The Aristotelian Heritage in Early Naval Architecture, From the Venice Arsenal to the French Navy, 1500-1700[*]

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ABSTRACT: This paper examines the Aristotelian roots of the mechanics of naval architecture, beginning with *Mechanical Problems*, through its various interpretations by Renaissance mathematicians including Vettor Fausto and Galileo at the Venice Arsenal, and culminating in the first synthetic works of naval architecture by the French navy professor Paul Hoste at the end of the seventeenth century.
Keywords: naval architecture; Aristotle; Archimedes; mechanics .

1. Introduction

Naval architecture has played a small but strategically vital role in the development of rational mechanics, yet until lately it has received scant attention from historians. Recent works on the development of naval architecture during the Scientific Revolution have focused on its origins in Archimedes' theorems for displacement and stability (Nowacki, 2001; Nowacki and Ferreiro, 2003). Yet some of the first theoretical problems in naval architecture, systematically analyzing important mechanisms such as rowing, the action of sails and buoyancy, actually appeared more than a century earlier in the works of the school of Aristotle. When a series of Latin translations were made during the sixteenth century of the Aristotelian treatise *Mechanical Problems*, many of these concepts were analyzed and even directly employed by scientists working in the late Renaissance and the beginnings of the Scientific Revolution. By the end of the seventeenth century these theories were being applied across the full range of ship problems; but by then Archimedes' theories had begun to displace Aristotle, leading to the modern system of naval architecture.

2. The Origins of Aristotelian Naval Architecture in the Mechanical Problems*, c. 300 BC-c. 15 BC*

In none of the known writings of Aristotle (384 BC – 322 BC) did he deal with mechanics *per se*, in the sense of the application of physical principles to machines, but rather he discussed the more general principles of causality and change. In his *Physics*, for example, Aristotle implies that physical change is proportional to the 'power' of an agent of change multiplied by the time of the change; but this concept was not merely applicable to mechanical elements such as a change of position, but also to changes of state, e.g. weight, or chemistry, e.g., heating (Aristotle, 1999, VII 5, 249b27-250a25 at pp. 182-183; Hussey, 1991, pp. 215-216).

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[*] My thanks to the two anonymous reviewers for their insights

The application of these general mathematical principles to the specific subject of mechanics was made in the short treatise *Mechanical Problems* (also called *Mechanical Questions*, *Questions of Mechanics* or *Mechanica*) apparently written after his death by a member of his Peripatetic school, circa 300 BC. Although the authorship of the work remains in dispute, it is usually described as 'Aristotelian' or 'pseudo-Aristotelian' (Aristotle, 1963, pp. vii-viii. Winter (2007) argues that *Mechanical Problems* was authored by Archytas). *Mechanical Problems* was in fact a collection of 35 practical problems in the form of short questions followed by extensive answers, describing how specific devices or techniques allow a greater force to be overcome by a lesser one by application of the principle of the lever (Damerow, et. al., 2002, p. 94). Of these problems, four were directly concerned with issues of naval architecture: one with rowing by oars; one with steering by rudder; and two with the action of sails.

Mechanical Problems began with a discussion of the lever, declaring that its first principle is based on the circle, on the grounds that the line of the circumference moves backwards and forwards simultaneously, thereby accounting for the movement of the opposite ends of a lever (Vilain, 2008). The first three problems in the treatise establish the basic theory of the lever, derived from Aristotle's argument in *Physics* that physical change is a function of the 'power of change' multiplied by the time of the change. In *Mechanical Problems*, the law of the lever was expressed as a dynamic proportion, the product of the weight and speed being equal on either side of a fulcrum: using modern algebraic formulation, force and velocity are equal: $Fv = fV$ (Aristotle, 1963: *Mechanical Problems* 848b − 850b, pp. 330-355). This is in contrast to the modern, statical concept of the lever, first rigorously elucidated by Archimedes of Syracuse (*c.* 287 BC − *c.* 212 BC) in his *Equilibrium of Planes*, that the products of the force times length are equal ($Fl = fL$) on either side of a fulcrum (Archimedes, 2002, pp. 238-239). A comparison of the two is shown in Figure 1.
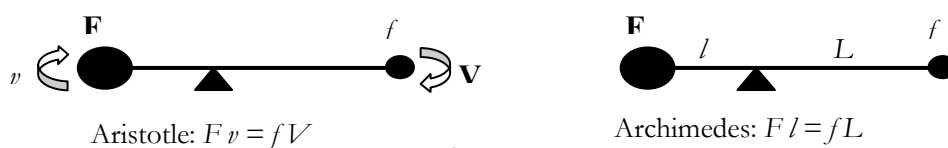

Aristotle: $F\,v = f\,V$ Archimedes: $F\,l = f\,L$

Figure 1

Lever laws in the Aristotelian *Mechanics* and Archimedes' *Equilibrium of Planes*

This principle of the lever formed the basis for the questions discussed in *Mechanical Problems*, including the four concerned with naval architecture, as follows (Aristotle, 1963: *Mechanical Problems* 850b − 851b, at pp. 355-361; Heath, 1949, pp. 237-239):

4) Q: Why do the rowers in the middle of the ship (i.e., amidships) contribute the most to its movement? A: The oar acts a lever with the thole-pin (i.e., oarlock) as the fulcrum, the moving weight (the rower) is on the inside of the ship, and the moved weight (the sea) is on the outside. Since the ship is widest at the middle, more of the oar is on the inside, so the movement of the oar against the thole-pin causes the pin (and therefore the ship) to move forward the greatest distance.

5) Q: How can the rudder, which is small and at the end of the ship, move the entire vessel so easily with a short tiller and the strength of just one man? A: As with the oar, the tiller is the lever, and the rudder pushes against the sea. Because it is at the end of the ship, the rudder can

move faster and thus cause the ship to turn. (There is then a further explanation of why an oar does not rotate precisely around the thole-pin, but rather at a point further away from the rower, because the ship moves forward a greater distance than the oar moves backwards, thus displaces the fulcrum.)

6) Q: Why does a sail attached to a higher yardarm push a ship faster than if the same sail were attached to a lower yardarm? A: The base of the mast is the fulcrum, so the higher the yardarm, the more rapidly it can move for a given force.

7) Q: Why, when running close-hauled across the wind, do sailors take in sail at the stern and let it out at the bow? A: More sail at the bow turns the ship away from the wind, and less sail at the stern allows the rudder push against the sea.

Thus, the mathematical mechanics of Aristotle and his followers were aimed at describing, in a qualitative sense, the laws of proportionality behind the actions of certain simple machines; for the problems in question, the proportion between force and speed across a lever (Hussey, 1991, pp. 215-220, 240-241). The *Mechanical Problems* became known to the Romans through the *Ten Books on Architecture* of Vitruvius, *c.* 80 BC – *c.* 15 BC, who also incorporated the naval architectural questions in his explanations of machines (Vitruvius, 1914, Book 10 Chapter 3 Elements of Motion, at pp. 291-294; see also Winter, 2007 pp. iv-v). It should be noted that these analyses were qualitative in nature, and did not provide measurable, quantitative explanations for the physical processes of how a ship moves under oar and sail.

3. The Venice Arsenal and the Application of Mechanical Problems to Practical Naval Architecture, 1517-1593

The rediscovery of the text of the *Mechanical Problems* at the dawn of the Scientific Revolution sparked at least two attempts within the Venice Arsenal to directly apply its lessons to the design of oared vessels. *Mechanical Problems* appears to have been unknown to European scholars throughout the Middle Ages (Laird, 1986; Laird, 2000). It was included in the works of Aristotle that were typeset and published by the Venetian printer Aldus Manutius from 1495-1498, part of a renaissance of Greek learning that quickly spread through Europe (Drake, 2000, p. 13). In 1517, the Venetian scholar and humanist Vettor Fausto was the first to translate the treatise into Latin, although he did so without any commentary (Fausto, 1517). Fausto (1480 – *c.*1551; his first name was also written 'Vettore' or given as 'Victor' or 'Victoris') was a professor of Greek at the Scuola Grande di San Marco, which was not a school in the modern sense of the word, but more of a meeting-place for both secular and religious activities. He was one of a growing number of Venetian scholars at the beginning of the sixteenth century to examine ancient military texts in order to assist in the defense of the territory against their erstwhile Ottoman enemies. At that time, the backbone of Venice's navy was the trireme galley, a long, light, ram-bowed warship with three banks of oars, which was mass-produced at the sprawling Arsenal dockyard to the east of the main square of San Marco. During his tenure at the Scuola, Fausto had carefully examined Greek and Roman texts concerning naval warfare with oared ships, as well as speaking with Venetian shipbuilders and ship masters, and mariners from many other ports who came to the great city on the Adriatic. He came to the conclusion that

the Venetian trireme, which had one oarsman per oar, could be improved by adding a second rower to each of the top two banks of oars, which was a common practice in Greece after the end of the Peloponnesian wars in 404 BC. In August 1525 Fausto presented to the Senate his model of a quinquereme, a 5-oarsman-per-tier galley, which he argued would be more effective than the trireme (Lane, 1934, pp. 64-71; Concina, 1984, pp. 108-134; Concina, 1990, pp. 70-90).[1]

Fausto was not a shipbuilder, so there was naturally a considerable uneasiness within the Senate to spend the money and manpower on building a full-sized version of his model, which would be both longer and wider than a standard trireme. However, since the only unknown was his proposed arrangement of oarsmen, they voted him funds to build a land-based model of his concept. When this showed that the oarsmen could row together reasonably well, he was voted additional funds for material and allowed the use of an Arsenal dock to build a full-sized quinquereme, which was completed in April 1529. It won a race against a lighter trireme, though it was harder to maneuver. The concept was not immediately accepted, but over the course of several decades the Arsenal built a number of quinqueremes, which continued to be in service for the next forty years. Indeed, a Fausto quinquereme was originally the flagship of Marcantonio Colonna, the Italian admiral who later fought at the battle of Lepanto, before it was struck by lightning and burned in October 1570 (a year before the battle) at Kotor in modern-day Montenegro (Capponi, 2007, pp. 147, 152. Guglielmotti (1862, p. 25) cites a letter in the Florence archives from Cosimo Bartoli, Venice ambassador to Florence, dated 15 June 1570, noting that Colonna's quinquereme had been built by Fausto some thirty years earlier, but had never before been in the water).

The link between Fausto's quinquereme and his translation of *Mechanical Problems* is at best conjectural, but there is enough evidence from contemporary sources to plausibly infer that he was either inspired by the ancient work to re-imagine how a galley could be improved, or used the ancient text to support his proposals. Problem 4, it will be recalled, asked: 'Why do the rowers in the middle of the ship contribute the most to its movement?' The answer, according to the author who undoubtedly saw many war galleys, was that since the ship was wider amidships, more of the oar was inside the ship. (It is here necessary to point out that the all the oars of a Greek galley were of about equal length and arranged to form a straight line outside the ship, so the oars at amidships were longer inboard than the ones at the narrower bow and stern (Morrison, Coates & Rankov, 2000, pp. 137-138)) The 'lever law' here assumes

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[1] It is here necessary to clarify some often-confusing terms. A *trireme – triere* in Greek -- is generally considered to be a ship with three vertically-arranged banks of oars for every tier, or column of oars, along the side of the galley, normally with one oarsman pulling each oar. The top oarsman was seated the furthest outboard, and the bottom two were progressively further inboard. Modern research, using full-scale vessels as well as virtual prototypes, has demonstrated that three banks of oars are the maximum number that can be effectively arranged within a vertical tier. Thus, the term *quinquereme* did not refer to the number of oars but rather the number of oarsman per tier; two each on the top two tiers, and a single rower on the bottom. Morrison and Gardiner (2004) provide an excellent overview of oared vessels; and see especially Morrison, Coates and Rankov (2000) for a detailed explanation of the construction and mechanics of rowing multi-tiered oared vessels.

that the paddle entering the sea is fixed, so the fulcrum (thole-pin) moves forward, pushing the ship forward. Fausto's insight was to connect this law with the ancient use of multiple oarsmen on each oar, which would be achievable by lengthening the inboard reach of the oars, requiring a widening of the ship overall. In other words, the benefit from using the *Mechanical Problems* was in the arrangement of oarsmen to provide the greatest mechanical advantage on each oar, rather than depending solely on the greater number of oarsmen. Fausto did not state any of this explicitly in his proposal to the Senate, but late in his life he remarked that 'having taken on the text of *Mechanical Problems* for translation… it had enriched the design of every splendid machine'. A contemporary of Fausto, Alessandro Zorzi, wrote some thirty years after Fausto's death that 'the thing does not consist in the number of people, but rather how much of the oar is within the galley, and how easy it is to row that oar; for as much as the inside and outside of the oar are the same length from the fulcrum, the easier it will be to lever the largest weight' (Concina, 1990, pp. 80-81, 166).

In 1545, after two decades of working on his quinquereme and other projects, Fausto had began revising his translation of *Mechanical Problems* with additional commentary based on his experiences, and including drawings of various inventions. Colleagues who viewed this now-lost manuscript asserted that it would have contributed greatly to the architectural discipline; however, he died before he could complete it (Concina, 1988, p. 162).

The Venice Arsenal was also the site of a second attempt to directly apply Aristotelian mechanics to naval architecture, though with quite different results. The great Italian mathematician and astronomer Galileo Galilei (1564-1642) had settled in the Venetian Republic in 1592, and was immediately fascinated by the workings of the great shipyard, the Venice Arsenal. The admiration was mutual, for soon after his arrival, one of the Commissioners of the Arsenal, Giacomo Contarini (1536-1595), wrote him asking for advice on the placement of oars in a galley. Contarini was no mere bureaucrat; a skilled observer, he had carefully documented the manner of laying out and constructing galleys in two manuscripts that circulated widely within the Arsenal (Contarini, ca. 1590; Contarini, ca. 1592). Contarini and his Venetian colleagues were, at the time, attempting to build a more maneuverable fleet after the great victory at Lepanto in 1571, in order to meet the renascent threat from the Ottoman Empire.

Contarini's question concerning the optimal position of oars and rowers for propulsion and maneuverability caused Galileo to reflect upon the *Mechanical Problems*, in much the way Fausto had done long before his birth. As noted by science historians Jürgen Renn and Matteo Valleriani, Galileo, like Fausto, had developed a "mental model" of the balanced lever to explain how different mechanical devices can achieve a large effect with a small force. But his reading of *Mechanical Problems* led to a completely opposite conclusion from Fausto. Instead of placing more of the oar inside the vessel, as Fausto evidently did, Galileo wrote back to Contarini suggesting that the inboard reach, where the rowers sit, should be as *short* as possible. Galileo assumed (as did Fausto) that the oar blade was immobile in the water, but he argued that the longer oar length *outside* the boat would transfer the maximum amount of motion to the thole-pin and therefore to the vessel.

Contarini's response to Galileo, written just a few days later, made it clear that the scientist had not given careful thought to the practical aspects of Aristotelian mechanics, and in fact this letter seems to have provided Galileo a catalyst for a complete reexamination of the subject. The length and position of the oars have to be balanced, Contarini explained, not only with regard to the limited human force of the rowers, but also due to the structural limits of the oars themselves. A much longer oar on the outside would break under the loading; and for it to be structurally resistant, the thickness would have to increase so much that an oarsmen would no longer be able to move it. This response by Contarini caused Galileo to reconsider his conception of mechanics and begin examining the strength of materials. The results of this research would only be published in his famous *Two New Sciences* some forty years later, where he complimented the Arsenal workers on their expertise and analysis in the field of mechanics (Renn & Valleriani, 2001, pp. 14-27. My two anonymous reviewers also contributed to the analysis of Galileo's work. For other Aristotelian influences on Galilean mechanics, see Wallace (1991, pp. 368-378)).

4. Further Analysis of Mechanical Problems in Late Renaissance Mechanics, 1531-1669

About the time Fausto was building his quinqueremes in Venice, a Portuguese mathematician named Pedro Nunes (1502-1578) was reinterpreting Aristotle's works. As a young professor and cosmographer at the University of Lisbon, he was principally concerned with navigation, which at the time incorporated aspects of shipbuilding and maneuver. Around 1531 he began using Fausto's translation of *Mechanical Problems* in his teachings, but quickly found flaws in the assumptions related to the oar problems. Specifically, Nunes argued that the rowing motion involved not one but two types of motion: the linear one of the ship, assumed by the original author; but also, overlaid on that, the circular motion of the oar around the thole-pin. Using a series of geometrical arguments, Nunes refuted the assertion made in *Mechanical Problems* that the thole-pin acts as the fulcrum of the lever, which according to its author enabled the ship to move further forward than the oar blade moves backward; rather, he stated, the blade of the oar in the water is the actual pivot point (Sousa Leitão, 2002 and 2003. Note that Nunes' assertion is actually fairly close to modern theories of rowing). Although justifiably proud of his rigorous analysis, he did not publish his findings until thirty years later in 1566. Nunes' results were reproduced almost integrally by Henri de Monantheuil (1536-1606) in his own 1599 commentary on Aristotle, and in 1615 by Giuseppe Biancani (1566-1624) in his *Aristotelis loca mathematica* (Monantheuil, 1599 pp. 82-90; Biancani, 1615, pp. 159-168). Biancani actually copied Nunes' results verbatim, stating that the Portuguese mathematician had developed the 'finest, most accurate and most meritorious' explanation of the Aristotelian problems (p. 162)).

The Italian mathematician and writer Bernardino Baldi (1553-1617) was the next to elaborate on *Mechanical Problems*, beginning his commentary in the 1580s, though it was only published posthumously in 1621. Using different geometrical principles, Baldi also argued – as did Nunes – that the blade within the ocean is the fulcrum of the oar, not the thole-pin. He then spent a considerable amount of time on Question 5

regarding the action of the rudder. He apparently performed an experiment using a pontoon fixed by a rope in a flowing river, in order to determine the course a ship would take when the rudder was put over. He then analyzed Question 6 (regarding the height of the mast), arguing that it is the same type of fulcrum as a claw-hammer; the higher the mast, the more it pulls the stern up and the faster the ship goes. Baldi argued that constructors cleverly place the mast forward of amidships in order to give it a greater lever arm, so as to drive the ship faster (Baldi, 1621, pp. 60-76; Rank, 1984, pp. 33-35).

In 1627, the Italian theologian Giovanni di Guevara (1561-1641), a friend of Galileo, published one of the most thorough commentaries on *Mechanical Problems,* in which he argued that mechanics was less natural philosophy than a man-made one, and was therefore a fundamentally mathematical discipline (Guevara, 1627, p. 5). He extensively covered the problems of naval architecture in 30 dense and well-illustrated pages, explicitly basing his analysis on the works of Nunes and Baldi. Of particular interest is Guevara's analysis of Question 7, on the effect of the forward and after parts of the sail on the ship's maneuvering when running close-hauled across the wind. In Guevara's view, a lateen sail (a triangular sail with the highest part aft of the mast) would tend to billow out before the wind, causing a change in the angle of incidence to the wind between the forward part and the after part of the sail. Guevara argued that the after part of the sail would, like an open bag, capture more wind (in modern terms, the pressure point of the sail moves aft), thereby interfering more with the rudder; hence sailors will take in the after part of the sail first to improve maneuverability (Guevara, 1627, pp. 90-129; Rank, 1984, pp. 72-75).

The 'wind bag' model of the sail was further extended by the Jesuit mathematician Honoré Fabri (1607-1688), in his monumental *Physica* published in 1669. Fabri, drawing on the analysis of Guevara, argued that a sail transfers its energy to the ship because it is pliable and holds the wind; if it were flat then the wind would bounce off it. For the sails to hold the wind, however, they must be porous like a bird's wing, which he assumed let air through the feathers in order to fly (Fabri, 1669, pp. 471-472; Rank, 1984, pp. 74-76. This 'wind bag' model of the sail was further expanded by Johann and Jakob Bernoulli in the 1690s, and in the mid-1700s by Leonhard Euler; the model remained current through the early 1900s, when aerodynamic theory became systematically applied to sail design; see Simón Calero, 2008, pp. 254-264).

These *pensées* of Nunes, Baldi, Guevara and Fabri on the mechanical problems of oars and lateen sails associated with Mediterranean vessels ultimately had little impact on the evolution of naval architecture. They were never referred to by later authors, who by then were concerning themselves with problems of stability and masting inherent in large ocean-going ships.

5. *Aristotle and the Problem of Buoyancy in Late Renaissance and Jesuit Mechanics, 1611-1673*

Although *Mechanical Problems* proved to be the principal focus for the efforts of natural philosophers examining naval architecture during the late Renaissance and early part of the Scientific Revolution, they also wrestled with another maritime aspect of the Aristotelian corpus that was at odds with observed facts; the problem of buoyancy,

specifically the rationale for why a solid body floats in water. Aristotle had argued that the properties of floating and sinking were due to the relative weight of the material in each medium, as well as the shape of the body. In *De Caelo (On the Heavens)*, he extensively discussed the concepts of lightness and heaviness of objects; and in a final chapter, he briefly stated the reasons why an object floats upon water (Aristotle, 1984, 312-313a, at pp. 402-405):

> In air, for instance, a talent's weight of wood [about 26 kg] is heavier than a mina of lead [about 0.4 kg] but in water the wood is lighter… the reason why broad things keep their place is because they cover so wide a surface and the greater quantity is less easily disrupted. Bodies of the opposite shape sink down because they occupy so little of the surface, which is therefore easily parted.

In conflict with Aristotle's explanation was the principle developed by Archimedes: an object will float if it displaces a volume of water equal to or greater than its weight. Although many scientists – and even some shipbuilders – had long since adopted Archimedes' model, the debate between these two theories was still so contentious that in the year 1611 Galileo found himself refuting Aristotle's 'shape concept' in favor of a more Archimedean explanation involving the density of floating bodies, over the course of a now-famous three-day discussion of the matter which he recorded in his 1612 work *Discourse on Floating Bodies* (Drake, 1981; Palmieri, 2005).

This discourse, along with the well-known elucidations of Archimedes' hydrostatic principles by Simon Stevin and Blaise Pascal, helped to fundamentally shift scientific sentiment away from Aristotle and towards Archimedes during the mid-seventeenth century (Stevin, 1586; Pascal, 1663). However, Aristotle still held sway in the philosophy of the Jesuit academies, which were arguably the most influential educational system in Europe at the time. The Jesuit curriculum outlined in the *Ratio Studiorum*, the plan of studies employed by its network of schools across Europe and around the world, leaned heavily on Aristotelian writings in the fields of mathematics and mechanics, including *Physics*, *De Caelo* and *Mechanical Problems*. The study of mechanics as a 'mixed science' (i.e., combining principles of both 'pure' mathematics and 'practical' physics) included collisions, fluids, hydrostatics and the motion of bodies in resisting media, all of which found a home in the nascent field of naval architecture.

Honoré Fabri (mentioned above) was not the first Jesuit to extend Aristotelian mechanics into the realm of naval architecture, nor was it unusual that a Catholic priest, ostensibly focused on matters of theology, be so deeply immersed in such secular concerns. Jesuit professors were at the forefront of commenting and expanding upon these works, often writing conflicting interpretations that fueled free and lively debates both inside and outside the Jesuit community (Wallace, 1984, pp. 202-209; Lennox, 1986; Hellyer, 2005, pp. 83-84, 119-122; Meli, 2006, pp. 6-7).

Starting in 1623, several Jesuit colleges in France began teaching hydrography, a subject that included navigation and piloting as well as ship design and construction. The first major work on the subject, *Hydrographie contenant la théorie et la pratique de toutes les parties de la navigation*, written in 1643 by the Jesuit mathematics professor at La Flèche and Clermont, Georges Fournier (1595-1652), included a substantial discourse

on naval architecture (Fournier, 1643; Vergé-Franceschi, 1991, pp. 210-211; Romano, 2006, pp. 362-364).

However, the Jesuit curriculum continued to place Aristotle on a pedestal, and he would not be easily dislodged. For example, when Georges Fournier attempted to explain why a ship floats in *Hydrographie*, he continued to mix Archimedean principles (i.e., correctly asserting that the displacement of a ship equals the weight of the water that it pushes aside) with such Aristotelian concepts as there being a difference in the weight of material according to the medium it inhabits (Fournier, 1643, pp. 608-609, 612-614):

> There is a difference in the weight of the parts that are in the water and those in the air….the same piece [of the ship] may be partly in water and partly in air, and the part in the water weights less. …For all these reasons and others, I conclude that it is *moralement impossible* [impossible by rational standards] to be able to precisely determine and give general practice by which one can know the force which would support a vessel. Also, I know of no mathematician who has attempted this, even none who has proposed the question.

Nevertheless, at the same time Fournier was explaining in scholarly terms why the displacement of ships could *not* be measured, naval constructors across the English Channel, unencumbered by Jesuit philosophies, were in fact routinely doing just that. Anthony Deane, in the best-known example, applied the principles of Archimedes to paper drawings of hull curves (such drawings where then coming into vogue in England, but were still almost unknown in France) to graphically calculate a warship's immersed volume, displacement and draught in order to ensure that gunports would be sufficiently high above the waterline so they would not flood while under sail (Deane, 1981, pp. 7-20). This was a very practical calculation that required only rudimentary arithmetic; but as yet, this did not represent an attempt to extend Archimedes' mathematical principles into an overall science of ship design.

6. The Apogee of Aristotelian Naval Architecture in the French Navy and the Works of Paul Hoste, 1685-1700

The first tentative ventures into developing a science of ship design based on mathematical theories occurred during the reign of Louis XIV, when the moribund French navy, under the ministry of Jean-Baptiste Colbert (1619-1683), was rebuilt to compete with the powerful English navy. Colbert, who famously created the Paris Academy of Sciences to bolster French commerce and policy, also turned to science as a way to make every French ship better than its English counterpart. Colbert and his successors sponsored scientific research on naval architecture, including a famous series of experiments conducted in the Grand Canal at Versailles to test mathematically-based shipbuilding theories (Ferreiro, 2007, pp. 51-112). At the same time, a series of schools were created to professionalize the naval officers who would man the warships. The Ecoles des Gardes de la Marine (cadet academies) were established in the dockyards of Rochefort, Brest and Toulon, incorporating practical training in gunnery and fencing with theoretical instruction in mathematics, fortifications and hydrography, with instruction by Jesuit professors.

One such professor was Paul Hoste (1652-1700), a mathematician born on May 19, 1652 in Pont-de-Veyle in Bresse, about 400 km south of Paris. He attended the Jesuit College in the town, and was admitted into a Jesuit seminary around 1669 at age 17. In 1685 at age 33, he was appointed as professor of mathematics and hydrography at the newly-formed Ecole des Gardes de la Marine in Toulon. While there, he met Admiral Anne-Hilarion de Cotentin, Comte de Tourville (1642-1701), with whom he would later serve as chaplain (Lambert, 1751). Tourville took a keen interest in Hoste's scientific and mathematical ideas, and sponsored a series of experiments to confirm Hoste's concept that a ship having a hemispherical bow and stern would be faster than a conventional hull form. Though the model tests were inconclusive, Tourville encouraged Hoste to continue with his research on mathematics, which the Jesuit soon applied to the principles of naval warfare (Hoste, 1692).

As chaplain aboard Tourville's ships, Hoste witnessed naval warfare first-hand, including the battle of La Hogue in 1692 where he survived the burning and sinking of the flagship *Soleil Royale*. In 1697 Hoste collaborated with Tourville to a produce a groundbreaking and widely-read book on naval tactics, *L'Art des Armées Navales*, which combined the admiral's fighting instructions with the neat geometry of the mathematics professor. Appended to the text was a shorter work on naval architecture, *Théorie de la construction des vaisseaux*, where at Tourville's express orders, he elaborated on his mechanical theories of ship design and performance. Yet these published ideas were incomplete, for he was working on the manuscript of a second book, titled *Architecture navalle*, when he died prematurely of an illness on February 23, 1700, not quite 48 years of age (Hoste, 1697; Hoste, 1714; Lambert, 1751, p. 58).

Taken together, *Théorie de la construction des vaisseaux* and *Architecture navalle* represent the apogee of the Aristotelian heritage in early naval architecture. They were the first synthetic works on the subject, linking ship theory with practical shipbuilding (for example, directly relating the effects of fluid resistance on hull form; Hoste argued that since spheres and hemispheres had the lowest surface-area-to-volume ratio of any solid, they had the least resistance, which is why his ship models had round ends). At the same time, these works combined the mechanics of both Aristotle and Archimedes to explain and quantify the behavior of ships (Hoste, 1697, pp. 8, 12-13, 23-28, 41-45; Hoste, 1714, pp. 11-12).

Hoste's analyses of ship theory were a complete departure from his predecessors, for two reasons: first, instead of providing qualitative explanations, he developed mathematical equations which could be analyzed to give direct numerical results; and second, rather than limiting himself to discourses on rowing and the position of oars based on the *Mechanical Problems* (which Hoste never mentioned or even alluded to), he analyzed the problems of sailing warships, which were now the main concern for modern navies. For example, in 1664 the 54-gun *Lune* had broken apart and foundered just off Toulon with the loss of over 500 men, a disaster later (incorrectly) blamed on loss of stability. Paul Hoste used this catastrophe to introduce his discourse on the theory of ship design, stating 'there is no greater fault than a vessel which cannot carry sail' (Hoste, 1697, p. 46).

Hoste's examination of ship stability, the 'ability to carry sail', demonstrates the subtle and sometimes confusing mix of Aristotelian and Archimedean mathematics that marked his entire corpus. He began by explaining, like Anthony Deane before him, the importance of calculating the displacement of a ship to ensure that the gun-ports are sufficiently high above the water. He then demonstrated just how far the Jesuit curriculum had advanced since the time of Fournier, when instead of complaining that it was *moralement impossible* to calculate displacement, he actually provided several methods to do so, all based on the same solid understanding of Archimedean principles as Deane: moreover, Hoste not only explained how to calculate graphically the volume and displacement of a ship based on drawings, but also provided methods to calculate the volume and displacement of actual ships by measuring them from the outside (Hoste, 1697, p. 48; Hoste, 1714, pp. 1-10).

Hoste went on to explain that the moment (he used the term 'force') the ship must have in order to properly carry sail, is that which it needs to resist the sail overturning moment. He defined this moment as the the product of the the wind-on-sail force times the speed of the mast rotation —in other words, he explained the force qualitatively in terms of the Aristotelian lever law ($Fv = fV$). However, he immediately (and unapologetically) used the Archimedean lever law ($Fl = fL$) to describe in mathematical terms how to determine the stability of the ship (Hoste, 1697, pp. 49, 54-56):

> If one knows the centre of gravity of the vessel, one easily can find the force it has to carry sail, which is nothing less than the product of the weight of the vessel times the distance of the centres [of weight and displacement].

Or, in modern terms:

$$\text{righting moment} = \Delta \, (BG)$$

where

Δ = displacement (weight) of ship
B = centre of displacement
G = centre of gravity
BG = distance from B to G

Although he did not provide a theoretical means for determining this 'force to carry sail', he did furnish a procedure that could empirically demonstrate this —the inclining experiment, which tangibly demonstrates stability by measuring the effect of a weight hung over the side. Hoste asserted that, by measuring the angle of inclination of the ship due to suspending a weight M from a boom at a certain height, that the 'force to carry sail' can be determined (Hoste, 1697, pp. 55-59). In Hoste's geometry using Figure 2, the center of gravity is A, the center of displacement is B, and the weight is hung from a yard connected to the mast at F, so that:

$$\text{inclining moment} = \text{righting moment}$$

$$M \times BF = \Delta \times BA$$

He therefore arrived at the following equation for the force to support sail :

$$\Delta \, BA = \frac{M}{\sin \angle BAN} \, (BA + AF)$$

Or in modern notation:
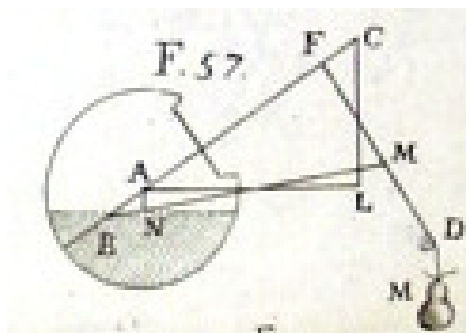
$$\Delta\, BG = \frac{W}{\sin\theta}\, BF$$

Figure 2
Hoste's diagram of an inclining experiment
(Hoste, *Théorie de la construction des vaisseaux*, figure 57)

There were several problems with this theorem, most notably that it leads to the conclusion that the higher the centre of gravity of the ship, the *more* stable it is, which is of course the opposite of what actually happens. Nevertheless, it represented the first attempt to develop a theoretical basis for ship stability, and was perhaps one of the few examples where Aristotelian principles found a direct expression in mathematical mechanics.

7. Conclusion: The Downfall of Aristotelian Mechanics and the Rise of Newtonian-Based Naval Architecture, 1727-1746

Paul Hoste's works were was the first true synthesis of naval architecture that treated the ship as a complete system, and would remain the only such work for almost half a century. Although they were enormously influential, they were already obsolete when written, for they appeared just as Isaac Newton's *Principia Mathematica* (1687) was starting to find acceptance. It was an awkward era, when mathematicians and scientists attempted to somehow fuse old and new concepts, as did Hoste when he combined Aristotle and Archimedes to explain ship stability. This combination of two disparate theories at first led the French hydrographer Pierre Bouguer (1698-1758) astray when he wrote a prize-winning treatise for the Paris Academy of Sciences on the masting of ships in 1727. To explain ship stability – a critical concept of naval architecture that was still poorly understood —he invoked Hoste's 'force to carry sail', which was founded on Aristotelian precepts of the lever, while at the same time mixing in Archimedean lever laws to explain the shift in buoyancy when a ship heels over. This combination of Aristotelian and Archimedean mechanics proved unsuccessful in providing a meaningful theory of ship stability (Bouguer, 1728, pp. 24-25).

Within a few years, however, two works were published that firmly established a complete synthesis of ship theory based solely on the mechanics of Archimedes and the mathematics of Isaac Newton, providing a set of tools that allowed naval constructors to predict how their ships would float and sail. In 1746 Bouguer published his groundbreaking *Traité du navire*, while in 1749 the great mathematician Leonhard Euler published his magisterial *Scientia Navalis*. Among their most durable concepts was a complete explanation of ship stability based upon Archimedean lever laws and hydrostatics, analyzed using Newtonian calculus, which remains the basis for modern stability theory. Yet perhaps something of Aristotle remains, for Bouguer also provided us with the practical method for verifying stability (Bouguer, 1746, pp. 199-324; Euler, 1749, pp. 42-130; Ferreiro, 2007, pp. 157-257). Today's naval architects use the same the inclining experiment, little changed from Hoste's first elucidation, to verify that a ship is safe and ready to sail.

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