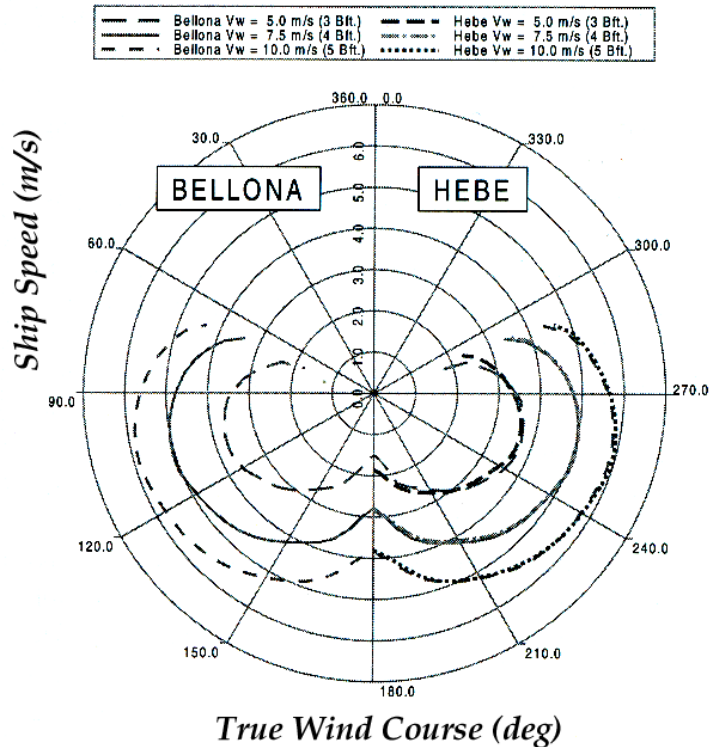


Fig. 16: Velocity diagram for the frigates *Bellona* and *Hébé* (from HARRIES, BOENDEL et al. [111])

the square of the frequency, can therefore become extreme. This holds in particular for the accelerations in roll near the top of the masts in near resonant conditions. Thus there are reports of ships rolling away their masts, if they were too stiff. Designers and ship masters knew this problem and tried to alleviate it by proper “tuning” of ship stability and by operational measures concerning ship course and speed. Regarding pitching and heaving motions English constructors favored short, full bows in order to limit bow motion amplitudes by stronger restoring forces. They claimed that the French finer and longer forebodies suffered greater pounding in way of the bow and corresponding deck wetness. This view, which was not shared by the French constructors, needs to be more closely examined. The risk of pounding the structure at the stern has to be weighed in. The comparison must also take into consideration that the more the volume centroid (LCB) moves forward of amidships, as it does with the full bows, the stronger is the coupling of heaving and pitching motions. Thus near resonant motions in pitch reinforce the simultaneous heaving and vice versa. Therefore the ship operator must beware of unfavorable synchronisms in pitch and heave. In any case the controversy about this issue has remained inconclusive.

It is difficult to understand why the sailing ships of Trafalgar all had bow shapes where the side planking in way of the bow was not carried to the topmost deck. The resulting wetness in adverse sea states was well known. But it was only after Trafalgar in the era of SEPPINGS that the English constructors went to “round bows” closed all the way around and up to the top deck.

The masters and seamen of the fleets of Trafalgar had learned how to cope with the motions of their ships even in inclement operating situations. But to engage in battle required favorable conditions of wind and sea. In battle military actions required moderate sea states, presumably not much beyond sea state 3.

o Hogging resistance

For the ships of Trafalgar hogging was a problem. It not only jeopardized the structural integrity of the hull, but its prevention and more often cure necessitated frequent actions of careening, recaulking and repair. It put some ships out of operation for considerable periods. The reasons were not always convincingly understood. English constructors claimed advantages stemming from their fuller, blunt forebody shapes and slightly shorter ship lengths. But was this a welcome price to pay?

Hogging was often explained as a consequence of hull girder loads by heavy guns at the ship ends, i.e., by the effect of bending moments. Actually the longitudinal bending moments in the “small ships” of Trafalgar are very small and cannot be the cause of the substantial hogging deformations of about 1 or 2 ft observed in those ships, often right after launching. In practice the deformation pattern in the Trafalgar ship ends is not mainly flexure, but results from a longitudinal slippage between planks once the friction of the caulking in the seams is overcome. The resistance of the structure against such slippage is much weaker than its bending stiffness. This is also mentioned by COATES [43].

To demonstrate the insignificance of longitudinal bending in the ships of Trafalgar a few simple, approximate calculations were made for a 74-gun ship, whose cross-sectional scantlings are given by STEEL [23], and a frigate, the *Hébé* of the *Venus* Class whose structure is described by BOENDEL [12]. As an upper bound to the bending moments, bending stresses and strains an approximation formula was used, as recommended by HENSCHKE [112] for smaller modern cargo ships:

$$M_{B_{max}} = (\Delta * L) / C, \quad C = \text{abt. } 33 \text{ for a modern small cargo ship on wave crest}$$

To check whether this approximation also holds in the case of our historical ships with heavy cargo or guns near the ends a simple load case was investigated : Weights distributed uniformly over ship length, buoyancy distribution over length parabolic so that a considerable excess weight load dominates over buoyancy near the ends. This load case (for still water bending) can be treated analytically by closed form integration and yields the constant $C = 32$ in the above expression. The agreement is convincing.

Table II: Maximum Bending Moments and Stress at Deck Level in Trafalgar Ships

Ship	$M_{B_{max}}$ (tm)	I (m ⁴)	S_D (m ³)	σ_D (kg/cm ²)
74-gun ship	4575	37.65	13.37	34
Frigate	1806	17.27	7.23	25

Carrying the analysis further for the two ships and their bending moments $M_{B_{max}}$, the midship section moment of inertia I , the section modulus at deck height S_D and the stress at deck level σ_D we obtain the results shown in Table II:

The ultimate tensile strength of oak wood in the direction of its grain is:

$$\sigma_{Bult} = 1370 \text{ kg/ cm}^2.$$

Thus the actual maximum longitudinal bending stress amidships is only a fraction of the permissible stress in the material. The maximum deflections at the ends in this load case are proportional to the bending moments amidships and can be shown to be equally insignificant. Thus it is not the hull girder bending mode that causes the large hogging

deformations observed in the great wooden sailing ships. Rather it is the lack of local structural integrity against longitudinal slippage between the planks.

As discussed, this slippage can be prevented by diagonal braces across the planking or diagonal riders attached to the frame timbers as ceilings. These measures were known as possible remedies in the 18th c., as the literature documents (BOUGUER [30], DUHAMEL [19], CHAPMAN [21]), but were only hesitantly applied before Trafalgar. In England they were still controversial when SEPPINGS introduced them by 1810. But they proved effective when used (COATES [43]), substantially reducing the hogging deformations.

Thus it appears that the lack of earlier insights into a known technological remedy to hogging caused the designers not to venture into further lengthening their ships. Their concern about hogging thus made them sacrifice possible hydrodynamic performance advantages, as later developments would demonstrate.

4.3 Design issues

To analyze the logical pattern of the design problem for the Trafalgar sailing ships with respect to their principal dimensions and proportions it is convenient to formulate the design task in accordance with the format of the design decision-process in optimization studies in Nonlinear Programming, which has found wide-spread acceptance in modern ship design (see e.g. NOWACKI [113]). For this purpose the design task is stated as follows:

Given: The functional requirements for the ship and in particular its desired payload (e.g. gun armament and ammunition, any other equipment and outfitting, crew complement and provisions etc.) and usually the desired speed. The requirements are generally specified by the navy or owner.

Find: A ship as a technical solution to these requirements, characterized by the following free variables and constraints:

Free variables of design:

Principal dimensions:

L, B, T, D, C_B (length, beam, draft, depth, block coefficient),

or stated nondimensionally, as far as possible:

$L, L/B, B/T, L/D, C_B$.

The problem initially has five free variables.

Inequality constraints:

$\Delta \leq \Delta_{\text{Max}}$
(Size limit: No unnecessary displacement)

$(L/B) \leq (L/B)_{\text{HOGGING}}$
(The length for a given beam must not exceed the given safety limit)

$(B/T) \geq (B/T)_{\text{STAB}}$
(Transverse stability constraint)

Measure of merit:

For these historical ships the measure of merit was not explicitly stated. Implicitly a mission effectiveness was desired for the fleet to which each ship was to contribute by

means of a favorable gunpower and availability per unit building and operating cost. But we need not quantify the measure of merit because the design solution is governed by the given constraints.”

Let us disregard ship depth D or L/D because it is actually determined separately from considerations of freeboard and deck arrangement. The remaining four free variables must then be suitably chosen in compliance with the three inequality constraints.

In the most frequent case the three inequalities are all active constraints, i.e., these conditions are met as equalities because the designer does not want to make unnecessary concessions by deviating from these given target values. Else the ship would become heavier, shorter and beamier than necessary and achievable. With three equalities to be met only one of the three variables can still be freely chosen, the others follow from the constraints.

E.g., for a frigate similar to the *Venus Class*, let:

$$\Delta_{\text{Max}} = 1500 \text{ t}, (L/B)_{\text{HOGGING}} = 3.8, (B/T)_{\text{STAB}} = 2.5.$$

Then, if we choose $L = 45$ m, we obtain:

$$B = 45/3.8 = 11.84 \text{ m}, T = 11.84/2.5 = 4.73, C_B = \Delta / (\gamma * L * B * T) = 0.58.$$

If any design variable is freely chosen, the others follow from the constraints. Greater freedom of variation could only be obtained if the constraint target values were relaxed. But what are the chances for that?

A greater displacement for a given payload is not desired (for economic reasons), a narrower beam would jeopardize stability (for physical reasons). A greater (L/B) is feared as a risk to structural integrity (hogging), a technological limit of material, assembly method and structural design. This technological limit might have been shifted by new technological solutions. But this did not happen to a sufficient degree before Trafalgar.

To rephrase the crux of the design problem in simpler terms: The ships tended to be unfavorably short and beamy. Let us accept the beam as a necessity for stability and gun handling. If the displacement is kept constant, then lengthening the ship is feasible only if simultaneously T and/or C_B are lowered. This is technically feasible within limits and might offer some advantages, but was prevented by the upper bound on (L/B) in the interest of structural integrity.

This describes a dilemma in design freedom which the constructors of the Trafalgar ships did not overcome fast. In the longer run, beginning soon after Trafalgar, the hogging problem was gradually resolved and the ships grew in (L/B) . The clippers of 1845/46 e.g. reached $(L/B) = \text{abt. } 5.0$, though admittedly without the demanding stability requirements of the sailing warships. But hogging was no longer the limiting factor for (L/B) .

4.4 Assessment

The ships of Trafalgar were designed on the basis of specifications with very stringent and narrow constraints, as discussed in Section 4.3. Thus it would be unfair to criticize particular performance features without remembering the whole context of requirements. The dominant constraints were those related to stability for the heavy weights of guns high in the ships and those which limited ship length, presumably in consideration of technological limits of structural integrity. Most properties of the ships, including their principal dimensions, can be derived from these assumptions. With this caveat in mind let us nevertheless in all brevity present a critical assessment:

- Stability:

Adequate in ships of the line despite their tendential topheaviness, more readily achieved also in frigates, at the expense of wide beam in both ship types.

- Resistance and Speed:

Not optimal in ships of the line, mainly due to their functional purpose as gun platforms. Frigates much better proportioned for fast sailing. Sailing rigs state of the art and properly placed and operated.

- Maneuvering:

A strong quality in both types of sailing vessels, favored by their relatively short length. A good balance between coursesteadiness and turning ability was reported for many of the better designs, though not consistently for all.

- Weatherliness:

Good within the limits of square rig potential.

- Seaworthiness:

Both relatively small ship types are susceptible to strong ship motions.

- Hogging strength

A weak point of technology. Potential of available options not yet fully exploited.

Under the given circumstances and in view of the restrictive constraints the constructors had achieved very effective solutions within the confined feasible domain.

5. Conclusions

Let us now return to the questions raised in the Introduction:

- How were hydromechanically relevant design decisions taken in practice and how did this affect ship performance?
- Where did ship design actually benefit from growing scientific insight?
- Where and how did emerging new theories still fall short of practical applicability?

Design decisions by responsible practitioners were taken on the basis of long experience with similar ships, observation of current designs, also those of the competing navies, and whatever scientific insight was available and helpful. Ship hydrostatics had made major advances in the 18th c. and the naval constructors benefitted from it, either directly or indirectly. The French Navy, e.g., had begun routinely to calculate metacentric height at the design stage. Admittedly this evaluation was limited to initial stability at small angles of heel and estimates of the Center of Gravity were not very accurate. But the use of rational criteria helped to steer the design in the right direction and to learn fast by analyzing mishaps. A similar understanding developed during this period for ship motions in roll, heave and pitch, which helped to avoid excess stability and ship stiffness. In the English Navy before Trafalgar stability and motion calculations were not routinely performed. But the background knowledge on these matters had become public domain and may have helped the constructors to understand the hydrostatic performance of their designs.

With respect to hydrodynamic and aerodynamic theories the constructors had no comparable scientific guidance. The existing theories were at best inaccurate and at

worst misleading. Constructors thus had to rely on their empirical knowledge and trial and error learning processes. The fact that the navies had pretty stringently standardized their designs in their dimensions and scantlings (“establishment design”) prevented rapid and adventurous changes. The tendency to imitate successful ships of opponent navies did the same. Thus major pitfalls were avoided. On the other hand a certain stagnation resulted from this. The ships of the line changed only very gradually although the 74-gun ship matured and grew into a cost-effective solution. The frigates during the second half of the 18th c. developed faster toward greater displacements, greater lengths and elegant, slender hull forms. Their limitation to a single gun deck and austere deadwork was a fortunate decision for ships of this operational profile.

In short summary new scientific methods were successful in geometric hull form design and hydrostatic stability evaluation. But the theoretical foundations were still inadequate for applications in ship resistance, sail forces, maneuvering and ship motions. Despite these remaining weaknesses the overall balance of ship theoretical knowledge gains in the 18th c. is very positive. In geometric hull form design the developments in lines plan generation and fairing by means of French curves and splines brought the necessary freedom from circular arc constructions and simple, but inflexible longitudinal interpolants. The invention and application of the Sectional Area Curve by CHAPMAN as a tool for longitudinal volume allocation was a major breakthrough in design methodology. BOUGUER’s and EULER’s ideas on ship stability laid the foundations for safer, more rational ship design.

The later 18th c. shed the yoke of impact theory and embarked on the promising path of fluid mechanics field theory. The late recognition by such scientists as Jorge JUAN and BEAUFOY that gravity effects and frictional or viscous flow phenomena were of great practical significance in ship fluid dynamics opened the door to new research which in the 19th c. led to new methods in hydromechanic theory and experimentation based on multiple parameters of similitude. This seed was sown before Trafalgar.

In conclusion hydrodynamic theory alone was insufficient to support ship design for lack of valid theoretical models. Experiments alone were inadequate, too, in the absence of physically correct theories to correlate against, e.g., scaling laws. The design practitioners’ approach alone, if it was based on trial and error and empiricism, was not a suitable learning tool either because the ships built were too few and their variations too narrow for any systematic learning. The success stories in the 18th c. are those where the synergies of science, experimentation and practical ship design were brought to bear together. The lesson I draw from this agrees precisely with the view expressed by J. SEWELL in 1798:

“It is important that Shipbuilding be studied by Philosophical as well as Practical Men”!

Nothing prevents anybody from being both philosophical and practical.

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